Single Frequency GPS for Bridge Deflection Monitoring: Progress and Results

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Key words: GPS, single frequency, ambiguity resolution, bridge deformation monitoring

SUMMARY

The use of single frequency GPS for bridge deflection monitoring is limited by the time it takes to resolve integer ambiguities at the beginning of an observation session and after a cycle slip. Typically a single frequency code/carrier phase system can take anything up to 30 minutes to resolve the integer ambiguities in an on the fly manner, compared to a minute or so a for dual frequency system. Research into rapid resolution of single frequency ambiguities in the context of bridge monitoring has been conducted. Depending on the size and amplitude of the bridge deflections, various methods may be employed. Good results have been achieved for experiments conducted on the Wilford Suspension Bridge in Nottingham and the Humber Bridge near Hull. For smaller amplitude bridges the techniques discussed will resolve single frequency ambiguities instantly. For larger bridges ambiguity resolution varies from almost instantly to within about 10 minutes depending on rover location. This paper explains the methods of accelerating single frequency ambiguity resolution, outlines the experiments conducted and discusses the results obtained.

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1. INTRODUCTION

The University of Nottingham was awarded a three year grant from the UK's Engineering and Physical Sciences Research Council (EPSRC) to research the monitoring of the deflection of structures, specifically bridges. One of the specified project aims is to use single frequency receivers instead of more expensive dual frequency ones. Dual frequency receivers have been used with good results for bridge monitoring by the University of Nottingham (Ashkenazi, et al. 1996; Dodson, et al. 2001; Roberts, et al. 1999b).

The main challenge when using single frequency GPS in a kinematic environment is the length of time it takes to resolve the integer ambiguities at the beginning of the session and after a cycle slip in an on-the-fly (OTF) manner. It can take anything up to 30 minutes to resolve single frequency ambiguities OTF (Sharpe 1999), while for dual frequency receivers this is reduced to less than a minute in most cases. Dual frequency ambiguity resolution is accelerated by the availability of the second frequency which allows a wide lane observable to be formed, reducing the number of possible ambiguity combinations.

It has been shown that, once the ambiguities are resolved, single frequency receivers are as good and in some cases better than dual frequency receivers in the context of bridge monitoring (Cosser, et al. 2003; Young 1998). However Young (1998) suggests that single frequency receivers are only feasible in areas where cycle slips are not likely to occur. A cycle slip could mean that ambiguities are lost and it could take a further 30 minutes to resolve them again. The environment surrounding receivers on a bridge is likely to have many opportunities for cycle slips such as the cables and towers. So, long ambiguity resolution times can severely affect the accuracy and reliability of a monitoring system.

This paper outlines how this problem of long ambiguity resolution times for single frequency receivers has been solved in the context of bridge monitoring. The first method of ambiguity resolution is only used for receivers on a short bridge with small amplitude movements of a couple of centimetres. Speeding up ambiguity resolution on a longer bridge with large amplitude movement up to several tens of centimetres is also discussed. Results from a bridge trial on a short suspension bridge, the Wilford Footbridge in Nottingham, and a long suspension bridge, the Humber Bridge in Hull, are introduced and discussed. The movement of traffic on the Humber Bridge is linked into the large bridge displacements.

2. BRIDGE TRIALS

Data from two bridges of very different sizes was used for the results shown in this paper. The Wilford Bridge is a pedestrian suspension footbridge over the River Trent in

Nottingham. It is about 68 metres long and 4 metres wide. The main purpose of the bridge, owned by Severn Trent, a water company, is to conduct water and gas via pipes, laid underneath the footpath, to the other side of the river. This bridge has been used as a test bed for this project because moves quite a lot and it is located quite close to the University of Nottingham. For more information on other trials conducted on the Wilford Bridge see for example Roberts, et al. (2001). The Humber Bridge in Hull has the third largest span of any suspension bridge in the world (Virola 2003). It has four lanes of traffic crossing the 1410m main span and the 280m and 530m side spans. It was opened to the public in 1981 and at the time was the world's largest single span suspension bridge (The Humber Bridge Board 2001).

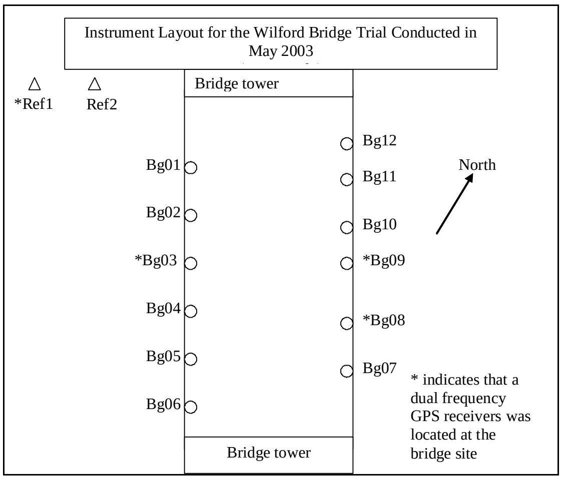

Figure 1: The layout of the receivers on the Wilford Bridge trial conducted in May 2003 (not to scale). Dual frequency GPS receivers are located at the bridge sites with a *.

A GPS and accelerometer trial on the Wilford Bridge was conducted in May 2003, the layout of which can be seen in Figure 1. Twelve Leica System 500 GPS receivers, a mixture of dual and single frequency, were secured to the handrails along the length of the bridge recording data at a 10 Hz data rate. Two reference receivers were located on the riverside footpath next to the bridge about 50 metres from the rover locations (Figure 2). Two triaxial accelerometers were located at the mid span sites (Bg03 and Bg09) in a specially designed cage that housed the accelerometer and the GPS antenna (Figure 3), so that they would sense the movement at the same time. Volunteers from the University of Nottingham and Nottingham City Council jumped on the bridge to force movement and vibration.

A three day GPS and accelerometer bridge trial was conducted on the Humber Bridge in March 2004. This bridge has been the subject of other trials conducted by the University of Nottingham which are documented in for example Roberts, et al. (1999a). There were nine Leica System 500 GPS receivers used as rovers, a mixture of dual and single frequency, the layout of which can be seen in Figure 4. The two reference stations located on top of the Humber Bridge board building can be seen in Figure 5. The data was collected at a 10 Hz data rate. Accelerometers were located at points Bdg1, Bdg3, Bdg8 and Bdg9. The bridge was continuously excited by traffic travelling over it in both directions.

Figure 2: The two riverside reference stations with the Wilford Bridge in the background

Figure 3: The accelerometer and Leica AT504 choke ring GPS antenna housed together as one unit

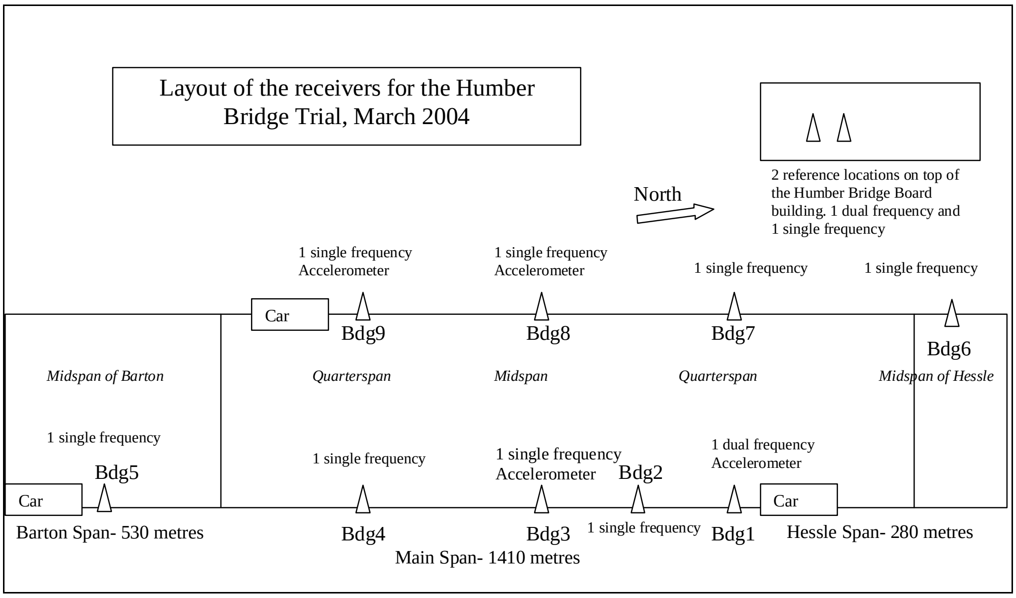

Figure 4: The layout of the receivers on the Humber Bridge trial in March 2004 (not to scale)

Figure 5: The two reference stations on top of the Humber Bridge board building with the bridge in the background

3. SINGLE FREQUENCY GPS

When ambiguities are not resolved in a GPS solution, the resulting positions can be as inaccurate as the metre level, and this is not good enough for all engineering applications specifically bridge monitoring. So, reducing the amount of time it takes to resolve ambiguities is always an important research goal. For dual frequency receivers the use of the wide lane combination allows ambiguities to be resolved in less than a minute in most cases, and for much of the work conducted by the authors dual frequency ambiguities can usually be resolve instantly.

Some processing software does not even attempt to resolve single frequency ambiguities on-the-fly (OTF) and one such software, SKI-Pro of Leica Geosystems, was used until recently to process most of the bridge monitoring data. For single frequency ambiguities to be resolved in SKI-Pro a static initialisation of 10 minutes or more must be conducted. This meant that there were coordinate outages while ambiguity resolution took place. At the beginning of the observation session this could be tolerated but when a cycle slip occurred and ambiguities were lost no further attempt was made to resolve ambiguities. A further static initialisation had to occur, which meant further coordinate outages. This method of ‘stop and go’ initialisation could be used for short bridge such as the Wilford Bridge as its movement is small (its maximum displacement is about 5cm), but this method would not be at all appropriate for long bridges such as the Humber Bridge where movements could be in excess of 1m.

To overcome these ambiguity resolution problems it was necessary to develop in-house software to process single frequency receiver OTF. Kinpos is in-house software developed at the University of Nottingham to process dual frequency kinematic data. The authors modified this software so that it would also process single frequency data OTF. The main challenges when modifying the software were the cycle slip detection method and of course the ambiguity resolution method(s).

The current ambiguity resolution procedure used the Helmert-Wolf method to accumulate the normal equations and form float solutions (Cross 1983). These float solutions are passed to a LAMBDA (Least squares AMBiguity Decorrelation Adjustment) subroutine. The Fortran 77 code of this subroutine had been obtained from Delft University of Technology in the Netherlands (De Jonge and Tiberius 1996).

For dual frequency receivers this ambiguity resolution method usually only took one epoch, but for single frequency receivers it took between 10 and 20 minutes for the same data set. If a cycle slip or loss of lock occurred then it would take a further 10 to 20 minutes to re-resolve the ambiguities. For the Wilford Bridge trial there were periods of particular interest where there was a lot of movement on the bridge and during some of these times ambiguities were lost for the single frequency receivers. Due to these coordinate outages no useful information could be gained about the bridge movement during these times.

Kinpos calculates the double difference between satellites S and T and receivers i and j forming the double difference observation equation at time t:

$$\Phi_{ij}^{ST}(t) = \frac{1}{\lambda}\rho_{ij}^{ST}(t) + N_{ij}^{ST} + \varepsilon_{ij}^{ST}(t) \quad \textbf{(1)}$$

where:

Φ	is the measured carrier phase observation (cycles)
λ	is the L1 wavelength (metres)
ρ	is the true range between satellite and receiver (metres)
N	is the unknown integer ambiguity (cycles)
ε	is the measurement noise, atmospheric influences, multipath (cycles)
ij	is the single difference between receivers i and j
ST	is the single difference between satellites S and T

For short bridges, whose movement is considerably less than an L1 wavelength, a method of ambiguity resolution has been developed as part of Kinpos. The data from the rover is processed for the whole observation session as static and so an average coordinate is established and input into Kinpos. It is known from experiments that the average coordinate needs to be accurate to within about 3cm for this method to work. This average coordinate is used as the 'known' position of the rover and it is recognised that the receiver will not deviate more than 3-5cm from it.

This method is based on the semi-kinematic initialisation technique where the rover is placed on a known location for a small amount of time so that the ambiguities can be resolved almost instantly. From equation (1), if the coordinates of the rover are known then equation (2) can be applied (assuming that the measurement noise is 0 or very close to it) to solve for the integer ambiguities.

$$N_{ij}^{ST} = \Phi_{ij}^{ST}(t) - \frac{1}{\lambda}\rho_{ij}^{ST}(t) \quad \textbf{(2)}$$

The solution to equation (2) is the observed minus computed double differences, which are set to the nearest integers to form the ambiguity values. This method resolves the ambiguities instantly and so there are no coordinate outages at all. This method could be used in real-time but requires the initial rover coordinates to be established in advance.

If the bridge moves more than one L1 wavelength (in practice the figure is probably closer to a movement of more than 5-10cm) then this method of ambiguity resolution cannot be used. A different method had to be explored so that single frequency data from the Humber Bridge could be processed. Upon investigation of the float solutions calculated by the Helmert-Wolf method in Kinpos it was discovered that they were very far away from the 'truth'. Ambiguities resolved by the above method from the Wilford bridge trial were compared to the float solution calculated from the accumulated normals by the Helmert-Wolf method. Since these float solutions were so far from the true values it was taking 10-20 minutes for them to converge to the actual ambiguities.

The maximum displacement of receivers on the Humber Bridge is likely to be in the order of 50-60cm (even though the bridge is designed to move a maximum of 4 metres). So, although the receivers do move more than an L1 wavelength, they do not move very much. For the rovers on the Humber Bridge an average coordinate of their location was also processed. Using this coordinate and equation (2) very accurate float values were calculated, which were passed to the LAMBDA subroutine. Having accurate float values meant that the time it took to converge to the actual ambiguity values was greatly decreased.

4. RESULTS

Data from both the Wilford Bridge and Humber Bridge trials were processed in Ski Pro as dual frequency data and in Kinpos as single frequency. The purpose of this was to directly compare the results from both processing software. It is worth pointing out here that SKI-Pro is a post-processing software which takes advantage of repeated searches and backwards processing for more reliable ambiguity resolution (Kotthoff, et al. 2004). All the subroutines in Kinpos work in a real-time scenario so no repeated searching or backwards processing takes place. Because of this it is expected that for the dual frequency data SKI-Pro will produce better results.

4.1 Wilford Bridge

Figure 6 shows the vertical time series for Bg09 on the third day of the Wilford Bridge trial processed with both SKI-Pro and Kinpos. It can be seen from the graph that both sets of data seem to suffer from the same multipath signature. Multipath is the main limiting factor for small bridges such as the Wilford Bridge as it masks the real bridge movement. It is known that the first fundamental frequency of the Wilford Bridge is faster than 1 Hz, due to its size and design (Meng, et al. 2003). So, a moving average filter of 10 seconds can be applied to the data removing all signals less than 0.1 Hz. This is carried out so that the low frequency multipath signature is removed from the data. The resulting residual time series can be seen in Figure 7.

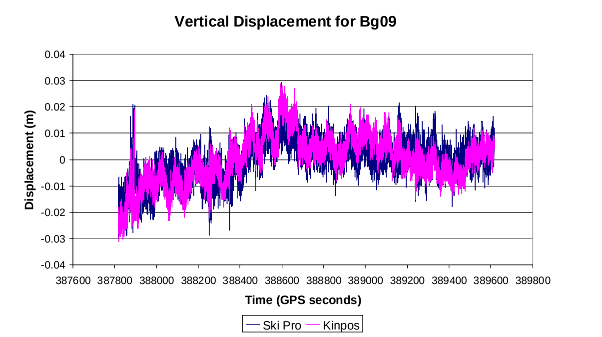

Figure 6: The vertical displacement of Bg09 on Wilford Bridge processed as dual frequency in SKI-Pro and single frequency in Kinpos

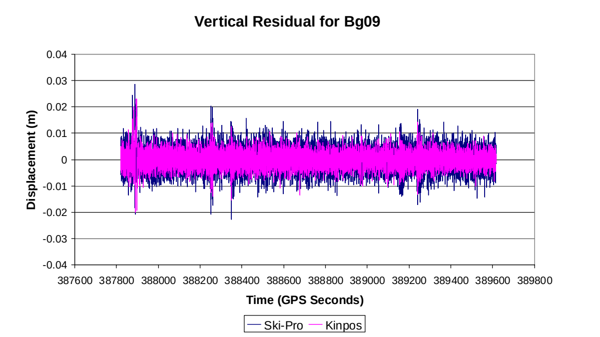

Figure 7: The vertical residual of Bg09 on Wilford Bridge after a moving average of 10 seconds (100 epochs) was applied to the data for both SKI-Pro and Kinpos

After the moving average has been passed through the data the multipath signature appears to have been removed and Figure 7 is more of a representation of the actual bridge movement which has been left behind. Some of the movement on this small bridge is actually masked by GPS noise and only periods where there is a large amount of movement can be distinguished from the background noise. This can be seen more clearly in Figure 8 which shows a period where there was a lot of movement on the bridge and this displacement can be seen above the GPS noise. The level of GPS noise is a problem for measuring displacements of short bridges, however through frequency identification bridge characteristics can still be identified (which will be the subject of further papers).

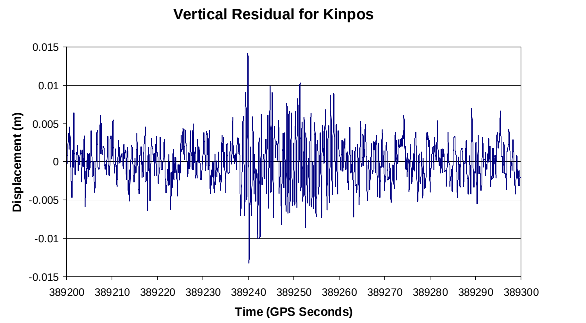

Figure 8: A section of the vertical residual for Bdg09 processed with Kinpos

	Standard Deviation (m)		
Bg09	Latitude	Longitude	Height
Ski Pro	0.0044	0.0049	0.0079
Kinpos	0.0057	0.0061	0.0092

Table 1: The standard deviation of latitude, longitude and height for Bdg09 processed as dual frequency data in SKI-Pro and single frequency data in Kinpos

The results do show that for the Wilford Bridge dual frequency data processed in SKI-Pro and single frequency data processed by Kinpos produce similar results. A summary of the standard deviations for the time series produced by SKI-Pro and Kinpos before a moving average was passed through the data can be seen in **Error! Reference source not found.**. It can be seen from this Table that although the standard deviations are lower in every component for SKI-Pro the difference is only about 0.001m in each case.

This has demonstrated that for a short bridge instant single frequency ambiguity resolution is possible and the results obtained are in line with those from a dual frequency receiver at the same site.

4.2 Humber Bridge

The data for site Bdg1 can be seen in Figure 9 processed in both SKI-Pro and Kinpos. The largest displacements shown in the graph are around the 20-25cm level. This is the only bridge site that had a dual frequency receiver located at it during the March 2004 Humber Bridge trial. It can be seen from the graph that the agreement between SKI-Pro and Kinpos is good, with the same patterns of bridge movement being identified by each software package. For this bridge site there are small periods where due to a cycle slip the integer ambiguities are lost (Figure 10). When this happens it usually only takes a few epochs for the ambiguities to be resolved again. There are a few epochs where cycle slips occur and these can be seen as spikes in the data.

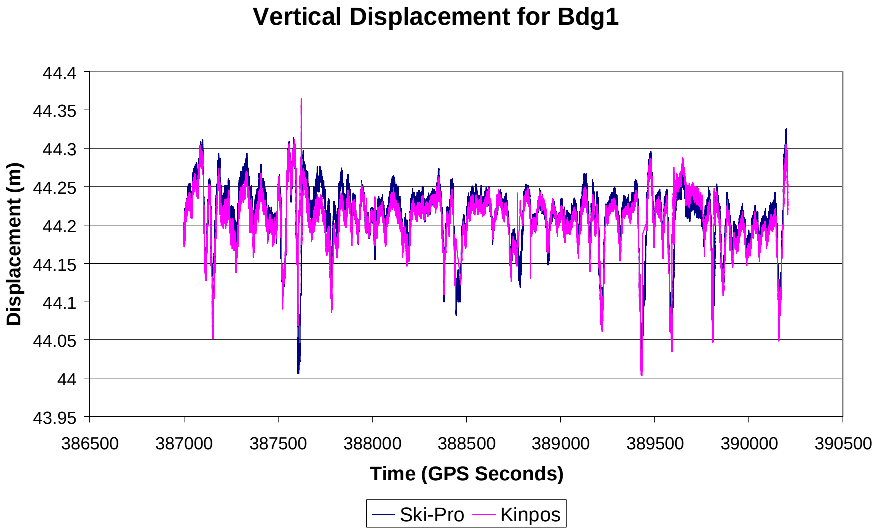

Figure 9: The vertical displacement of Bdg1 on the Humber Bridge processed as dual frequency in SKI-Pro and single frequency in Kinpos

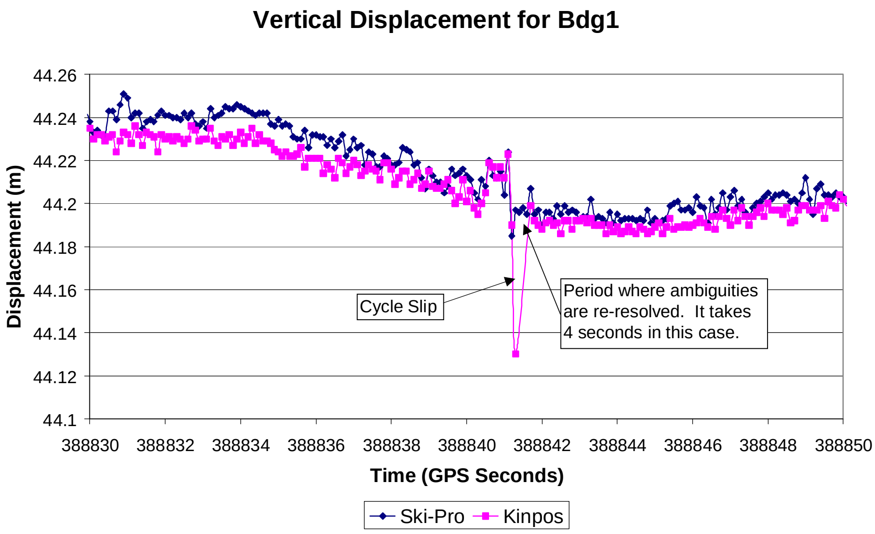

Figure 10: A close up of Figure 9 where a cycle slip has occurred and subsequently a loss of lock. The ambiguities take 4 seconds to re-resolve in this case

During the trial, a video of the traffic movement across the bridge was recorded. It was hoped that the complex traffic movement could be linked into the deformations of the structure. A record was taken of all the lorries that crossed the bridge at certain times, but cars and other light vehicles were ignored. Figure 11 shows the displacement of Bdg7, Bdg8 and Bdg9 which were all along one side of the main span of the Humber Bridge. Their displacement is linked in with the movement of lorries along the bridge. In Figure 11 the movement of the lorries is recorded at bridge site Bdg1, so the time of a passing lorry should correspond to a displacement at Bdg7 as this site was exactly opposite Bdg1. Interesting results were obtained from this comparison of the lorry movement and bridge displacement.

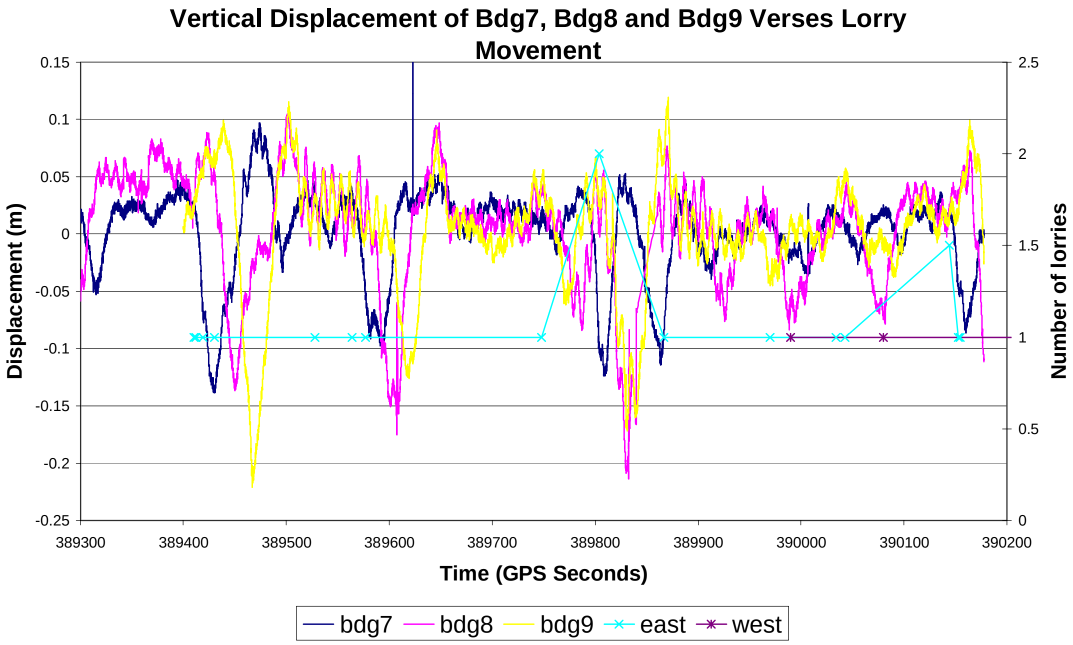

Figure 11: The displacements of Bdg7, Bdg8 and Bdg9 linked in with lorry movement along the Humber Bridge. East refers to the lorries moving along the east side of the bridge from north to south and west refers to the lorries moving from south to north

At GPS time 389430 three lorries are on the bridge and the last one is just passing Bdg7. This corresponds to a displacement at Bdg7 of about 15cm. It can clearly be seen that this displacement moves along the bridge to Bdg8 and then Bdg9 as the lorry passes along the bridge. It takes roughly 19 seconds for the displacement to move from Bdg7 to Bdg8 and about the same from Bdg8 to Bdg9. The distance between Bdg7 and Bdg8 is the same as the distance between Bdg8 and Bdg9 at 352.5 metres. This corresponds to a lorry speed of approximately 67 km/hour or about 42 miles/hour. The speed limit on the bridge is 50 miles/hour and so this speed is perfectly reasonable for a lorry.

The unusual thing about the movement of the bridge described above is that the displacement is largest at Bdg9 which is one of the quarter span sites. It would be expected that the largest displacement would be seen at Bdg8, the mid span. However, as only the movement of the lorries is recorded it is uncertain how many other vehicles were on the bridge at the same time. There may have been a large amount of cars near Bdg9 at this time causing the bigger displacement.

Another three lorries cross the bridge with the third one passing Bdg7 at GPS time 389577 which again corresponds to a large displacement there. This is displacement is seen moving along the bridge to Bdg8 and Bdg9. This time a slightly larger displacement is observed at Bdg8.

A heavy lorry crosses the bridge at GPS time 389748 causing a displacement of similar value to when three smaller lorries cross the bridge. This displacement again moves along the bridge to Bdg8 and Bdg9, with the largest displacement at Bdg8.

Up until this point all lorries have been moving on the east side of the bridge from north to south, and so linking in the movement of the lorries to the movement of the bridge has been relatively straight-forward. However, after GPS time 389866 the movement becomes a little harder to distinguish as there are lorries moving both on the east and west sides of the bridge. It is clear that the displacements after this point are smaller in amplitude, perhaps due the balancing affect of lorries being on both end of the bridge. When the lorries are coming from both directions it is much harder to link in the affect of individual lorries to the movement of the bridge. Roberts, et al. (1999a) conduct a controlled experiment where there are only five lorries on the bridge at one time. For that trial it is much easier to link in the lorry movement with the bridge displacement.

5. CONCLUSIONS

This paper introduced two bridge trials conducted on very different bridges, the short Wilford Bridge in Nottingham and the long Humber Bridge in Hull. The main challenge when monitoring with single frequency GPS is the length of time it takes to resolve integer ambiguities at the beginning of an observation session and after a cycle slip. This challenge is solved in two different ways for the two different bridges.

Results from bridge trials conducted on both bridges are introduced. On the Wilford Bridge it is difficult to identify anything but the largest bridge movement over the noise of GPS. Low frequency multipath masks much of the bridge movement but this is removed easily by a moving average filter and could also be removed by adaptive filtering (for more information on this see for example Dodson, et al. (2001)). GPS can however identify fundamental bridge frequencies even though the data is noisy.

On the Humber Bridge GPS data identifies large displacements in the order of 20-25cm. The results from SKI-Pro and Kinpos compare well to each other showing similar bridge movement. The complex movement of the traffic along the Humber Bridge is linked into the bridge movement. This is successful when the lorries are only moving in one direction but becomes more complex when the traffic is moving in both directions.

It has been shown that it is possible with single frequency receivers to monitor the movement of both short and long bridges. Ambiguity times have been greatly reduced increasing the accuracy and reliability of a single frequency GPS monitoring system.

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BIOGRAPHICAL NOTES

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