Using GPS to Monitor the Forth Road Bridge

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Key words: GNSS, bridges, deflection monitoring, deformation monitoring.

SUMMARY

The use of GPS to monitor the deflections of large bridges has been an ongoing topic of research between the University of Nottingham and Brunel University for about a decade.

In February 2005, an extensive survey was carried out on the Forth Road Bridge in Scotland. The suspension bridge itself has a main span length of 1,005m long, and is designed to withstand large movements.

During the field trials, 46 hours of continuous GPS data was gathered using Leica 500 series GPS receivers at a rate of 10Hz. GPS receivers were located upon the bridge deck at 5 locations and on top of the two southern towers. These data were then all post processed relative to two reference GPS receivers located adjacent to the bridge as well as data that was downloaded from the Ordnance Survey's Active Station Network in the area. In addition to this, a weather station was used to record the wind speed, direction, temperature, pressure and relative humidity.

During the majority of the trials, normal traffic flow was observed, however, during the second night, two lorries with a combined weight of 80 tonnes were hired and were driven across the bridge in a variety of maneuvers. During the maneuvers, the bridge was closed to other traffic. The known traffic loading and wind loading were therefore known, and this data used to compare the GPS results to a Finite Element Model of the structure.

Further to this, the wind loading for part of the field trials was high, with gusts of up to 60mph (90 km/hr). In addition, a lorry weighing approximately 100 tonnes passed over the bridge during part of the trials.

All of the above phenomena add up to give the data some very interesting results. The following paper details the trials, as well as some of the results.

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1. INTRODUCTION TO BRIDGE MONITORING BY GPS

The use of GPS to monitor the deflections of large bridges, notably suspension brides, is an area of research that has been ongoing between the University of Nottingham and Brunel University for about a decade (Ashkenazi et al., 1996, Ashkenazi et al, 1997, Brown et al., 1999, Meng, 2002; Meng et al., 2004, Roberts et al., 1999). This work has evolved in both the analysis of the GPS data to include multipath mitigation (Roberts et al, 2002), using the internet to transfer GPS data (Dodson et al 2004) as well as the GPS processing itself, both using single ad dual frequency code/carrier data (Cosser et al, 2003).

Further to this, the GPS results have been successfully compared to computer models, including Finite Element Models of the structures (Brown et al, 1999).

The initial trials showed that the use of carrier phase GPS could indeed allow sub-centimetre movements to be detected. In addition to this, the frequencies of the movements could also be calculated.

To date, four Bridges have been used as test beds; these include the Humber Bridge located near Hull in the North East of England, the London Millennium Bridge, and the Wilford suspension bridge in Nottingham and now the Forth Road Bridge in Scotland.

The Humber Bridge was the first bridge to be used by the group in such trials. In 1996, Brunel University was commissioned by the Humber Bridge Board to create a FEM of the bridge. Following this, the group at the University of Nottingham carried out initial Bridge Monitoring trials on the Bridge, whose data was then compared to the FEM. This then led to further trials and comparisons over the next decade.

2. DEFLECTION MOITORING OF THE FORTH ROAD BRIDGE BY GPS

The Forth Road Bridge has an overall length of 2.5 km and a main span length of 1,005m. It was opened in 1964. Traffic has steadily increased over this bridge, from 4 million vehicles in 1964 to over 23 million in 2002. In addition, the heaviest commercial vehicles weighed 24 tonnes; the current limit is 44 tonnes. When the bridge was opened, it brought to an end an 800 year history of ferry-boat service across the river at Queensferry in Scotland.

During the 8 to 10th February 2005, staff from the IESSG at the University of Nottingham and from Brunel University gathered data from GPS receivers located upon the Forth Road Bridge in Scotland. This was conducted as part of a feasibility study, investigating the use of GPS to establish the magnitude and frequencies of the Bridge's deflections (Roberts, et al. 2005).

During the trials, 7 survey grade GPS receivers were located upon the bridge, and a further two located as reference stations adjacent to the structure. In addition, a high accuracy Applanix INS, POS-RS, was also located upon the bridge. The use of INS for bridge deformation monitoring his is discussed by Hide et al. (2005). Of the 7 receivers on the bridge, four were located at the $^{1}/_{8}$, ¼, ½ and ¾ span on the East side of the deck, whilst a fifth was located at the ½ span on the west side of the bridge. A further two receivers were located on top of the two towers at the south end of the bridge. The Bridge's GPS receivers were coordinated relative to two reference receivers located adjacent to the bridge, on the southern end viewing platform. The receiver layout is shown in Figure 1. The reader should be aware that the bridge is orientated in an almost North to South direction.

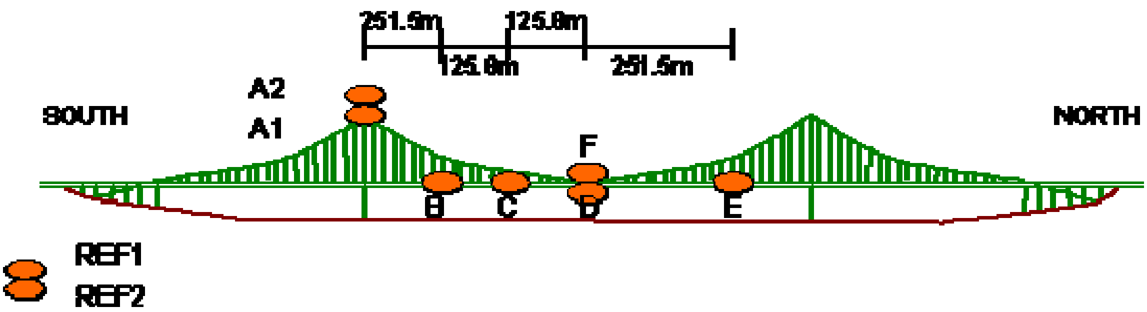

Figure 1. The GPS receiver locations on the Forth Road Bridge.

All the GPS receivers gathered data, almost non-stop, for more than a 46 hour period, at a rate of 10Hz or 20 Hz. Leica 530, 510 and GPS1200 receivers were used during the trials. Table 1 shows a list of the receivers and antennas used in the trial. Clamps were fabricated by FETA to allow the GPS antennas to be attached to the Bridge's handrail, but constructed in such a way as not to pose a danger to passing people either on foot or cycling. AC power was supplied at each receiver site which made the trials a lot easier. Figure 2 illustrated a Leica AT503 Choke Ring antennas used as reference stations, and Figure 3 illustrates a GPS receiver located on the bridge, with the AT504 antenna attached to the handrail with the specially fabricated clamp.

Location	Receiver Type	Antenna Type	Location
B	Leica SR530	AT503	E 1/4 span
C	Leica SR530	AT503	E 3/8 span
D	Leica SR530	AT503	E 1/2 span
E	POS RS	NovAtel600	E 3/4 span
F	Leica GX1230	AT504	W 1/2 span
A1	Leica SR530	AT504	Tower West (S)
A2	Leica SR510	AT501	Tower East (S)
R1	Leica SR530	AT503	Reference
R2	Leica SR530	AT503	Reference

Table 1. Antenna and Receiver Types

Figure 2. Two Leica AT503 Choke Ring antennas located adjacent to the Forth Road Bridge.

Figure 3. A GPS receiver located on the bridge.

During the trials, a digital weather station was installed at site F to continuously gather the wind speed and direction, as well as the air temperature, and humidity at a sampling rate of 15 seconds. This could then be used to evaluate the total force of wind and traffic loadings, experienced by the bridge.

During previous trials upon other bridges, the 10Hz GPS data has been densified with accelerometers capable of gathering data at up to 1,000 Hz (Roberts et al. 2004). However, as this structure is so large, such high speed movements were not expected, and hence no accelerometers were used. The INS was used as a means of investigating its application for such a monitoring work (Hide et al. 2005).

The Ordnance Survey of Great Britain has over 50 active station GPS receivers located around the UK. These stations gather data at 1Hz, but then the data is made available at a 15s epoch rate to the public via their web site (http://www.gps.gov.uk/). In addition to this, the OS are currently establishing their own Network RTK GPS system in the UK. During the trials, the GPS data from an OS station located adjacent to Edinburgh (EDIN) were gathered at a rate of 1 Hz for the IESSG in order to use these as a comparison with the bridge data processed relative to the reference stations next to the bridge.

During the trials, gusts of up to 60 mph were experienced, and the traffic loading was very heavy, especially at rush hour times in early morning and evening time. In addition, during the trials, a 100 tonne lorry passed over the bridge, and a series of known load trials were carried out with two 40 tonne lorries, equipped with DGPS to ascertain their locations, and having the bridge closed to other traffic. This is the most controlled of all the trials, as the wind loading was recorded by the weather station and the only traffic present on the bridge were the two 40 tonne lorries. The expected movements were calculated from the FEM, and the true results compared very well to these. Further to this, during the trials, IESSG staff took shifts to occupy the points, sitting in cars parked the pedestrian paths on each side of the bridge whilst the GPS receivers gathered the data to post-process in an On The Fly manner. During the data gathering exercise, it was evident that the bridge did move, and it was also possible to see a rippling effect on the bridge deck.

The following paper details the trials, as well as the post processing techniques carried out on the single and dual frequency carrier phase data. However, real time processing is possible, but establishing the real time communications for this feasibility trial was seen as beyond the scope. The results are given for all the locations upon the bridge, showing how the bridge moves over a 46 hour period with a variety of loading. Further to this, detail is given on how the GPS results were compared to the FEM, and how such results can indeed be used for structural health monitoring.

The paper illustrates the technique, but analyses only a small portion of the vast amount of data gathered during the trials. However, this subset of data is sufficient to demonstrate the accuracy and repeatability of the procedure.

On processing the data, movements of almost a metre were seen and the rippling effect was evident in the data as well.

3. RESULTS

Some of the initial results are presented in this paper. Figures 4, 5 and 6 illustrate the absolute height, longitudinal and lateral displacements of the Bridge in a bridge coordinate system with the bridge main axis as its longitudinal axis and the lateral direction perpendicular to this axis and vertical direction as the height component, over the whole 46 hour period for site F. Different colours are used to indicate 8 sessions of data processing due to the limitation in the computer's capacity in handling 10 Hz data rate.

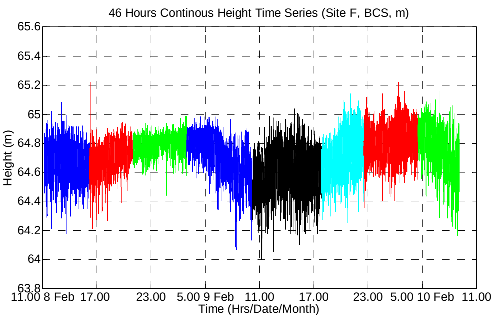

Figure 4. Height Deflections of Bridge site F over the 46 hour trial (Bridge Coordinate System).

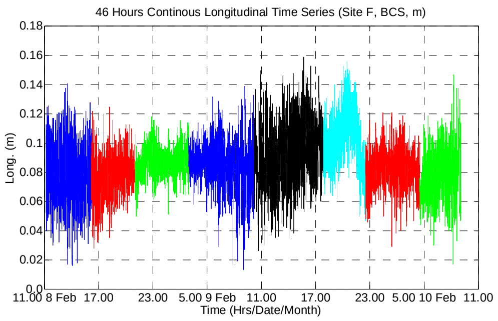

Figure 5. Longitudinal Deflections of Bridge site F over the 46 hour trial (Bridge Coordinate System).

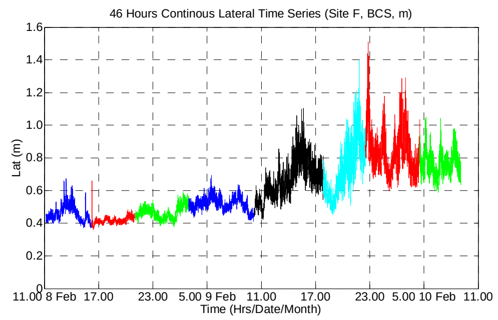

Figure 6. Lateral Deflections of Bridge site F over the 46 hour trial (Bridge Coordinate System).

It can be seen from these figures alone that the Bridge moves by an order of decimetres, and during the second night the lateral deflections were large, reaching metre level. This is due to the existence of high wind speeds.

The results are also compared to a finite element models (FEM) that exist of the bridge. The 3D coordinates available from the GPS results were transformed into frequencies of the structure's movements as shown in Figure 7. In this figure the first graph shows the natural frequencies extracted from vertical coordinate at site F, midspan west. This is similar as those of the same size bridges such as the Tsing Ma Bridge in Hong Kong and the Humber Bridge in the UK and the frequencies and magnitudes of the movements compared very well with the FEM.

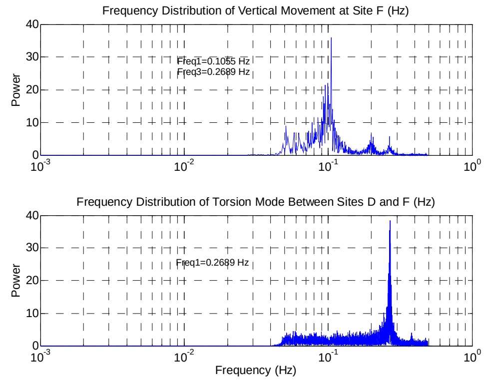

Figure 7. Natural Frequencies and Torsional Frequency of the Bridge.

The second graph in the figure shows the corresponding frequency of the torsion mode at the midspan of 0.2699 HZ, using the vertical coordinates of two opposite GPS receivers through differencing approach.

Figure 8 illustrates the relationship between the air temperature and height deflections at site F. Again it can be seen that there is a clear relationship here. Changes in temperature will change the lengths of the cables and hence the vertical position of the Bridge's deck.

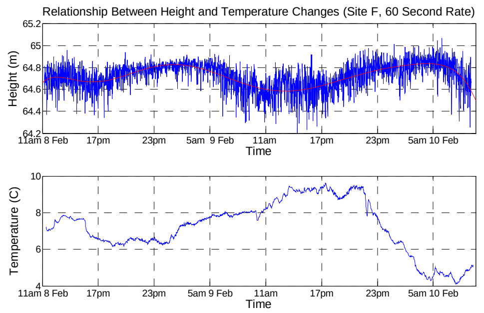

Figure 8. Relationship between air temperature and height location of the Bridge Deck at site F.

This shows the relationship over a temperature change of approximately 5.5 ºC. In reality, over a year's period, the air temperature at this location could well change from -10 ºC to +30 ºC, hence a larger vertical change could be expected. This demonstrates the capability of GPS for monitoring the response caused by the ambient loading.

During the trials a 100 tonne lorry passed over the Bridge. The lorry was precisely weighed and this section of the data was analysed in more detail. Figure 9 illustrates the height component of all the Bridge deck GPS receivers. It can be seen that the Bridge deflects by approximately 40cm, and that the maximum deflections at each point are offset from each other, indicating that the mass causes a wave effect along the Bridge.

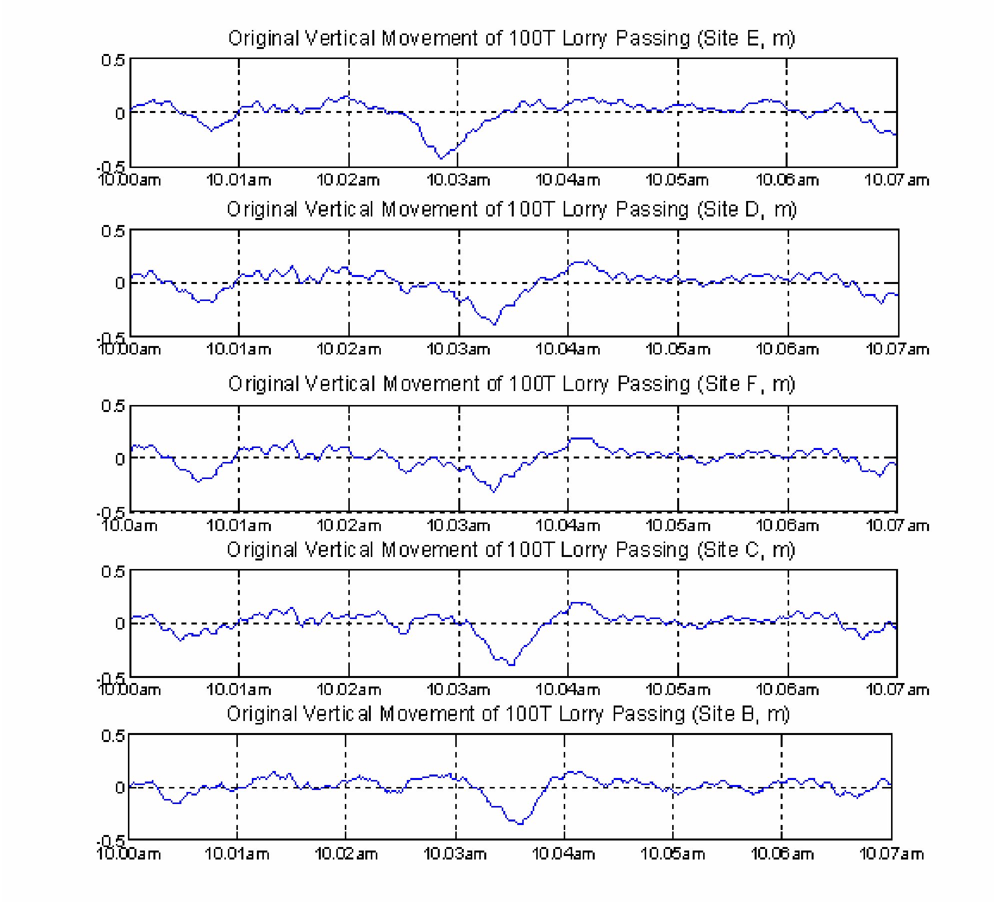

Figure 9. Height Deflections during the 100 tonne lorry

During the second night, two 40 tonne lorries were hired by FETA, accurately weighed and used as a controlled loading of the Bridge. These trials were carried out a couple of hours after the high winds experienced subsided slightly, and during these specific trials the Bridge was closed off to other traffic. The trials were carried out in the early hours of the morning, when the traffic flow over was at a minimum, and only closed whilst the control lorries passed over the Bridge ad re-opened whilst they turned around before subsequent crossings. The lorries started the trials at the North end of the Bridge, and the manoeuvres were as follows:

- 1 lorry ran from North to South
- 1 lorry ran from South to midspan on west side, stopped then the other lorry moved north to south
- 1 lorry moved from north to south and stopped at midspan, other moved south to north
- 1 lorry moved from south to north, and then both moved side by side north to south

During these trials, the lorries travelled at approximately 20 mph (30 km/hr). Figure 10 illustrates the overall movements experienced by the GPS receivers at different Bridge sites in the height component for the whole trials. The results show that the Bridge deflected by up to 400mm due to the combined 80 tonne loading.

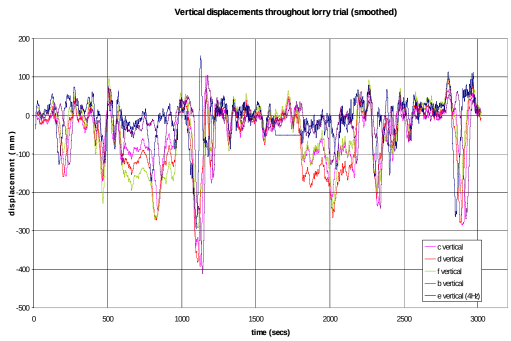

Figure 10. Height Deflections of the Bridge during the lorry trials.

Figure 11 illustrates the final maneuvers whereby the two lorries travelled from North to South whilst located side by side at approximately 20mph. The reader should note that vehicles travel on the left hand side of the road in the UK. The graph also shows the physical location of the lorries at any time e.g. Midspan, North Tower etc.

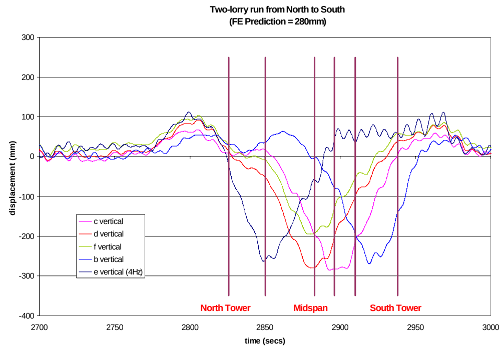

Figure 11. Height deflections during the two 40 tonne lorries passing over the Bridge side by side.

Three main phenomena are evident in Figure 11. Firstly the deflections at each GPS receiver site are offset from each other, in the same was as they were for Figure 9. Secondly, the GPS receivers located at sites D and F, midspan, deflect by different magnitudes, even though they start off at the same height. This is due to the torsional movement of the Bridge. The lorries, travelling on the left hand side of the carriageway from North to South, were in fact travelling on the East side of the Bridge. Hence the eastern side (site D) deflects more than the Western side (site F). Thirdly, the reader should note that the Bridge consists of three separate spans, each connected through a cable which passes over the top of the towers. As the lorries pass over the Northern side span, the load pushes this smaller span down, which in turn pulls the hanger cables down and the suspension cable which they are attached to. This then results in the suspension cable pulling up on the main span. This is evident in Figure 11 at around 2,800s. The lorries pass into the main span, and their passage over the measured positions are shown in Figure 11. As the lorries pass into the southerly side span, upward movement of the main span – described above – is observed.

4. CONCLUSIONS

The trials have shown that it is indeed feasible to use GPS on such a structure to measure the magnitude and frequencies of the Bridge's deflections in 3-D. This is possible at a rate of up to 10Hz, and all the results are synchronised to each other. Although the trials were carried out in a post processing manner, it is possible to have carried out these trials in real time as discussed by Dodson et al (2005).

The results have been compared to a FEM of the Bridge, and this could well be the basis of future bridge monitoring whereby real GPS data from specific points on a bridge are used in conjunction with FEM, or similar model, to assess the behaviour of a bridge. If the structure deteriorates over time or if any specific mishaps occur then these actions may well be picked up through the model and GPS data.

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BIOGRAPHICAL NOTES

Dr **Gethin Roberts** is an associate professor at the Institute of Engineering Surveying and Space Geodesy (IESSG), The University of Nottingham. He is chair of the FIG’s Working Group 6.4 “Engineering Surveys for Construction Works and Structural Engineering” as well as Task Force 6.1.4 ” Measurements and Analysis of Cyclic Deformations and Structural Vibrations”. He is the UK’s delegate for commission 6, and an active member of the UK’s Institution of Civil Engineering Surveyors.

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Dr **Xiaolin Meng** is a senior research fellow at the IESSG, he is currently working on the task of multi sensors for positioning buried piped and cables in built up areas. He has also worked for many years on the field of using GPS for deflection monitoring of bridges.

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