DEFLECTION MONITORING AND FREQUENCY ANALYSIS OF THE FORTH ROAD BRIDGE USING GPS

Gethin Wyn Roberts[1], Chris Brown[2], Xiaolin Meng[1]
[1]Institute of Engineering Surveying and Space Geodesy
The University of Nottingham
[2]School of Engineering and Design, Brunel University West London
Email: Gethin.Roberts@nottingham.ac.uk

Abstract: GNSS (Global Navigation Satellite Systems), in particular GPS (Global Positioning System), has been developed for deformation monitoring for twenty years or so. In addition, GPS has been used over the past decade to monitor the deflections of structures, notably large suspension bridges. Over time, the GPS receivers available have improved resolution and increased data rates. The resolution of the carrier phase observable is now typically 1mm or less, and the data can be gathered at up to 100 Hz. Furthermore, the research conducted in this field has investigated the mitigation of multipath through Adaptive Filtering techniques. The following paper discusses the deflection monitoring trials undertaken on the Forth Road Bridge in Scotland. The Bridge consists of 3 spans of dual carriageway, the main one being 1,005 m long, and the Bridge having an overall length of approximately 2.5 km. The Bridge itself is a very busy Bridge; its traffic loading when built in 1964 was 4 million vehicles per year, in 2002 it was 23 million. In addition, in 1964 the heaviest commercial vehicle weighed 24 tonnes, today it is 44 tonnes. It is evident that the Bridge's loading is far in excess of that when it was built. 46 hours of GPS code/carrier data were gathered upon the bridge at 7 locations; 5 on the deck and two on the southern tower. The GPS receivers comprised of Leica GPS1200, SR530 and SR510 (dual and single frequency receivers).The data was processed in an On The Fly (OTF) manner relative to the reference receiver located adjacent to the Bridge. Adaptive Filtering was used to mitigate multipath. During the trials, the traffic was halted at intermittent periods and the wind speed also monitored. In addition, traffic flow was monitored through video recording, or by conducting controlled trials with only specific pre-weighed traffic travelling over the Bridge. The results illustrate the magnitude and frequency of the deflections and are compared to the Finite Element Model (FEM) of the Bridge. In addition, the results were analysed to determine whether the GPS technique could well be used to assess the loading on the Bridge.

1. Introduction

During the period from the 8th to the 10th February 2005, staff from the IESSG at the University of Nottingham and from the School of Engineering and Design, Brunel University West London 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 both in the vertical and plan components.

Trials were conducted at 7 locations upon the Forth Road Bridge, over a 46 hour period starting at 11am on the 8th February 2005. The Bridge's GPS receivers were coordinated relative to two reference receivers located adjacent to the Bridge, on the southern end viewing platform. In addition to which, data from nearby Ordnance Survey's Active Station Network were downloaded at a rate of 1Hz for future processing. The Bridge is orientated in an almost north-south direction. The GPS receivers upon the Bridge were located at the east side mid span, quarter span, 3/4 span and 3/8 span, as well as the west side mid span and the top of the two southern towers.

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.

During the majority of the trials, normal traffic loading was experienced. In addition, a weather station was used to gather ambient temperature, relative humidity, atmospheric pressure, wind speed and direction all at a 15 second epoch interval. During the trials a 100-tonne lorry passed over the Bridge and also two 40-tonne lorries were hired to pass over the Bridge, whilst shut to other traffic, on the second night. During these trials, the 40-tonne lorries passed over the Bridge on a number of manoeuvres and had GPS receivers located upon them as to synchronise their position with the Bridge's movements.

The results illustrate that it is possible to measure 3D displacements of the Bridge to millimetre precision. The frequencies of the Bridge that were estimated during the trials were compared to the FEM.

The trials were carried out in a post processed manner, i.e. the data were gathered and then processed after the event. However, real time processing is possible, but establishing the real time communications was beyond the scope of this feasibility trial.

2. Background to the Work

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 [1, 2, 3 and 4]. This work has evolved in both the analysis of the GPS data to include multipath mitigation [5], using the internet to transfer GPS data [6] as well as the GPS processing itself, both using single and dual frequency code/carrier data from survey grade GPS receivers [7].

Further to this, the GPS results have been successfully compared to computer models, including Finite Element Models of the structures [4].

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.

3. The Forth Road Bridge

The Forth Road Bridge was opened in 1964, during which it was the longest suspended bridge outside of the USA. The Forth Road Bridge has an overall length of 2.5 km, a main span length of 1,005m. 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 opened, it brought to an end an 800 year history of ferry-boat service across the river at Queensferry.

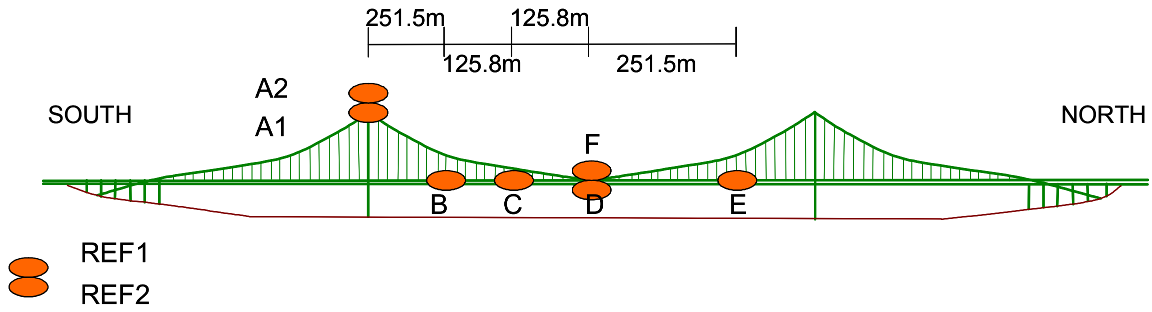

Figure 1. GPS location of the GPS antennas on the Forth road bridge

4. Forth Road Bridge GPS Survey

The data gathering trials were conducted over a nearly continuous 46 hour period from 11am on the 8 February 2005 to 9am on the 10 February 2005. For the whole period, 7 GPS receivers were located upon the bridge, as illustrated in Figure 1, and two reference GPS receivers were located on the viewing platform adjacent to the FETA building, Figure 2. The GPS receivers gathered data at a data rate of 10Hz. In addition, an Aplanix INS was located adjacent to point E [8]. The layout of the GPS was such that an antenna was located at each of the east side mid span, 1/4 span, 3/4 span and 3/8 span as well as the west side mid span and on top of the two southern towers. Table 1 illustrates the antenna and GPS receiver type located at each point.

Figure 2. The two reference GPS receivers

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 E
A2	Leica SR510	AT501	Tower W
R1	Leica SR530	AT503	Reference
R2	Leica SR530	AT503	Reference

Table 1, Antenna and Receiver Types

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. Figure 3 illustrated a Leica Choke Ring antenna attached to the Bridge's handrail.

Figure 3. A Leica AT504 choke ring antenna clamped onto the bridge's handrail

In addition, FETA provided an electrical socket at each location, which made the trials much easier to carry out. The GPS data were recorded onto internal data cards in the GPS receivers, and all simultaneously downloaded every 12 hours or so. In all, 11 University of Nottingham and Brunel University staff were involved in addition to the FETA staff, taking shifts being on the bridge; staff presence was necessary for security and not technical reasons. The raw GPS data were gathered at a rate of 10Hz, and due to the high resolution of the GPS carrier phase data used the precision of the 3D results are millimetres in level. Once gathered, the GPS data were then processed using a technique known as "On-The-Fly" (OTF) kinematic processing, resulting in data files that consisted of coordinates in the WGS84 coordinate system, with corresponding intervals of 0.1 seconds. Subsequently, the resulting 3D coordinates were transformed into Bridge coordinate. In all, approximately 11 ½ million coordinates resulted from the post processed OTF data. This was conducted in order to allow the resulting movements to correspond with the orientation of the Bridge. The orientation of the Bridge was calculated from the bearing of the GPS antennas located along the Bridge. This is a large amount of data, and initial analysis has focused on specific occurrences.

In addition, an Omni Instrument weather station was located adjacent to the west side GPS receiver, gathering air temperature, pressure, relative humidity and wind speed and direction every 15 seconds.

5. Results

Some of the initial results are presented in this paper. Figures 4, 5 and 6 illustrate the height, longitudinal and lateral displacements of the Bridge over the whole 46 hour period for site F.

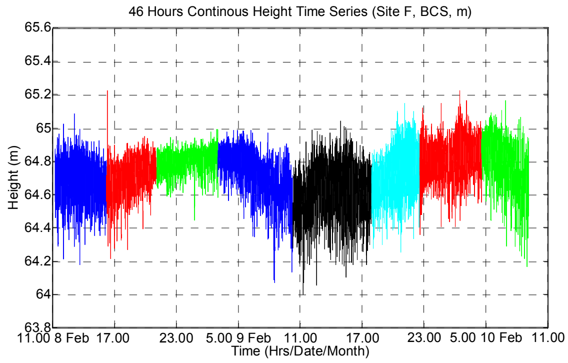

Figure 4, Height Deflections of Bridge site F over the 46 hour trial

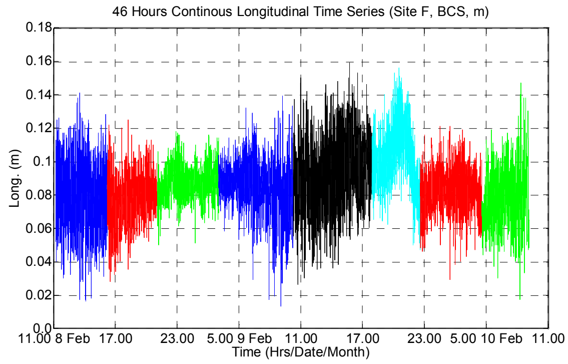

Figure 5, Longitudinal Deflections of Bridge site F over the 46 hour trial.

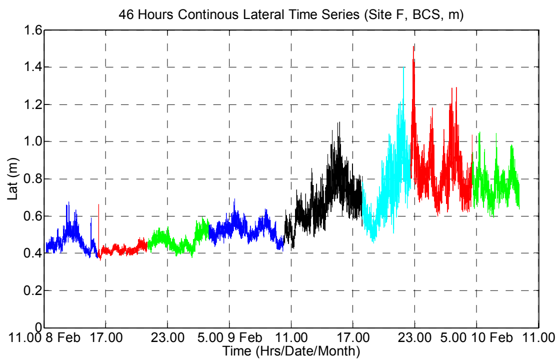

Figure 6, Lateral Deflections of Bridge site F over the 46 hour trial.

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 generally large. Wind speeds approaching 60 mph were measured.

Figure 7 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.

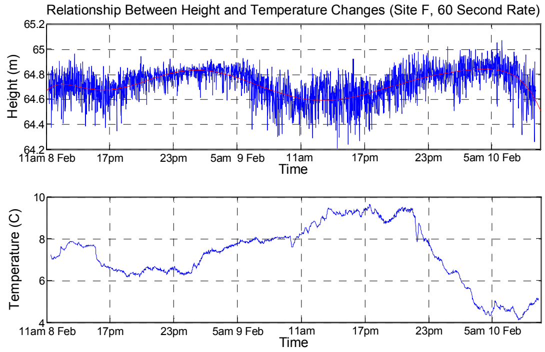

Figure 7, Relationship between air temperature and height location of the Bridge Deck at site F.

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 by the order of 35ºC, hence a larger vertical change could be expected.

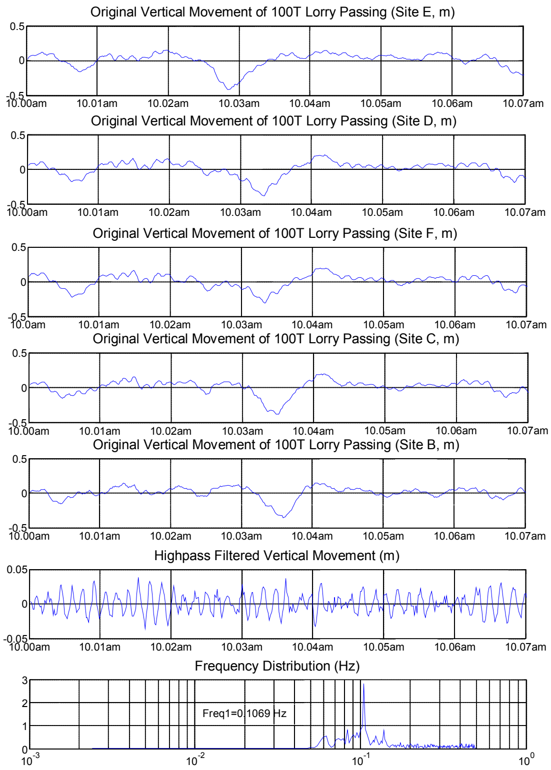

Figure 8, Height Deflections during the 100 tonne lorry

During the trials a lorry weighing approximately 100 tonnes passed over the Bridge. This section of the data was analysed in more detail. During the passage of the lorry from north to south, the other traffic travelling along this carriageway was stopped and waited off of the bridge. However, the traffic travelling due north was allowed to travel as normal. Figure 8 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 the influence of the travelling load.

Further to this a spectral analysis was applied to the data. Figure 9 illustrates the results from site F. It can be seen here that there are three distinctive spikes in the results. The main spike corresponds to 0.1055Hz, which is the first natural frequency of the Bridge.

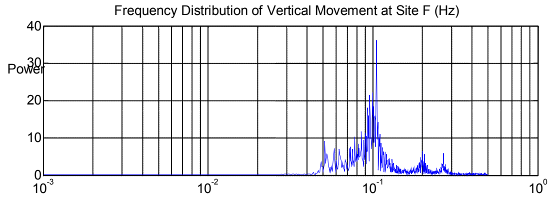

Figure 9, Natural Frequencies and Torsional Frequency of the Bridge.

During the second night, two 40 tonne lorries were hired by FETA, accurately weighed and used as a control loading of the Bridge. These trials were carried out a couple of hours after the 60 mph 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

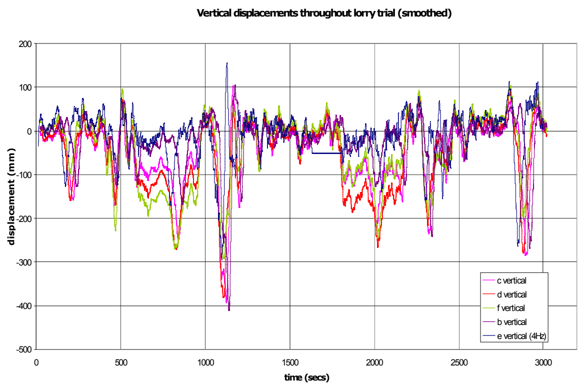

Figure 10, Height Deflections of the Bridge During the lorry trials.

During these trials, the lorries travelled at 20 mph. Figure 10 illustrates the overall movements experienced by the Bridge in the height component for the whole trials. The results show that the Bridge deflected by up to approximately 280mm due to the combined 80tonne loading. This is precisely the value predicted by the FE model from data provided by consultants WAFairhurst. The 400mm deflection seen in Figure 10 is due to the traffic that was allowed to build up whilst waiting for the manoeuvre to take place all crossing the bridge together.

Figure 11 illustrates the final manoeuvre whereby the two lorries travelled from North to South whilst located side by side at 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.

Three main phenomena are evident in Figure 11. Firstly the deflections are offset from each other, in the same was as they were for Figure 8. 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). Finally, 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 loads the hanger cables and the suspension cable to which they are attached. This then results in the suspension cable pulling up on the main span. This is evident in Figure 11 at around 2800s. 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.

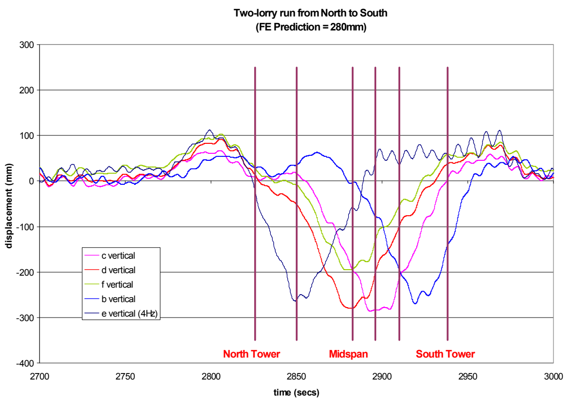

Figure 11, Height deflections during the two 40tonne lorries passing over the Bridge side by side.

6. 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.

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.

7. Acknowledgements

The research for this paper was funded by the Forth Estuary Transport Authority.

Our thanks are due to WAFairhurst and Partners for their cooperation.

The authors are very grateful for the help and time given by various staff and students at the IESSG and FETA, making the data collection during the 8th to 10th February a success. Particular thanks are due to Dr Samantha Waugh and Sean Ince at the IESSG.

8. References

[1] Ashkenazi, V; Dodson, A H; Moore, T; Roberts, G W; (1996) Real Time OTF GPS Monitoring of the Humber Bridge, Surveying World, Vol. 4, Issue 4, ISSN 0927-7900, pp 26-28, May/June 1996.

[2] Ashkenazi, V; Dodson, A H; Moore, T; Roberts, G W; (1997) Monitoring the Movement of Bridges by GPS, Proc ION-GPS-97, The 10th International Technical Meeting of the Satellite Division of the Institute of Navigation, pp 1165 - 1172, Kansas City, USA, September 1997.

[3] Roberts, G W; Dodson, A H; Ashkenazi, V; (1999) Twist and Deflect: Monitoring motion of the Humber Bridge, GPS World, Vol. 10, No 10, ISSN 1048-5104, pp 24-34, October 1999.

[4] Brown, C J; Karuna, R; Ashkenazi, V; Roberts, G W; Evans, R; (1999) Monitoring of Structures using GPS, Proc Institution of Civil Engineers, Structures, ISSN 0965 092X, pp 97 - 105, February 1999.

[5] Roberts G W; Meng X; (2002) Dodson A H; Using Adaptive Filtering to Detect Multipath and Cycle Slips in GPS/Accelerometer Bridge Deflection Monitoring Data, Proc XXII International Congress of the FIG, TS6.2 Engineering Surveys for Construction Works and Structural Engineering II, Washington DC, USA, April 19 – 26 2002

[6] Dodson, A H; Meng, X; Andreotti, M; Roberts, G W; and Walker, M; (2004). Design and Realization of RTK GPS over Internet for a ‘Smart Bridge’, Transactions of the Journal of Nanjing University of Aeronautics and Astronautics. Vol 22 (2), pp 91 – 97.

[7] Cosser, E; Roberts, G W; Meng, X; Dodson, A H; (2003), The Comparison of Single Frequency and Dual Frequency GPS for Bridge Deflection and Vibration Monitoring. Proc 11th International Symposium on Deformation Measurements, International Federation of Surveyors (FIG), Commission 6 - Engineering Surveys, Working Group 6.1, Santorini, Greece, May 2003.

[8] Hide, C; Blake, S; Meng, X; Roberts, G W; Moore, T; Park, D; (2005) An Investigation in the use of GPS and INS Sensors for Structural Health Monitoring, Proc ION GNSS 2005, 13-16 September, 2005, Long Beach, California.