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Gethin Wyn Roberts

Chris Brown

Xiaolin Meng

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Gethin Wyn Roberts[1], Chris Brown[2], Xiaolin Meng[1]
[1]*Institute of Engineering Surveying and Space Geodesy, The University of Nottingham, UK.*
[2] *School of Engineering and Design, Brunel University, Uxbridge, UK.*

BIOGRAPHY

Dr Gethin Roberts is a senior lecturer at the University of Nottingham. He holds a PhD in Engineering Surveying and a Bachelors degree in Mining Engineering, both from The University of Nottingham. He is also the chairman of the FIG's Working Group 6.4 "Engineering Surveys for construction works and structural engineering", as well as chair of Task force 6.1.1 "Measurements and Analysis of Cyclic Deformations and Structural Vibrations". He is also the UK's commission 6 delegate.

Chris Brown is a Senior Lecturer in the School of Engineering and Design at Brunel University. Having graduated from Leeds University in Civil Engineering he went to Brunel University in 1974, transferring to Mechanical Engineering in 1984. He is a Fellow of The Institution of Mechanical Engineers. His research interests in structural mechanics encompass bridge monitoring, silo design, and design of biomedical devices amongst others.

Dr Xiaolin Meng is a senior research fellow at the Institute of Engineering Surveying and Space Geodesy, the University of Nottingham and Professor in Space Geodesy of Chinese Academy of Surveying and Mapping. He holds a PhD in Highway, Urban Road and Airport Engineering from Tongji University in Shanghai, China and a PhD in Space Geodesy from the University of Nottingham. His research interests are in engineering surveying, satellite geodesy, spatial database development and quality control, GIS for Transportation (GIS-T), Intelligent Transportation System (ITS), integration of GIS and GPS, and GPS, pseudolites and INS for structural integrity monitoring.

ABSTRACT

Researchers at the IESSG at the University of Nottingham, in conjunction with colleagues from Brunel University, have carried out deflection monitoring work on structures, notably bridges, for a decade. Initial work was carried out on the Humber Bridge, London's Millennium Bridge and the Wilford Footbridge in Nottingham. These trials were carried out over a number of years, using a whole succession of GPS receivers. The initial trials showed that the use of carrier phase GPS could indeed allow sub centimetre movements to be detected, in addition to which, the frequencies of the movements could be calculated. Today, the authors are carrying out such work using state of the art dual frequency surveying grade code and carrier phase GPS receivers.

The Forth Road Bridge has an overall length of 2.5 km, a main span length of 1,005m, and 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 opened, it brought to an end an 800 year history of ferry-boat service across the river at Queensferry.

Such bridges experience traffic loading greater than that initially anticipated. The following paper details how GPS can be used to evaluate the performance of such a structure. On the 8 and 9 February 2005, a series of tests was conducted upon the Forth Road Bridge in Scotland. 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; this is the subject of another paper. 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. All the receivers gathered data, almost non-stop, for a 48 hour period, at a rate of 10Hz or 20 Hz. Leica 530, 510 and GPS1200 receivers were used during the trials.

During the trials, a weather station was used to gather the wind speed and direction, as well as the temperature. This could then be used to evaluate the total force i.e. wind and traffic, experienced by the bridge.

During previous trials upon structures, the 10Hz GPS data has been densified with accelerometers capable of gathering data at up to 1,000 Hz. However, as this structure is so large, such high speed movements were not expected, and hence no accelerometers were used, and only the INS.

The Ordnance Survey of Great Britain has 74 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. In addition to this, the OS are currently establishing their own Network RTK system in the UK. During the trials, the GPS data from a number of OS stations located adjacent to Edinburgh were gathered 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 addition, during the trials, a 100 tonne lorry passed over the bridge, and a series of 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 is known from the weather station and the only traffic present on the bridge are 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 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. On processing the data, movements of almost a metre were seen and the rippling effect was evident in the data as well.

The results are compared to 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. These frequencies and magnitudes of the movements compared very well with the FEM.

The following paper details the trials, as well as the post processing techniques carried out on the single and dual frequency carrier phase data. 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.

INTRODUCTION

During the 8 to 10th February 2005, staff from the IESSG at the University of Nottingham and from 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.

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 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 trials, normal traffic loading was experienced. In addition, a weather station was used to gather ambient temperature, pressure, wind speed and direction. 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 for this feasibility trial was seen as beyond the scope.

BACKGROUND

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, Roberts *et al*, 1999, Brown *et al*, 1999]. This work has evolved in both the analysis of the GPS data to include multipath mitigation [Roberts *et al*, 2001], 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].

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.

THE FORTH ROAD BRIDGE

The Forth Road Bridge was opened in 1964, during which it was the longest suspended bridge in the World 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.

FORTH ROAD BRIDGE TRIALS

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 [Hyde *et al*, 2005]. The layout of the GPS antennas meant that a GPS 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.

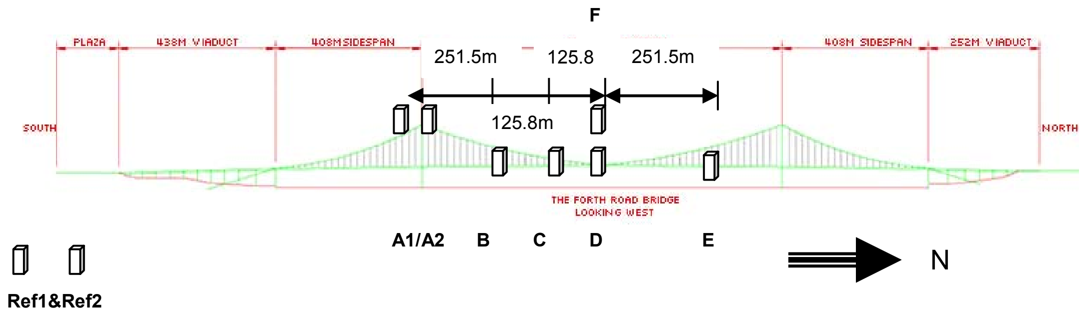

Figure 1, GPS receiver locations

Figure 2, The two reference GPS receivers located adjacent to the Forth Road Bridge.

Table 1, Antenna and Receiver Types

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
A2	Leica SR530	AT501	Tower
R1	Leica SR530	AT503	Reference
R2	Leica SR530	AT503	Reference

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 Choke Ring antenna located on the Bridge.

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, Brunel University staff were involved in addition to the FETA staff, taking shifts being on the bridge and looking after the receivers. 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 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 ad direction every 15 seconds.

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.

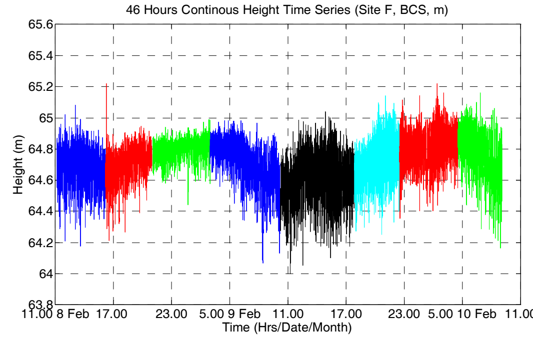

Figure 4, Height Deflections of Bridge site F over the 46 hour trial.

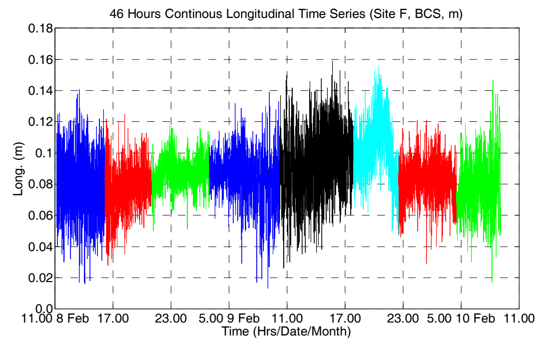

Figure 5, Longitudinal Deflections of Bridge site F over the 46 hour trial.

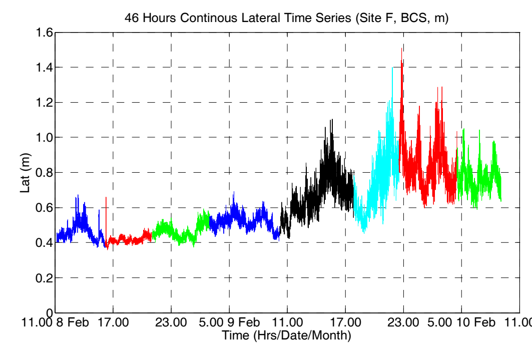

Figure 6, Lateral Deflections of Bridge site F over the 46 hour trial.

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 large. This is due to the existence of high wind speeds.

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.

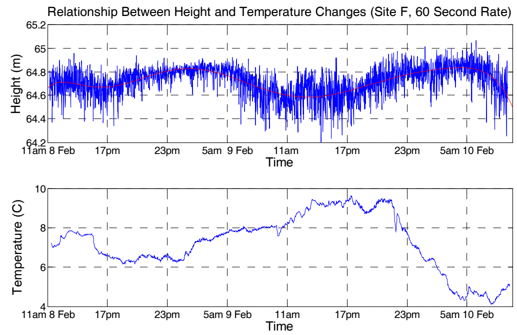

Figure 7, Relationship between air temperature and height location of the Bridge Deck at site F.

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 from -10 ºC to +30 ºC, hence a larger vertical change could be expected.

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 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 that the mass causes a wave effect along the Bridge.

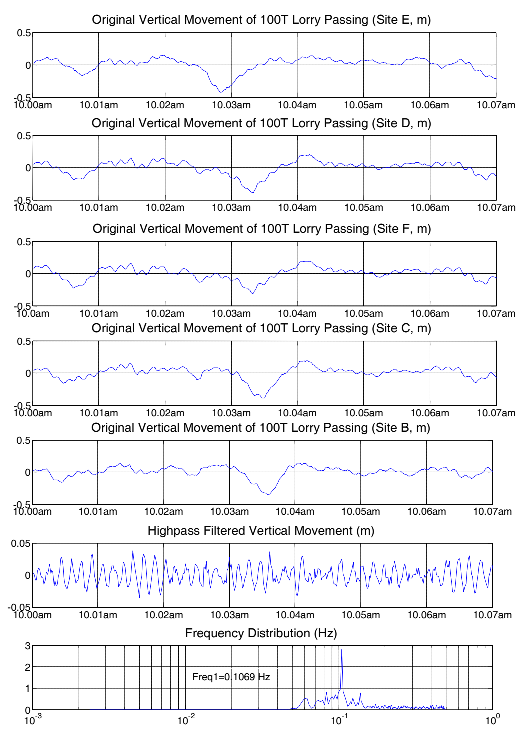

Figure 8, Height Deflections during the 100 tonne lorry

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.

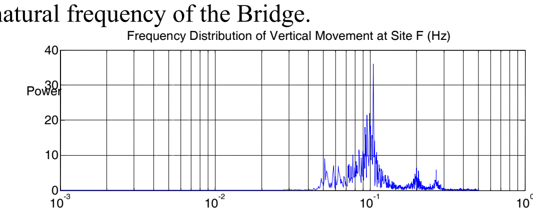

Figure 10, Natural Frequencies and Torsional Frequency of the Bridge.

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 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

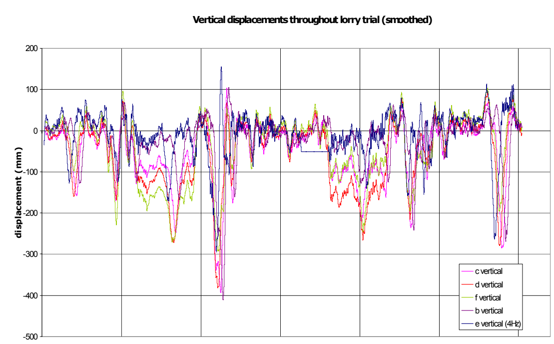

Figure 11, Height Deflections of the Bridge During the lorry trials.

During these trials, the lorries travelled at 20 mph. Figure 11 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 400mm due to the combined 80tonne loading.

Figure 12 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 12. 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). 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 12 at around 2800s. The lorries pass into the main span, and their passage over the measured positions are shown in Figure 12. As the lorries pass into the southerly side span, upward movement of the main span – described above – is observed.

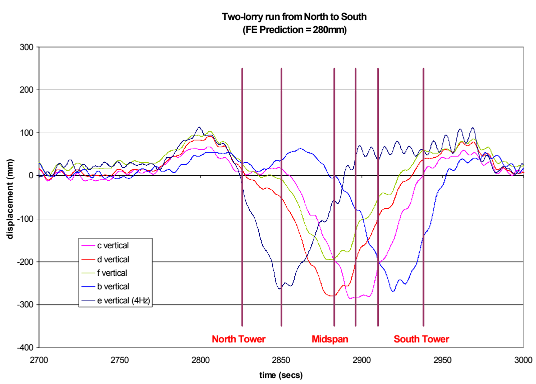

Figure 12, Height deflections during the two 40tonne lorries passing over the Bridge side by side.

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.

ACKNOWLEDGEMENTS

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