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THE COMPARISON OF SINGLE FREQUENCY AND DUAL FREQUENCY GPS FOR BRIDGE DEFLECTION AND VIBRATION MONITORING

Emily Cosser, Gethin W Roberts, Xiaolin Meng, Alan H Dodson

Institute of Engineering Surveying and Space Geodesy (IESSG), University of Nottingham

Abstract

The use of dual frequency code/carrier phase GPS data has been shown to be a feasible tool for bridge deflection monitoring. This is due to the quick On The Fly integer ambiguity resolution that is possible through using the dual frequency data in order to create the wide lane observable. The applications of OTF dual frequency data are numerous, whereby OTF ambiguities are resolved in seconds. Single frequency code/carrier phase GPS receivers are less expensive than dual frequency receivers however the time taken to resolve integer ambiguities in an OTF manner is in the order of 15 minutes. This is due to the wide lane observable not being available. The following paper details the precision obtainable using single frequency receivers compared to dual frequency, in the context of measuring the deflections of a bridge. Instead of using OTF, a stop and go technique is used to resolve integer ambiguities within a few minutes.

1. Introduction

The University of Nottingham (UoN) has been awarded a three year grant from the UK's Engineering and Physical Sciences Research Council (EPSRC) to conduct research into deflection and vibration monitoring of structures, specifically bridges. One of the specified aims of the project is to use less expensive single frequency receivers for this research. Typically single frequency receivers are around half the price of dual frequency. Research at the UoN into bridge monitoring has been underway for almost 10 years and dual frequency receivers have been used with good results (Ashkenazi, et al. 1996;Roberts, et al. 1999;Roberts, et al. 2001).

Single frequency receivers have the obvious weakness in that it takes longer to resolve integer ambiguities at the beginning of an observation session and after a cycle slip, compared to dual frequency receivers. Typically for L1 data it can take anything up to 30 minutes (Sharpe 1999), whereas for dual frequency receivers this is reduced to under a minute in most cases. Some processing software does not even attempt to resolve integer ambiguities OTF for single frequency receivers. Leica Geosystems' Ski-Pro is one example of software that will not process single frequency data in and OTF manner. Since this software is currently being used to process most of the bridge monitoring data at the UoN it presents a problem.

For single frequency data Ski-Pro uses 'stop and go' processing, with a static initialisation of about 10 minutes usually needed for integer ambiguity resolution to be possible. For the test bed bridge that is being used at present the movements are very small (maximum about 5 centimetres but usually only a few centimetres) and so this method of stop and go can be used to resolve the ambiguities. However, if a larger bridge with bigger amplitude movements were to be used, this method would not be appropriate, and a method for speeding up integer ambiguity resolution OTF would be needed.
This paper outlines results from zero baseline trials conducted on the UoN campus, as well as research from a bridge trial conducted at the Wilford Suspension Footbridge in Nottingham.

Processing of single and dual frequency rover receivers connected via a splitter to the same antenna with dual and single frequency reference receivers is conducted. Results when using riverside reference stations (about 50 metres away from the rovers) and reference stations 3.6km away are compared. A method for speeding up stop and go integer ambiguity resolution is discussed.

2. Zero Baseline Trials

A static zero baseline trial was conducted at the IESSG building on two consecutive days. On the first day, 2 single frequency Leica 510 receivers were connected via a splitter to a Leica AT503 choke ring antenna on the roof of the building. On the second day 2 dual frequency Leica 530 receivers were connected via a splitter to the antenna in the same position. The idea was to compare the data from the dual and single frequency receivers under similar conditions. Due to the GPS constellation repeatability the receivers would see the same satellites on the two days. The dual frequency data was processed in an OTF manner and the single frequency data had a static initialisation of 10 minutes before being processed as kinematic data. Zero baseline tests mean that most of the errors associated with GPS are eliminated from the solution, i.e. multipath, ionospheric and tropospheric delays, as they are exactly the same at both receivers. All that is left is the independent receiver noise.

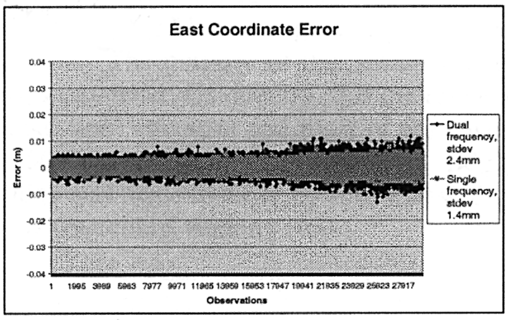

Figure 1 The coordinate error in the east direction for the zero baseline tests

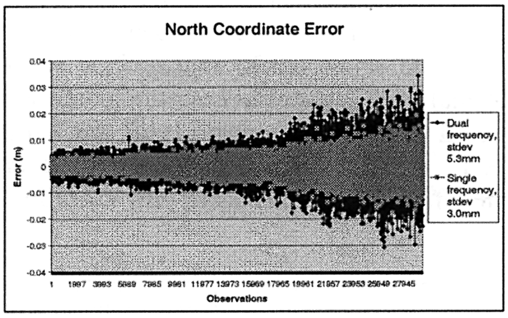

Figure 2 The coordinate error in the north direction for the zero baseline tests

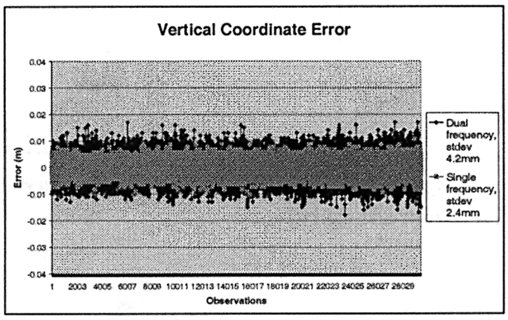

Figure 3 The coordinate error in the vertical direction for the zero baseline tests

The results are shown in Figure 1 to Figure 3. It can be seen from these Figures that the results with the single frequency receivers are less noisy than those with dual frequency. It is surprising that for both receivers the vertical component is more precise than the north. This is due to degradation in the horizontal direction that begins approximately half way through the observation period. This degradation is caused by an increase in the GDOP (geometric dilution of precision) which particularly affects the north component.

The reason that better results are seen with the single frequency receivers could be because they are newer and so have upgraded hardware compared to the dual frequency. Similar results were discovered by Meng (2002). For future trials the dual frequency receivers could be upgraded and compared again to the single frequency. The only error sources affecting this data are caused by the internal receiver noise and the satellite constellation. By conducting the test on two consecutive days at similar times, the receivers have been forced to see the same satellite constellation; any error must be caused by receiver noise. The benefits of the dual frequency receivers, which are the fact that ionospheric errors can be modelled and reduced by a significant amount and faster ambiguity resolution time, do not affect the solution in a zero baseline test. From this data it can be seen that the accuracy and precision achievable from the single frequency receivers is comparable, and in this case better, than that from dual frequency receivers.

3. Bridge Trial

A GPS, accelerometer and total station bridge trial was conducted at the Wilford Suspension Footbridge, over the River Trent in Nottingham, on the 19th, 20th and 21st June, 2002. This bridge has been the focus for a number of trials carried out by the UoN (for more information on trials see for example Roberts, et al. (2001)). The layout of the equipment can be seen in Figure 4 and Figure 5. A mixture of dual and single frequency receivers were used in this trial. At Ref1, Ref4, Bdg1 and Bdg2 there were Leica system 500 dual frequency GPS receivers. At Ref2, Ref3, Ref5, Bdg2, Bdg4 and Bdg5 there were Leica system 500 single frequency GPS receivers. Bdg2 had a single and a dual frequency receiver connected via a splitter to the same antenna. The purpose of this set up was to compare the performance of the single and dual frequency receivers directly. All the reference receivers were connected to Leica AT503 (small choke ring) antennas and most of the rover receivers (except Bdg1) were connected to Leica AT504 (large choke ring) antennas. Bdg1 was connected to a Leica AT502 antenna. The bridge was made to move by staff and students from the IESSG who passed across it in different ways (marching, running etc.).

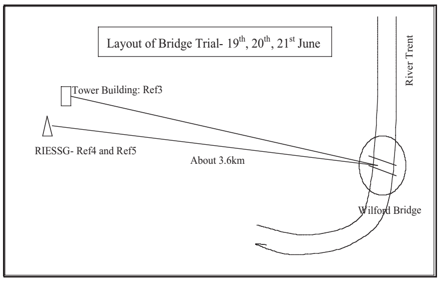

Figure 4 The layout of the 3 remote reference receivers in relation to the Wilford Bridge

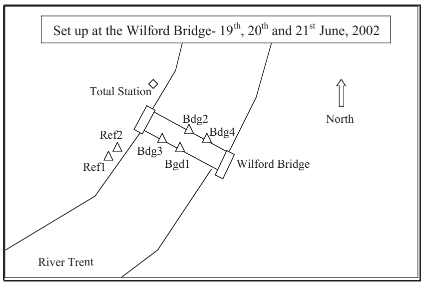

Figure 5 The layout of the receivers at the Wilford Bridge site (not to scale)

Figure 1 The two riverside reference receivers Ref 1 on the right and Ref2 on the left with the Wilford Suspension Footbridge in the background

4. Bridge Trial Results

1.1 Ref1 and Ref2 as reference receivers

To compare the performance of the single and dual frequency receivers the data from the bridge trial was processed in a number of ways. At first the riverside reference stations Ref1 and Ref2 (Figure 1) were used for the processing. These reference stations were only about 50 metres away from the rovers on the bridge. Processing was concentrated on Bdg2 as this was the site that had a dual (Bdg2d) and single frequency (Bdg2s) receiver connected by a splitter to the same antenna. Bdg2d was processed with Ref1 (dual) as the reference station while Bdg2s was processed with both Ref1 and Ref2 (single) as the reference station. In each case the dual frequency rover was processed in an OTF manner, while the single frequency rover had 10 minutes static initialisation before being processed as kinematic.

	Standard Deviations (m)		
	Easting	Northing	Height
Ref1- Bdg2d	0.00349	0.00550	0.01086
Ref1- Bdg2s	0.00310	0.00533	0.00966
Ref2- Bdg2s	0.00267	0.00379	0.00666

Table 1 The standard deviation of the north, east and height components for the second day of the bridge trial, for the dual and single frequency rover receivers processed with dual and single frequency reference receivers.

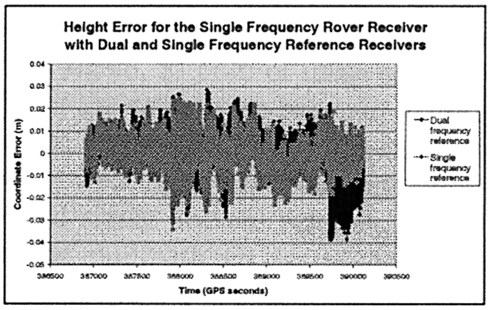

Figure 2 The height error for the single frequency rover processed with dual and single frequency references.

The results of the initial processing are listed in Table 1. As it can be seen from the Table the best result is found when the single frequency rover is processed with the single frequency reference. In this case the standard deviation is lower in every component with the most noticeable difference being in the vertical direction. It can also be seen that even with the dual frequency reference the single frequency rover is better. Figure 2 shows the vertical error for the single frequency rover processed with the dual and single frequency reference receivers. It can be seen from this Figure that with the dual frequency reference the coordinates are indeed noisier. There are two noticeable times within the observation period where the coordinate, for the dual frequency reference, is offset from the zero mean. This is perhaps due to multipath or more likely a cycle slip. Plotting of the dual frequency rover with dual frequency reference reveals a similar pattern in the coordinates, implying that the cycle slips occurred in the dual frequency reference receiver.

Data from the first day of the bridge trial (19^{th} June) are processed for the same sites as for the second day. The purpose is to use adaptive filtering (AF) to remove the multipath by comparison of the two day's data. A Matlab AF script is used, the principles of which are introduced in (Dodson, et al. 2001). The fundamental idea is that the GPS constellation repeats daily but shifted by about 4 minutes due to the difference between sidereal time and Universal Time (Hofmann-Wellenhof, et al. 2001). Due to this repeatability, the multipath at static or semi static sites should be the same on the two consecutive days. Using this information the multipath can be extracted from the signal leaving behind the real bridge movement. The desired signal is the time series from the second day of the trial and the reference signal is the time series from the first day. These two signals are offset by 4 minutes. The result of the AF in the vertical component can be seen in Figure 3 for the single frequency rover with dual frequency reference. The offset in the coordinates is obvious in both days' data and it can be seen that AF removes this offset. Investigation into the cause of the offset revealed that a cycle slip was to blame (explained later), so the use of AF can remove cycle slips as well as multipath.

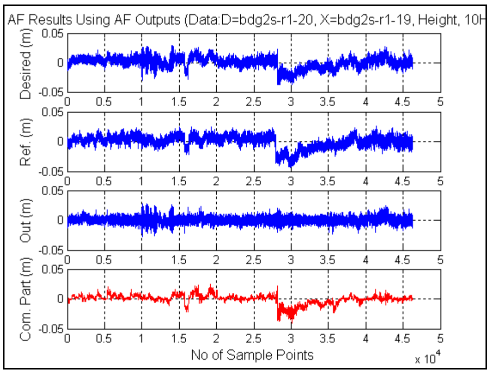

Figure 3 Vertical AF for two days time series for the single frequency rover with dual frequency reference. Desired signal is the coordinates from 20th June, reference signal is the coordinates from 19th June, the output signal is the bridge movement and the common part is the multipath and cycle slips.

To verify the success of AF the correlation level of certain components were calculated. Of particular interest was the correlation between the output signal and the common part and also the output signal and the reference signal, as both of these correlations should be close to zero for successful AF. It was found that the correlation between the reference signal and the output signal was -0.0243 and between the output signal and the common part it was 1e-5. Both of these values were very small and showed there was little correlation between these components. The correlation between the desired signal and the reference was found to be 0.6659, as they shared a common part which was the multipath but the bridge movement in each case should be different. The desired signal's correlation with the output signal was 0.5328 and with the common part was 0.8330, which showed that the more of the desired signal was made up of multipath than bridge movement. All these results showed that the AF was successful in this case and similar results were found for the other components and receiver combinations.

Table 2 shows the standard deviations of the east, north and vertical components after AF. The AF has removed the multipath and also the offsets caused by 2 cycle slips at the reference receiver Ref1. As it can be seen from the table the best results are now for the single frequency rover with dual frequency reference. The cycle slips were obviously causing degradation in the signal that has now been mitigated.

	Standard Deviations (m)		
	Easting	Northing	Height
Ref1- Bdg2d (AF)	0.00217	0.00318	0.00588
Ref1- Bdg2s (AF)	0.00187	0.00269	0.00492
Ref2- Bdg2s (AF)	0.00190	0.00276	0.00534

Table 2 The standard deviations for the east, north and vertical components for the second day of the bridge trial, after AF using the first day as the reference signal.

1.2 Removing Satellites

Removing the cycle slips that caused the degradation in the Ref1 signal could also improve the positioning solution when using this receiver as the reference. Since this cycle slip had only been caused in Ref1 and not Ref2, it was thought that some trees west of the reference station could have caused an obstruction. A sky plot revealed that satellite 4 was most likely to be the satellite causing problems. The results when this satellite was removed from the solution can be seen in Table 3. As it can be seen from this Table removal of this satellite greatly improves the solution for both cases when Ref1 is the reference receiver. The cycle slips on satellite 4 were both L2 cycle slips. The table shows that for the northing and height components the single frequency rover with the dual frequency reference has the smallest standard deviation; while for the easting component the single frequency rover with the single frequency reference has the smallest standard deviation.

	Standard Deviations (m)		
Remove sat 4	Easting	Northing	Height
Ref1- Bdg2d	0.00271	0.00405	0.00691
Ref1- Bdg2s	0.00280	0.00366	0.00619
Ref2- Bdg2s	0.00263	0.00387	0.00625

Table 3 The standard deviations for the east, north and vertical components for the second day of the bridge trial, with satellite 4 removed.

It is known that the indirect method of calculating the carrier phase for L2 results in weaker signal strength, and means that it is more prone to cycle slips than L1. This in turn means that dual frequency receivers are more prone to cycle slips than single, which has been demonstrated in the data collected at the bridge trial. Before the removal of satellites and/or AF, cycle slips and/or multipath had caused severe degradation in the dual frequency reference receiver, which had in turn affected the accuracy of all solutions computed in reference to it. By AF this degradation was removed.

It can be concluded that before AF and/or removal of satellites, using single frequency receivers as reference and rover produced a more accurate solution. Since cycle slips on L2 occur more often this is likely to be the case in future trials. After further processing has occurred and cycle slips have been removed, the dual frequency reference produces improved results. It has now the case that the most precise results are found when a dual frequency reference is used with a single frequency rover.

The fact that the dual frequency reference and single frequency rover now produce the most precise solution is as expected. It is known that one of the advantages of using dual frequency receivers is that ionospheric errors can be modelled and therefore mitigated in the solution. Ski-Pro uses a computed ionospheric model whenever dual frequency data is available and applies it to all positioning solutions. When single frequency receivers are used as both reference and rover no computed model of the ionosphere is available and so a 'standard' model has to be used. The standard model is a single layered model which has assumptions about the total amount of electrons and their distribution within the ionospheric layer, and it applies these assumptions to each satellite in turn. This may lead to a slight degradation in the positioning accuracy compared to the computed model, which would be based on actual conditions prevalent at the time of observation.

It was discovered earlier that for a zero baseline test, the results for the single frequency receivers were better than for dual frequency. This could have been due to upgraded hardware in the single frequency receivers. This may explain why for this situation, when the references are very close to the bridge, using dual frequency receivers as the reference and rover still produces the least precise solution. It is known that the ionospheric-free solution removes ionospheric disturbance on longer baselines. However, for short baselines the ionospheric-free linear combination would provide more noise with very little benefit. Perhaps this could also explain why on this short baseline the dual frequency data is the noisiest.

1.3 Coordinates for Static Initialisation

In Ski-Pro there is a function called init(track) which allows the user to input the coordinates of the static initialisation for the single frequency rover receiver. The subsequent coordinates are only as accurate as the initial coordinate. This function was investigated for the data from the bridge trial. The data from Bdg2s was processed as static and the average coordinate from the whole of the session was used as the input coordinate for static initialisation. This method was appropriate as it was only the relative coordinates that are of interest, not the absolute.

The minimum static initialisation that is allowed is 1 minute. So, using this amount of static initialisation and the coordinates from the static processing, the single frequency rovers were processed with both the dual and single frequency reference receivers. The average coordinates and standard deviations were the same as when 10 minutes of static initialisation had occurred. This meant that this method could be used to reduce the amount of time needed for static initialisation.

1.4 Ref4 and Ref5 as reference receivers

Processing had been undertaken when the reference receivers were very close to the rovers (only about 50 metres). The next stage was to use the reference stations which were at the IESSG which was approximately 3.6km away from the bridge. Ref4 was a dual frequency receiver and Ref5 was a single frequency receiver. The same processing took place of the dual frequency rover with dual frequency reference, and the single frequency rover with both dual and single frequency reference. When the dual frequency reference was used, ambiguity resolution was possible with dual frequency rover. At first for the single frequency rover, ambiguity resolution was not possible at all.

To allow ambiguity resolution to occur the single frequency receiver had to be given a known coordinate for static initialisation as in the previous section. When this coordinate was given ambiguity resolution was possible, but only when the dual frequency reference was used. For the single frequency reference no ambiguity resolution was possible at all, and so obviously the solution produced was not nearly as accurate. Table 4 shows the standard deviations of the components when the reference stations at the IESSG were used. As it can be seen from this table the most accurate results were found when the dual frequency reference and rover were used. When the dual frequency reference was used with a single frequency rover the results are slightly worse but the difference is quite small in each case.

Using the dual frequency reference and rover allowed the ionospheric-free linear combination to be used. Over this distance it will remove disturbances caused by the ionosphere and provide a more accurate solution. For the dual frequency reference with single frequency rover the standard solution will be used, but a model of the ionosphere will be computed. It is however surprising that there was no ambiguity resolution for the two single frequency receivers. The ionosphere should not make too much of a difference over this relatively short baseline.

	Standard Deviations (m)		
From IESSG Refs	Easting	Northing	Height
Ref4- Bdg2d	0.00697	0.01154	0.01708
Ref4- Bdg2s	0.00717	0.01228	0.01769
Ref5- Bdg2s (no ambig res)	0.61199	0.01945	0.47882

Table 4 The standard deviations of the east, north and vertical components for the second day of the bridge trial, with the IESSG points used as the reference receivers.

It was thought that the amount of static initialisation may not be enough for ambiguity resolution over this distance, so an initialisation of 20 minutes was used. After this amount of time the ambiguities were resolved even for the single frequency reference. However, a loss of lock occurred on one of the satellites during the observation period, only for one epoch, but this caused ambiguities to be lost on all of the satellites. Since the data is single frequency no further attempt was made to resolve the ambiguities. This is a fundamental flaw in the processing method that is currently undertaken for the single frequency receivers; if there is a cycle slip or temporary loss of lock no further ambiguity resolution is possible. The only option would be to have another static initialisation. Since ambiguities can be resolved in a minute when the riverside reference stations are used, this could be a possibility. However, when reference stations further away are used, a longer static initialisation is needed and so this would produce a longer 'outage' of coordinates.

5. Conclusions

When using the riverside reference stations in the bridge trials, cycle slips on L2 caused the data processed with the dual frequency reference to be of poorer quality than when processed with single frequency data only. Since cycle slips are more likely on L2 this could be a problem in future trials. After AF, multipath and cycle slips were removed. The most accurate results were then with a dual frequency reference used with a single frequency rover. The dual frequency reference allows a model of the ionosphere to be computed and so produces a more precise solution. With the riverside reference stations the worst results were found when using two dual frequency receivers.

For the reference stations that were 3.6km away difference results were found. The best results were with two dual frequency receivers. Ambiguity resolution was possible for the dual reference with single frequency rover, only when an initial coordinate was given. For two single frequency receivers a longer static initialisation was needed for ambiguity resolution to be possible. Ambiguities were resolved but they were lost due to a temporary loss of lock to one of the satellites. No further ambiguity resolution was attempted. This is the main flaw of the single frequency receivers processed in this manner; if ambiguity resolution is lost another static initialisation must take place for ambiguity resolution to be possible.

It has been seen that using single frequency receivers for bridge monitoring is a possibility. The 'best' solution in terms of accuracy and price seems to be to have a dual frequency reference receiver on the riverside and single frequency rovers on the bridge. With this set up the affects of the ionosphere can be calculated and applied to the rovers. However, ambiguity resolution at the beginning of the observation session and after a cycle slip is still of major concern and causes many problems for single frequency receivers.

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References

Ashkenazi, V., Dodson, A. H., Moore, T. and Roberts, G. W. (1996). "Real Time OTF GPS Monitoring of the Humber Bridge." *Surveying World*, 4(4): 26-28

Dodson, A. H., Meng, X. and Roberts, G. W. (2001). "Adaptive Methods for Multipath Mitigation and Its Applications for Structural Deflection Monitoring." *International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS 2001)*, Banff, Canada, pp.

Hofmann-Wellenhof, B., Lichenegger, H. and Collins, J. (2001). *GPS, Theory and Practice*, Springer-Verlag, Austria.

Meng, X. (2002). "Real-time Deformation Monitoring of Bridges Using GPS/Accelerometers," PhD thesis, University of Nottingham, Nottingham, UK

Roberts, G. W., Dodson, A. H. and Ashkenazi, V. (1999). "Twist and Deflect, Monitoring Motion of the Humber Suspension Bridge." *GPS World*: 24-34

Roberts, G. W., Meng, X. and Dodson, A. H. (2001). "The Use of Kinematic GPS and Triaxial Accelerometers to Monitor the Deflections of Large Bridges." *10th International Symposium on Deformation Measurement, FIG*, California, USA, pp. (CD-ROM).

Sharpe (1999). *Sharpe XR6 GPS Receiver User Manual*, Symmetricom Ltd.