REAL TIME MONITORING OF BRIDGES BY GPS

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ABSTRACT

GPS can now be used for the real time monitoring of large scale structures, such as reservoirs, tall buildings and bridges. The paper describes the way in which the Humber Bridge on Humberside and the Clifton Bridge in Nottingham were monitored using kinematic GPS. The results show remarkable accuracies of the order of a few millimetres in all three coordinate components. They demonstrate that the technique allows the collection of real time deflection data, which could be used to determine the deformation characteristics of the bridge and eventually provide a real time 'structural failure alarm' capability.

RESUME

On peut maintenant utiliser le GPS pour contrôler en temps réel des structures à grande échelle telles que des réservoirs, des bâtiments hauts et des ponts. L’article décrit la façon dont on a contrôlé Humber Bridge (le pont Humber) dans le Humberside et Clifton Bridge à Nottingham grâce au GPS cynématique. Les résultats montrent une précision remarquable de l’ordre de quelques millimètres pour les trois composants coordonnés. Ils démontrent que la technique permet de rassembler des données de déclinaison en temps réel qui pourraient être utilisées pour déterminer les caractéristiques de déformation du pont et finalement pourraient permettre d’avoir en temps réel la possibilité d’une “sonnette d’alarme “ en cas de faiblesse structurale.

ZUSAMMENFASSUNG

GPS kann jetzt zur Echtzeit-Überwachung von Großbauten, wie z.B. Staubecken, hohen Gebäuden und Brücken eingesetzt werden. Das Referat beschreibt die Art und Weise, mit der die Humber Bridge in Humberside und die Clifton Bridge in Nottingham mit Hilfe von kinematischem GPS überwacht wurden. Die Ergebnisse zeigen beachtliche Genauigkeiten in der Größenordnung von wenigen Millimetern in Bezug auf alle drei Koordinaten. Sie demonstrieren, daß die Technik die Sammlung von Echtzeit-Deflektionsdaten ermöglicht, die benutzt werden könnten, um die Deformations-Charakteristiken der Brücke zu bestimmen und schließlich die Möglichkeit eines "Structural Failure Alarm" (Konstruktionsversagens-Alarm) in Echtzeit bieten.

INTRODUCTION

Real time kinematic Global positioning System (GPS) surveying has consistently been shown to be reliable and accurate to the centimetre level. One of the many engineering applications of real time kinematic GPS is the continuous monitoring of large structures eg bridges, leading to information on deformation characteristics. Real time monitoring could provide engineers with a ‘structural failure alarm’ capability. To test this, experiments were carried out to monitor the continuous deflections of the Humber Bridge, Humberside England, using real time kinematic GPS. Further trials were conducted on the Clifton Bridge in Nottingham, England.

The Humber suspension bridge is located across the Humber Estuary on the east coast of England. Consisting of three spans, the bridge is 2220 m long, supported by two towers 155.5 m in height. The bridge itself lies in a generally north-south direction and has been designed to withstand movements of up to ±4 m.

The Clifton Bridge is a much smaller bridge, approximately 240 m in length. Little movement was expected during the experiments due to its rigidity. However, the results presented in this paper demonstrate the millimetric precision achieved.

The Humber Bridge is a large suspension bridge, which exhibits deflections in the order of tens of centimetres. This bridge was used to show that large deflections could be monitored on such structures. In contrast, the Clifton Bridge in Nottingham is a smaller structure and was used to show that small deflections of the order of a few millimetres could be monitored.

The use of relative kinematic GPS positioning of strategic points upon a bridge was intended to allow continuous, real time monitoring of its movements. Ultimately this could lead to the development of a ‘structural failure alarm’ system as well as the computation of long-term cumulative deterioration factors, which are essential for the maintenance and health of the structure. This could benefit future bridge design techniques and the development of traffic management schemes. Finite element models of such structures would also benefit from such data.

The equipment used for the bridge monitoring consisted of Ashtech ZXII dual frequency receivers, Racal Delta Link II UHF telemetry links, a real time version of Ashtech’s PNAV processing software run on a PC and in-house post processing software developed at the IESSG, University of Nottingham.

The following paper details tests conducted to evaluate the precision of kinematic GPS as well as the bridge results. The results demonstrate that kinematic GPS may be used on such structures, paving the way for similar work on other structures.

RESOLUTION OF KINEMATIC GPS SYSTEM

The potential accuracy of the kinematic GPS technique, over short distances and under low dynamics, was first determined through a "zero baseline" test carried out before the bridge trials. A zero baseline consists of two GPS receivers connected to the same GPS antenna, thus creating a baseline of length zero. The results shown in Figures 1, 2 and 3 illustrate that the system has a resolution and hence a potential accuracy of ±1 mm horizontally and ±3 mm in height around a mean value, once integer ambiguities have been resolved. The resolution of the integer ambiguities may take up to 1 minute, but only for the first set of GPS observations. It should be noted that the "zero baseline" tests were conducted in such a manner as to eliminate most of the external error sources on the GPS observables, such as multipath, atmospheric and satellite errors.

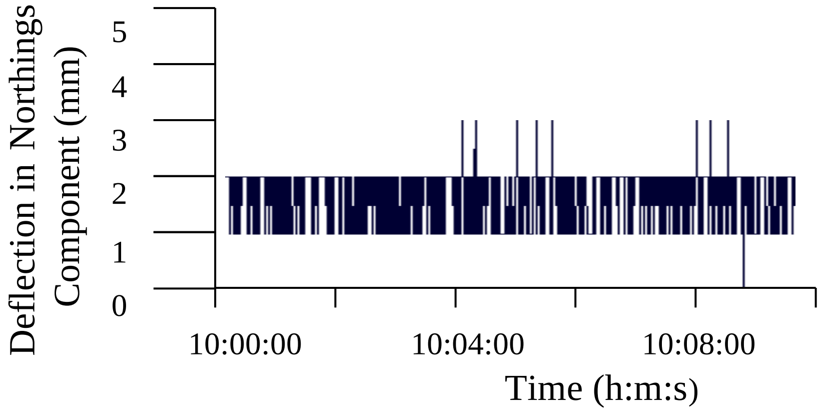

Figure 1 - Zero Baseline Kinematic GPS Test Results (Northings)

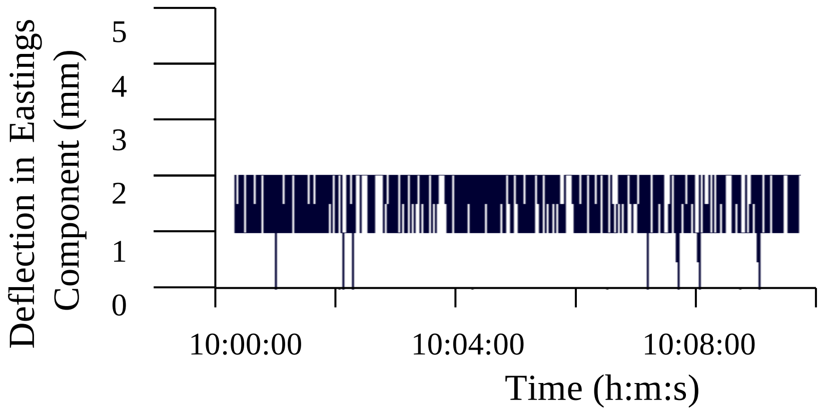

Figure 2 - Zero Baseline Kinematic GPS Test Results (Eastings)

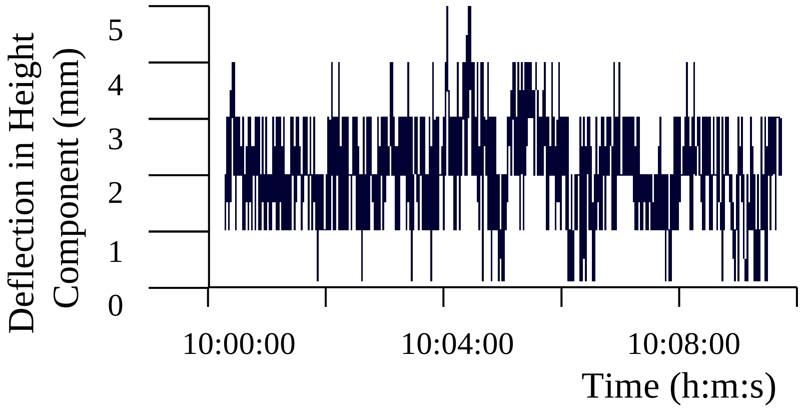

Figure 3 - Zero Baseline Kinematic GPS Test Results (Height)

HUMBER BRIDGE DECK RESULTS

The roving GPS antenna was first placed on the west side rail of the bridge deck, near the mid span, as illustrated in Figure 4. The bridge itself lies in a predominately north to south direction. All the position results were transformed from WGS84 into distances along and across the bridge length. Theoretically, this mid span location should experience the greatest deflections. The static reference receiver was positioned on top of the bridge's control tower, whose 3-d coordinates had been previously determined by conventional static GPS.

Figure 4 - The GPS receiver located at the mid span

Very few problems were encountered with the data links with this receiver configuration. The signal was only lost when substantially large vehicles, such as articulated lorries, blocked the signal path, which happened infrequently. It should be noted that the data link antenna at the roving receiver was positioned at a low height, which could have been easily increased to eliminate this problem, if necessary.

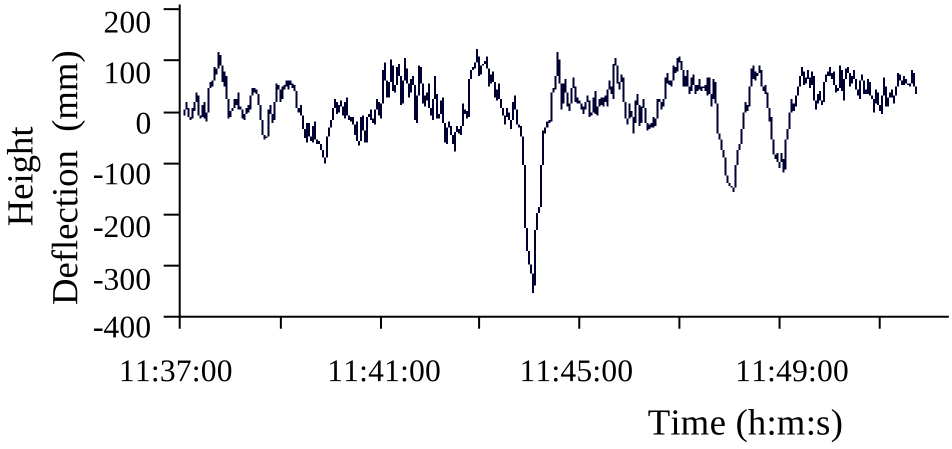

Figure 5 - Humber Bridge Real Time Kinematic GPS Test Results (Height Movement)

The vertical displacements of the bridge at its mid span during the trial are illustrated in Figure 5. These movements have an average range of about 15 cm, with a maximum of nearly 45 cm at one instant, probably due to heavy traffic load.

The displacements across the bridge, along the east-west direction are illustrated in Figure 6. These movements have an average range of about 8 cm, with several maxima of the order of 12 cm. On that day (7 March 1996), the wind was blowing approximately along the longitudinal axis of the bridge. Hence the relatively small horizontal displacements in the lateral direction

The north-south movement, along the longitudinal axis of the bridge, illustrated in Figure 7, shows a much smaller value of about 2 to 3 millimetres. This is very close to the GPS measurement noise, shown through the zero baseline results, thus indicating no (or very little) movement along this direction. This result, however, is not thought to be a characteristic of the bridge's movement. It would be expected that the bridge would in fact move along its longitudinal axis due to expansion joint movements, as well as thermal expansion over longer periods. This graph shows that over a short period of time and under particular circumstances the bridge does not move in this direction. Nevertheless, this is comforting to obtain, as this confirms that the 3-d kinematic GPS technique is indeed working successfully.

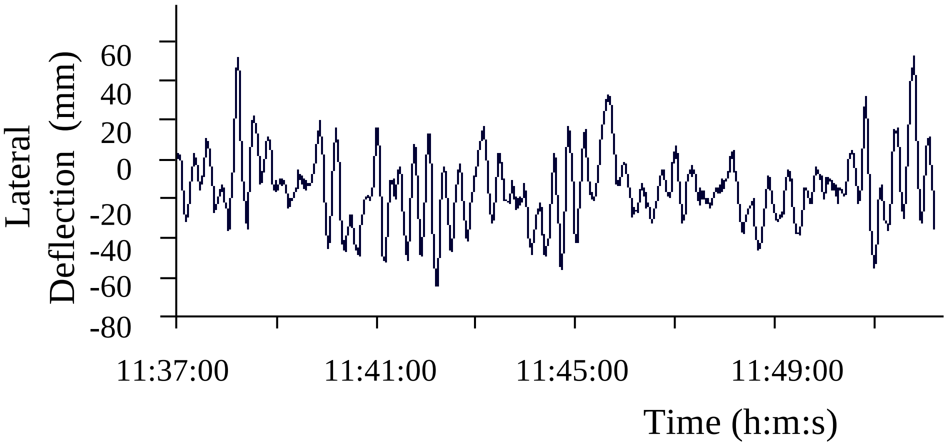

Figure 6 - Humber Bridge Real Time Test Results (Lateral Movement)

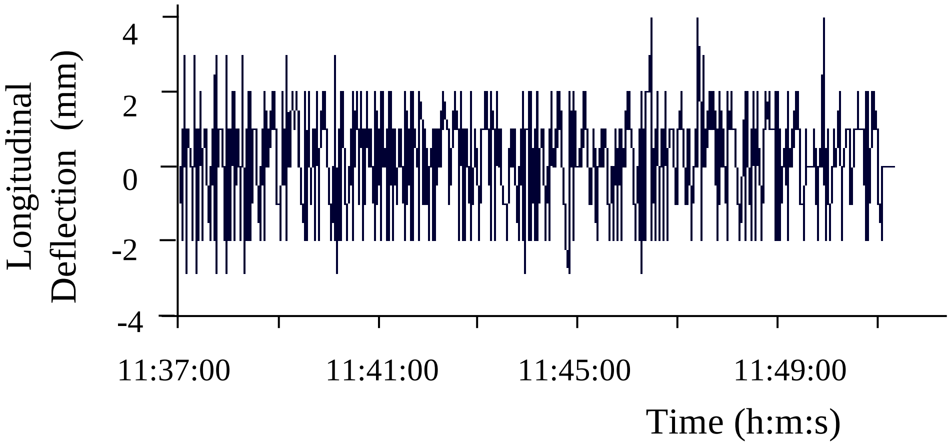

Figure 7 - Humber Bridge Real Time Test Results (Longitudinal Movement)

A second trial was conducted on the Humber Bridge on the 7 March 1996. This time a GPS antenna was placed at the top of the northern support tower, standing 155.5 m high as illustrated in Figure 8. The tower was expected to move horizontally due to the strain imposed by the flexible bridge deck, which is attached to the tower via the cable stays.

Figure 8 - The Ashtech ZXII Antenna Located on top of the Support Tower

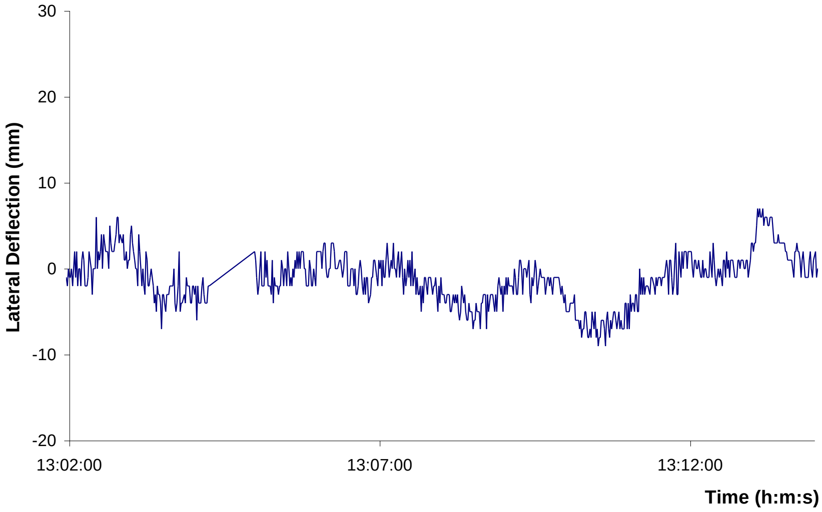

Figure 9 - The Support Tower's Lateral Movements

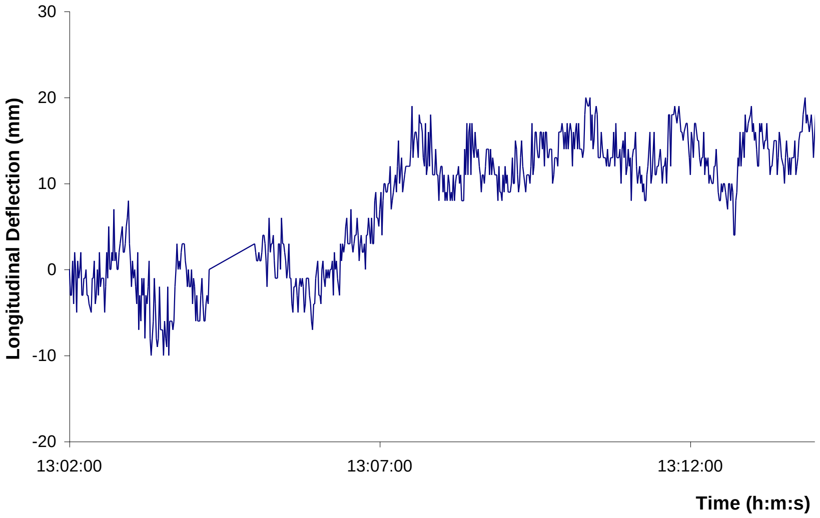

Figure 10 - The Support Tower's Longitudinal Movements

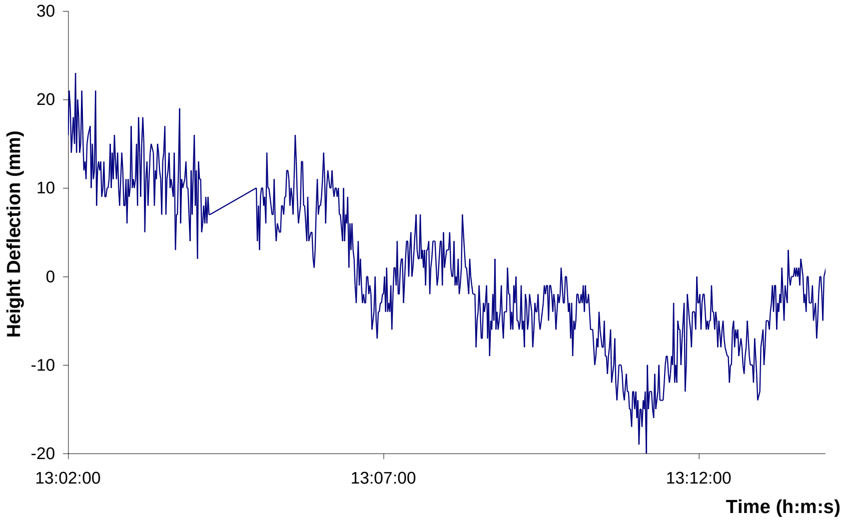

Figure 11 - The Support Tower's Height Movements

It can be seen from Figure 9 that the tower moves with an overall amplitude of about 10 mm. The noise within this movement is far smaller, in the expected region, from the zero baseline results, of approximately ± 3 mm in the lateral axis of the bridge. However, there's greater movement along the bridge's axis, as shown in Figure 10, which is as expected due to the bridge deck movement causing the tower to move via the cable stays. The overall movement is in the region of 30 mm over the 13 minute data set. It can be seen that at approximately 13:06 there is a large deformation, which takes place over duration of approximately 90 seconds. Correspondingly, the movement illustrated in Figure 11 also exhibits a sudden deformation at the same time. It is thought that the tower's movement along the bridge's longitudinal axis causes the tower to lean over somewhat, reducing its vertical height. However, in order to cause a height change of 30 mm, the tower would have to move by over 3 m along the bridge's longitudinal axis. It is now thought that some of the height change is due to the fact that the force induced by the cable stays compresses the tower.

It is clear from these results that the bridge's deformation can be monitored, in real time to a magnitude of millimetres. This would allow future finite element analysis of such structures to be confirmed and their results enhanced. Future bridge designs would also benefit from such work. In addition, the real time data could be used as a day-to-day monitoring system, allowing sudden and dangerous deformations to be detected.

CLIFTON BRIDGE RESULTS

Additional trials were conducted on the Clifton Bridge in Nottingham. This bridge is 240 m long and carries two lanes of traffic over the River Trent. The results are presented in this paper to demonstrate the resulting precision obtainable of the kinematic GPS system and to show that a real time kinematic GPS system could well be used on such a structure. The configuration of the trial was very similar to that used on the Humber Bridge, whereby a reference GPS receiver was located approximately 1 km from the bridge. This time, two GPS antennas were clamped onto the bridge 2 m apart. The vector between the two antennas, should remain constant and the analysis of the vector would further indicate the precision obtainable.

Figures 12, 13 and 14 illustrate the movements of the bridge across its longitudinal axis, along its longitudinal axis and in height respectively. It can be seen from Figure 12 that the bridge moves by about ±3 mm across its longitudinal axis. This is a very small movement and most probably the noise of the GPS solution. Due to the high rigidity of the bridge, no long axis movement was expected.

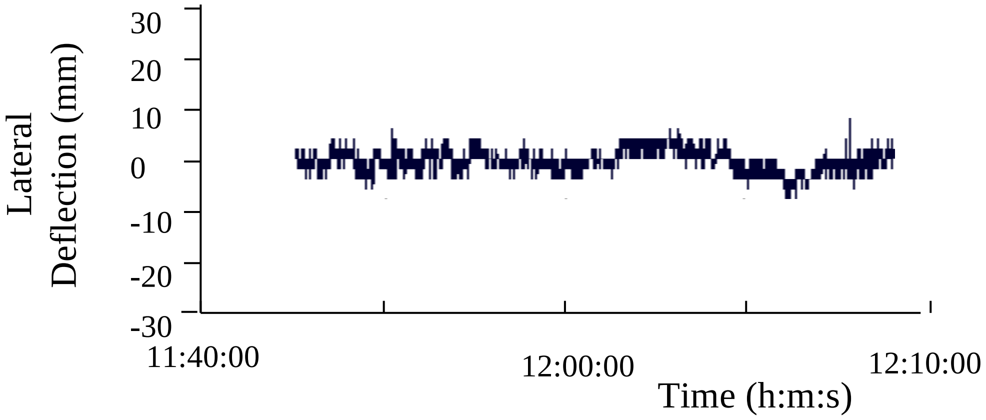

Figure 12 - Clifton Bridge Real Time GPS Test Results (Lateral Movement)

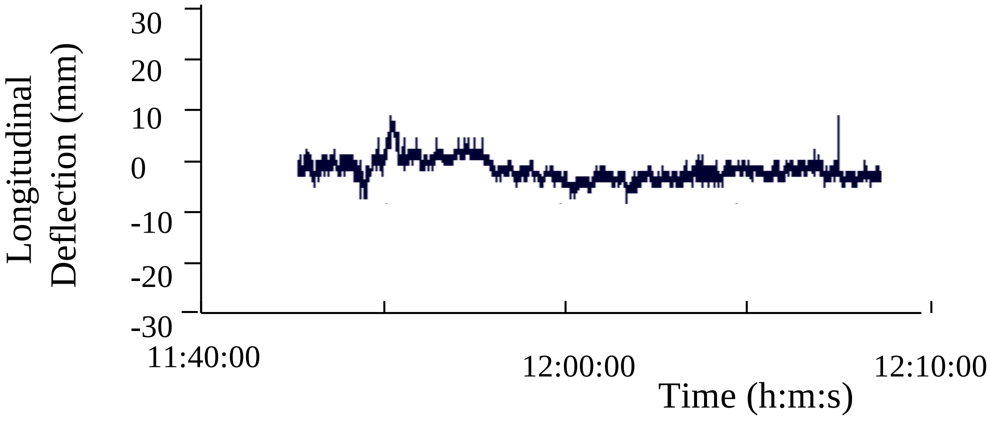

Figure 13 - Clifton Bridge Real Time GPS Test Results (Longitudinal Movement)

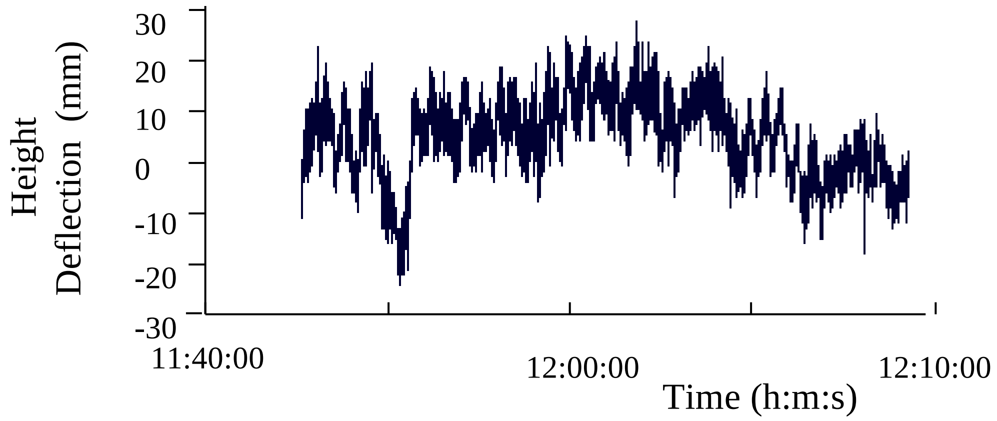

Figure 14 - Clifton Bridge Real Time GPS Test Results (Height Movement)

It can be seen from Figure 13 that a larger movement exists, in the region of 16 mm overall in the longitudinal axis of the bridge. This is expected, as the bridge will move along its longitudinal axis due to the expansion joints. The height deflection of the bridge, illustrated in Figure 14, indicates deflections of up to 40 mm. The dip in height at approximately 11:50 is thought to be due to large loading of the bridge. This also corresponds to the movement shown in Figure 13.

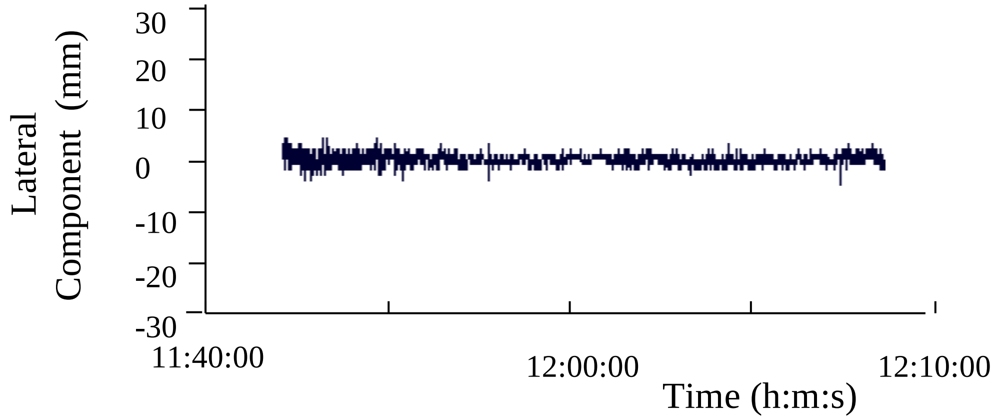

Figure 15 - Clifton Bridge Real Time GPS Test Results (Lateral Vector)

Figure 15 illustrates the component of the vector between the two GPS antennas located on the bridge, across its longitudinal axis. It can be seen that the vector is in the region of ±4 mm around a mean. This, however, is the sum of the resulting noise of the two GPS solutions and is greater than the noise expected from a single solution. It is reassuring that the magnitude is so small, showing that the two solutions agree so well with each other.

CONCLUSIONS

The zero baseline trials indicate that kinematic GPS has a potential resolution of ±1 mm in horizontal and ±3 mm in height.

The initial tests suggest that the Humber Bridge deck moved, during the test period on 7 March 1996, in a general east-west direction, as well as in the vertical direction.

The GPS antenna's location, some 5m from the main bridge support cable, did not appear to affect the GPS signal through signal loss or multipath and did not appear to influence or affect the data link signal.

These initial tests show that real time kinematic GPS could be used successfully to accurately monitor the movements of the bridge or a similar long (or wide or tall) structure, deforming under various loading factors. The mobility of the system allows positioning and monitoring strategic points with the reference and the roving receivers potentially providing useful data.

The preliminary tests were conducted during periods of relatively low wind speeds in the long axis bridge direction. The traffic along the bridge was also relatively high on the day. It is proposed to carry out further tests under adverse weather conditions, ideally with wind blowing across the bridge. Additional testing will also be conducted during peak rush hours, enabling a traffic load monitoring system to be developed.

Future trials are underway whereby a load weighing some 160 tons will travel across the Humber Bridge. GPS positional measurements will be taken at strategic points upon the bridge, allowing its movements as a whole to be monitored.

The Clifton bridge results demonstrated that such a kinematic GPS system would produce results with precision of the order of a few millimetres.

ACKNOWLEDGEMENTS

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The authors would like to acknowledge Mr Roger Evans, the Humber Bridge Master and Engineer for the assistance given and the enthusiasm shown during the trials.

Thanks are also due to Nottingham County Council for allowing the trials on the Clifton Bridge.