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Multipath Mitigation for Bridge Deformation Monitoring

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Abstract. GPS carrier phase multipath with varying amplitudes of up to several centimetres and periods of couple of minutes is a major error source, which affects the correct interpretation of bridge deformation. In this paper, a recursive adaptive filtering (AF) algorithm has been employed to mitigate multipath signature in the coordinate time series of GPS solutions. In order to maximise the suppression of the multipath signature, exact alignment of the input time series into the AF system is crucial. An algorithm using the cross-correlation coefficient of day-to-day GPS coordinate time series is presented to align GPS coordinates. To isolate multipath from the contaminated GPS coordinate time series, relative displacements calculated from the accelerations sensed simultaneously with GPS receiver by a triaxial accelerometer housed in a specially designed cage is used as the reference signal sequence within the AF system. Associated algorithm for the relative velocity and displacement calculation is also introduced in the paper. It demonstrates that it is possible to achieve millimetre positioning accuracy by the AF approach and an integrated sensor system of GPS receiver and triaxial accelerometer.

Key words: Multipath mitigation, Structural deformation monitoring, Adaptive filtering, GPS and accelerometer integration, Cross-correlation.

1 Introduction

With the development of real-time kinematic (RTK) GPS receiver and antenna technology, GPS is currently used in areas where high measurement precision is required within high dynamic environment. Attempts have been made in recent years to investigate the feasibility of applying GPS technology to monitor structural deformations and dynamic responses to active loadings, such as wind, temperature change, traffic, and even earthquakes (Duff et al. 1998; Ogaja et al. 2001; Roberts et al. 1999; Roberts et al. 2000). The advance of data processing algorithms further makes detailed component analysis and diagnosis of structural deflection possible (Meng 2002). It provides the opportunity for GPS researchers to conduct subtle studies into the potential error sources and their impacts on the data quality. Furthermore, it makes correct error modelling possible from such a component analysis. Of many error sources relevant to satellite geometry and signal propagation media, multipath is still a research focus for precise GPS positioning (Rizos 1999). The proposed approaches for mitigating multipath effects are far from practical and effective, especially when GPS is applied to monitor dynamic structural deformation. Ge et al. (2002) present a simple approach using an adaptive finite impulse response (FIR) filtering technique to reduce the impacts of multipath on continuous GPS (CGPS) sites.

Since 1993, the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham has initialised studies of the applications of kinematic GPS on structural deformation monitoring (Ashkenazi et al. 1997). The research emphases in the past were on the implementations of a GPS-based monitoring system, data collection, and simple analysis. Further work in this area discloses that an integrated system with other sensors is necessary in providing precise measurements and hence a robust monitoring system. It was also recognised that sophisticated signal identification, data processing, and deformation analysis techniques are essential. Recent research focuses of the IESSG in this field are on sensor integration of triaxial accelerometers with dual frequency geodetic GPS receivers (Roberts et al. 2001) and even more recently with single frequency geodetic GPS receivers. A new multipath mitigation algorithm based on recursive adaptive FIR filtering (AF) in the dynamic environment of bridge deflection monitoring scenario is proposed by Dodson et al. (2001) and further studied by Meng et al. (2001) and Meng (2002).

In this paper, the fundamental of the AF technique is briefly reviewed. GPS data collected on the turret of the IESSG building with Leica SR510 single frequency GPS receivers and associated antennas are employed to investigate the day-to-day multipath signature. A cross-correlation algorithm is used to estimate the time shift of the day-to-day position time series. The multipath pattern isolated from normally time shifted coordinate sequences of two consecutive days (four minutes) is compared with the exactly aligned coordinate time series, according to the estimated time shift of each individual direction in WGS84 during the two days. It attempts to emphasise the importance of aligning the input signals to an AF system.

As an alternative to mitigate multipath, a simple algorithm is presented in the paper to calculate the relative displacements from the accelerations sensed by a triaxial accelerometer, which is physically connected with the GPS antenna by a specially designed cage. Spectral analysis approach is applied to the input and output time series to evaluate the efficiency of adaptive filtering in suppressing multipath in a dynamic environment. Through the above geodetic signal diagnosis and analysis, millimetre positioning accuracy can be achieved which further confirms that with the proposed procedure even in a multipath hostile environment, an integrated sensor system of GPS receivers and accelerometers can still provide robust and highly accurate positioning solution.

2 Alignment of Day-to-day GPS Position Solutions

2.1 Fundamental of Adaptive Filtering (AF)

Multipath, receiver random noise, and unmodelled relative tropospheric delay are major error sources under the scenario of a bridge deformation monitoring as analysed by Meng (2002). Multipath impact on the positioning solution is related to the repetition of the satellite constellation between two sidereal days. This characteristic can be exploited to extract multipath signature from the positioning time series. If closely setup reference stations are employed and the height differences between the stations are within several tens of metres, the unmodelled tropospheric delay can be reasonably neglected. Otherwise meteorological data should be collected to cope with these residuals. Receiver random noise characterises pure white noise if systematic errors are properly modelled. So, in this case, three potential components form the positioning solution sequence, which are the real bridge movement, receiver random noise, and multipath signature. Isolation of these components in a dynamic bridge deformation environment is the main purpose of applying AF approach in the data processing.

Figure 1 is a simple schematic of an adaptive system that consists of an FIR filter (processor) and an adaptive algorithm. d is the application provided input signal or desired sequence. It can be the real measurement time series for a specific process that can be compared with the FIR filter predicted output y. x is the reference signal which is used to output prediction y with Eq. 1. In Eq. 1, a reference sequence X including the current input x with sequence length Q, which is the filter length, is employed to estimate instantaneous prediction at epoch n. Parameter b is the filter coefficient.

$$y(n) = \sum_{q=0}^{Q-1} b_q x(n-q) \quad (1)$$

In the actual calculation, it is possible to start with arbitrary initial values of filter coefficient sequence $\vec{B} = (b_0, b_1, b_2, ..., b_Q)^T$. Then as each new input sample $x(n)$ enters the adaptive filter, the corresponding output or filter prediction $y(n)$ is made and compared with $d(n)$. The error signal $e(n) = d(n) - y(n)$ is formed, and used to update the filter coefficients based on the method of steepest descent using Eq. 2 (Haykin 2001). μ is a parameter that controls the rate of convergence of an AF approach. The updated filter coefficients are then employed in the AF processor to predict the next signal output with the coming of new reference signal by an adaptive algorithm.

$$\vec{B}_{n+1} = \vec{B}_n + 2\mu e(n)\vec{X}_n \quad (2)$$

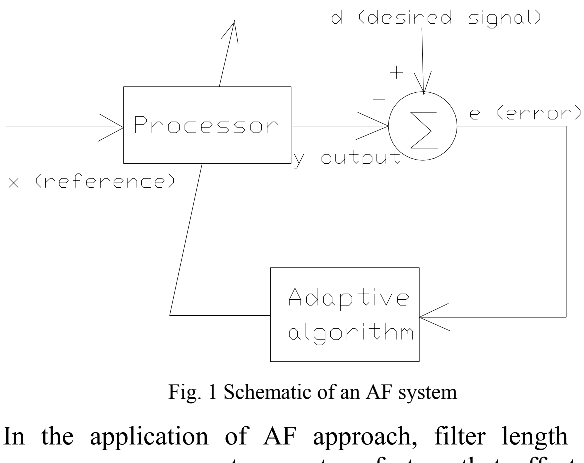

Fig. 1 Schematic of an AF system

In the application of AF approach, filter length and convergence parameter are two factors that affect the performance of an AF system. The determinations of the optimal values of these parameters are discussed by Meng (2002).

2.2 Result Comparison of Different Alignment Approaches

As explained by Roberts et al. (2002), finding the exact match point of two time series is very important in order to mitigate multipath and isolate deformation effectively.

Suppose two time series d_i and x_i, which could be the coordinate time series at one observation site on two consecutive days, or the raw pseudorange measurements. d_i and x_i could be same length vectors or vectors of different length. In the AF approach, only the same length vectors are used as desired and reference input signals.

Data from the first time series, of approximately 2 minute period, is chopped out to be compared with the second time series with a longer period for the calculation of each epoch's cross-correlation coefficient. In this paper the data used are the final coordinate time series via post-processing. The coordinate sequence starting at epoch t_{day1} of GPS time with a 2-minute interval on the first day is designated as $d_{i_{day1}}$. The data used on the second day is a coordinate sequence of four minutes within the interval of [t_{day1}+86040, t_{day1}+86280]. The coefficient of cross-correlation at each epoch j can be estimated by

$$\rho_j = \frac{(\sigma_{dx})_j}{(\sigma_d)_j(\sigma_x)_j} \quad (3)$$

where

$$(\sigma_{dx})_j = \sum_{a=1}^{N}\left((d_a^j - \bar{d}^j)(x_a^j - \bar{x}^j)\right)$$

$$(\sigma_d)_j = \sqrt{\sum_{a=1}^{N}\left((d_a^j - \bar{d}^j)(d_a^j - \bar{d}^j)\right)}$$

$$(\sigma_x)_j = \sqrt{\sum_{a=1}^{N}\left((x_a^j - \bar{x}^j)(x_a^j - \bar{x}^j)\right)}$$

are the covariance and standard deviations of the variances of two time series, respectively.

The epoch with maximum ρ is then used as the match point of the two time series. Using this approach and raw pseudorange measurement, Roberts et al. (2002) illustrate the day-to-day time shifts of each PRN satellite by using pseudorange measurements. The results reveal there are differences in the time shifts for each individual satellite. These estimated time shifts could be employed to mitigate multipath in pseudorange measurements. A new RINEX data file could be formed by the cleaned pseudorange measurements with the potential application in shortening ambiguity search time.

Since it is very difficult to correct the multipath impact directly from the carrier phase measurements by using day-to-day approach, it limits the applications of GPS in many areas where high accurate positioning solutions are required in a real-time mode. Therefore, the final positioning solutions via post-processing of raw measurements are usually used to estimate the time shifts in three dimensions in a specific coordinate system for mitigating coordinate multipath.

To evaluate the performance of Leica single frequency SR510 receivers, zero baseline and short baseline tests using the IESSG geodetic facilities were conducted over a period of two-weeks. Three kinds of Leica GPS antennas were used for two consecutive days in the short baseline tests with a sampling rate of 10 Hz. The calculated time shifts are listed in Table 1. The differences of time shifts on X and Y coordinates in WGS84 are all within 1 second range for three types of Leica antennas, but the time shift differences between Z with X or Y could reach several seconds. Also the results show that the time shifts based on the day-to-day position solutions are not necessarily 4 minutes. The calculated maximum cross-correlation coefficients of X, Y and Z using SR510 single frequency receivers and an AT501 single frequency antennas are 0.38, 0.35 and 0.74, which are different from those of AT503 lightweight chokering antenna, which are 0.25, 0.65, and 0.51, due to the differences in signal reception and filtering.

Tab. 1 Time shifts for each Leica antenna in three directions (WGS84)

	X	Y	Z
AT501 (Sample 1)	4'06''.3	4'06''.9	4'07''.8
AT501 (Sample 2)	4'10''.0	4'09''.3	4'05''.0
AT503	4'07''.6	4'07''.1	4'01''.7
AT504	4'09''.0	4'08''.7	4'03''.4

Further studies have been made on the Z coordinates in WGS84 to evaluate the impact of misaligned data on the efficiency of the AF approach. The approach and algorithm used here are similar to those illustrated by Dodson et al. (2001). Figure 2 and 3 are the results from two days' normally (4 minutes) and exactly (4 minutes and 7.8 seconds) aligned data sets using the SR510 receiver and the AT501 antenna (Sample 1 in Table 1). The first rows in both graphs are the desired signals of the AF algorithm for about a 2, 000 second period with 10 Hz sample rate, which represent the Z coordinate time series at the same location. The second rows are the time shifted reference signals of the following day's Z coordinate time series. The third rows in Figure 2 and 3 are the uncorrelated signal outputs, which contain mainly receiver noise for this short baseline and unfiltered multipath residuals. The final rows are the correlated components, which represent the multipath signatures. The residuals are calculated by comparing the corresponding output signals to evaluate the impact of misaligned time series on the efficiency of the AF approach. Figure 4 and 5 are these residuals for the uncorrelated components (receiver noise plus multipath residual) and correlated parts (multipath) of both time series. To further investigate the impacts due to the different antenna types, the same procedure is applied to the coordinate solution from AT504 and AT503 choke ring antennas with SR510 receivers.

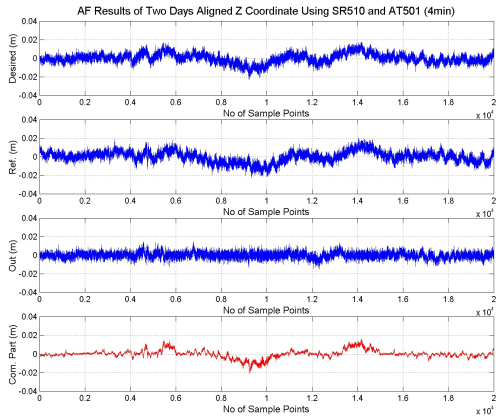

Fig. 2 AF results from normally aligned Z coordinates (AT501)

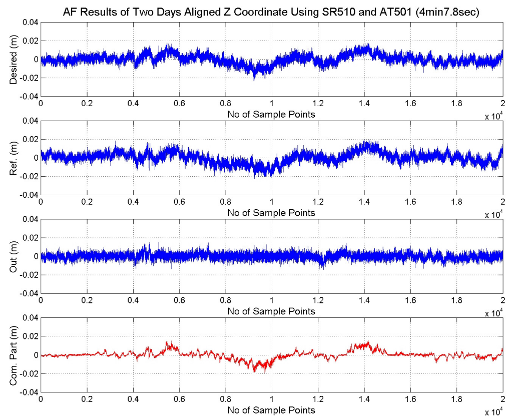

Fig. 3 AF results from exactly aligned Z coordinates (AT501)

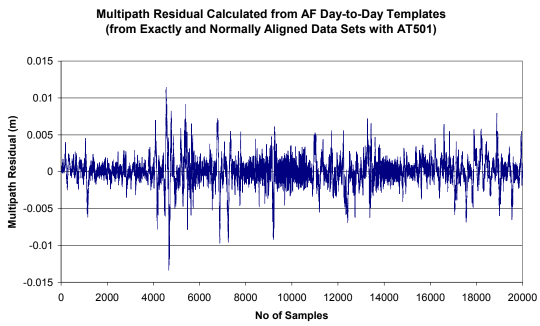

Fig. 4 Residual multipath due to misalignment (antenna AT501)

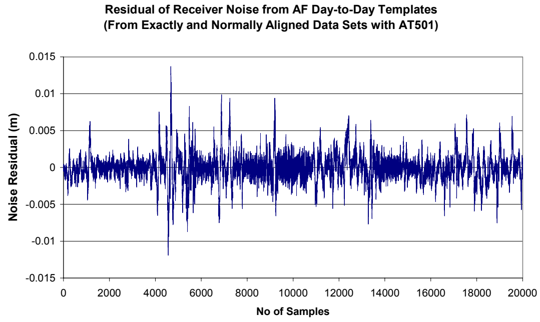

Fig. 5 Residual receiver noise due to misalignment (antenna AT501)

Figure 6 and 7 are the residuals of multipath and receiver noise for AT504 chokering antenna. It is obvious even with a single frequency receiver and misaligned time series that if a chokering antenna is adopted for data collection, significant improvement in position solutions can be expected.

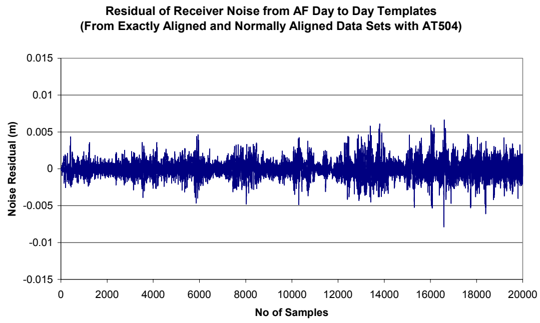

Fig. 6 Residual multipath due to misalignment (antenna AT504)

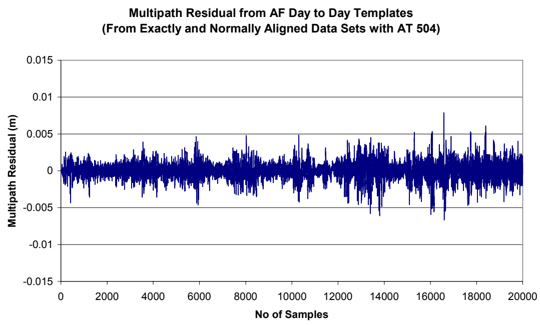

Fig. 7 Residual receiver noise due to misalignment (antenna AT504)

3 Estimating Relative Displacements from Accelerations

The raw measurements from a triaxial accelerometer are the discrete outputs in voltages on each axis via an analogue to digital converter. These data can be further converted into accelerations using the zero biases and scale factors corresponding to each axis. To reduce the computation burden in coordinate transformations between different systems, a specially designed cage is used to house a GPS antenna and accelerometer (Roberts et al. 2001). Figure 8 is the schematic of this device. It consists of two rotary plates connected with three bolts. The GPS antenna is mounted on the upper plate, which can be orientated to north. The triaxial accelerometer is fixed on the second plate with four screws. By rotating the second plate one of the three axes of a triaxial accelerometer can be aligned into the same direction of a bridge main axis (longitudinal direction).

Fig. 8 A cage used to house a GPS antenna and a triaxial accelerometer

Even though the two kinds of sensors are physically attached together, the direct comparison of GPS coordinates and accelerations using the AF approach is impossible due to different measurement units. The accelerations need to be converted into relative displacements by double integral. The accelerometer errors such as zero biases and scale factor errors will accumulate into distance errors according to the equation of motion (Lawrence 1998)

$$S = vt + 1/2at^2 \tag{4}$$

In Eq. 4, v is the initial velocity; a is the acceleration measurement; and S is the distance travelled in time period t.

Eq. 5 is used to calculate velocity from acceleration, an approach to approximate acceleration integral,

$$v(t) = v(t-1) + \frac{\Delta t}{2}(a(t) + a(t-1)) \tag{5}$$

where $v(t),\ v(t-1),\ a(t),\ a(t-1)$ are the velocities and accelerations at time t and $t-1$, respectively. Δt is the time interval of data sampling. Eq. 5 can also be applied to velocities calculated previously to output relative displacements.

Since the interest of the research is on the relative displacements, the initial velocity can be set to zero. A moving averaging (MA) filter is applied to cope with the drift problems of the velocities and displacements in the approximation procedure using Eq. 5. In principle, the MA approach is a low-pass filter. It can be used to isolate longer period movements from the time series of the integrated velocity and displacement, which are contaminated by the systematic errors of the accelerometer. The residual between the original time series and the smoothed output from the MA constitutes the local higher frequency variation (high-pass filter), which mainly represents real structural vibration. Simulation reveals that the selection of sample number used for averaging is crucial. This requires considerable experience plus knowledge of the frequency distribution of the time series. Spectral analysis is used for the purpose of frequency identification. In the spectral analysis of the bridge data gathered from GPS and the accelerometer, the frequency of this research interest is below 2 Hz. In order to use the relative displacements calculated from accelerometer data as a reference signal to the AF approach, the accelerations are resampled from 200 Hz down to 10 Hz. In this resampling procedure, due to the low-pass nature of resampling as an MA filter, accelerometer noise or outliers with high frequency are filtered out, which can be noticed from the following data processing.

$$MA(a_t) = \frac{1}{|s| + q + 1}\sum_{r=-q}^{+s} a_r \tag{6}$$

$MA(a_t)$ is the smoothed output for time series a at time t. a can be acceleration or filtered velocity.

Based on the above fundamental, a Matlab script used for relative displacement calculation was developed, with functionalities of MA sample length selection, velocity and relative displacement calculations and spectral analysis of output signals.

Figure 9 is the comparison of original vertical accelerations sampled with 200 Hz and the resampled vertical accelerations of 10 Hz. It is obvious that most abnormal acceleration measurements have been filtered out through the resampling procedure. The data set illustrated here is chopped from a one-hour accelerometer data set, which was collected on 20 February 2001 on the Wilford suspension footbridge over the River Trent in Nottingham, UK. The detailed experiment was introduced by Dodson et al. (2001). To investigate the bridge dynamic responses to the pedestrians, 8 people walked repeatedly over the bridge, which caused significant acceleration signatures.

Figure 10 and 11 are the time series of the relative vertical velocity and displacement by using the aforementioned algorithm. The first graph in Figure 10 is the integral of the resampled accelerations, which are illustrated by second graph in Figure 9. The second graph in Figure 10 is the output of MA, which is the smoothed drift caused by integral. The third graph is the calculated relative velocity activated by pedestrians. Similar graphs for relative displacement are demonstrated in Figure 11. The drift due to the double integral of accelerations has been successfully overcome.

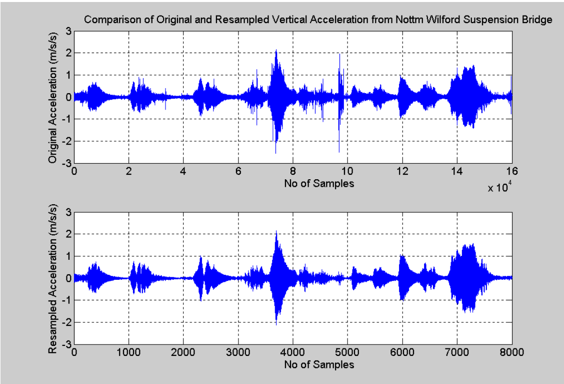

Fig. 9 Original acceleration vs. resampled ones

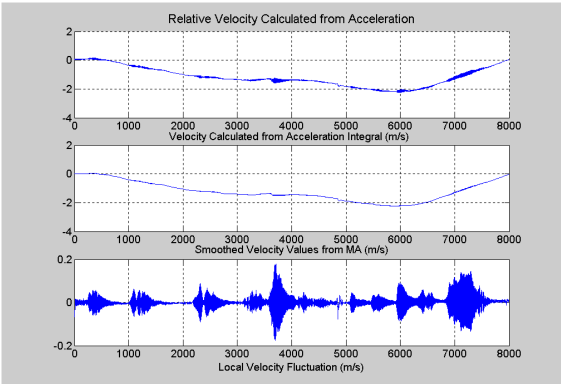

Fig. 10 MA approach for velocity calculation

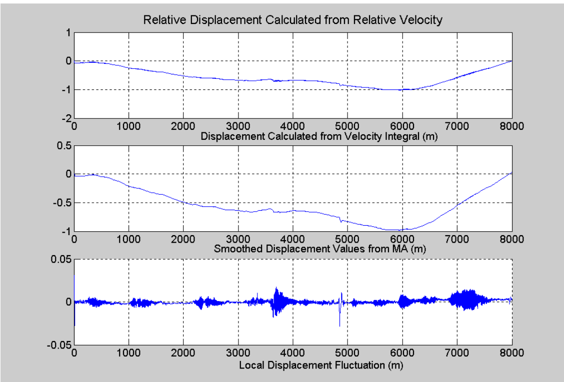

Fig. 11 MA approach for displacement calculation

Figure 12 is the result of spectral analysis on the original vertical acceleration sensed by a Kistler triaxial accelerometer. The main vertical vibration frequencies identified by the accelerometer are 1.75 Hz, 2 Hz, 3 Hz, 5 Hz, 9 Hz, 11 Hz, and 70Hz. By the principles of spectral analysis, the vibrations with frequencies higher than 5 Hz cannot be detected by a 10 Hz GPS receivers taking account of other error sources of GPS system alone (Jenkins and Watts 1968). To overcome this problem, either GPS receivers with a higher sampling rate or an integrated sensor system of GPS receivers and triaxial accelerometers could be employed. With current GPS technology, 20 Hz sampling rate can be immediately available which can be used to detect the vibration frequencies lower than 10 Hz. Under this circumstance, an integrated monitoring system of a GPS receiver and an accelerometer can provide a broader detectable frequency band except for outputting more measurements. Detailed analysis to the frequency distribution is illustrated later in the paper.

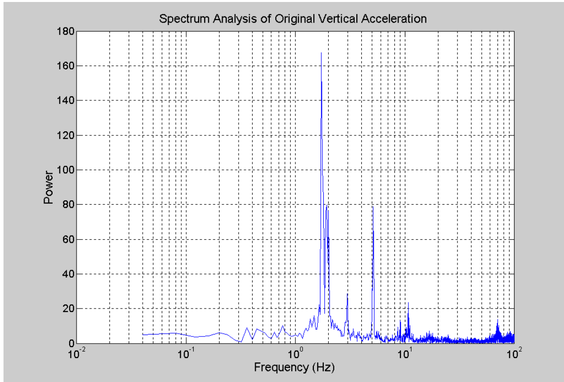

Fig. 12 More signatures can be identified with an integrated system

4 Acceleration Aided AF Approach for Multipath Mitigation

The relative displacements calculated from the accelerations by the proposed algorithm can be further used to mitigate GPS receiver noise and isolate the real bridge movements. Due to the high degree of multipath signature caused by the surroundings and receiver noise, accelerometer aided AF approach cannot be applied to GPS position solutions directly. Careful treatment is required to filter the multipath and receiver noise both at reference stations and rover stations. Meng et al. (2001) presented a hierarchical procedure to gradually reduce the impacts of multipath and receiver noise, in addition to modelling the relative tropospheric delay between reference station network. Even with such procedure, the final coordinates are still contaminated by a certain degree of the residual components aforementioned. Since the GPS and accelerometer are independent instrument, the only correlated component in both systems is the sensed force/movement. So, it is an ideal approach to use accelerometer aided AF technique to isolate relative movement of the bridge.

Figure 13 is the AF results using the vertical coordinate of two days' as the inputs signals at the same observation site. The two days' data are exactly time shifted with the approach proposed in this research. In the reference time series, there were signatures caused by casual pedestrains passing over the bridge but in the desired signal there were vibrations induced by organised crossing. Figure 14 is the frequecy distribution of desired signal. The power of multipath is much higher than that of the actual bridge movement and exhibits itself as a very slow movement pattern in Figure 13. It is very difficult to identfy the excited movement without any further data treatment. From Figure 14 the dominant multipath frequencies identified by spectral anaysis are 0.0038 Hz (4 minutes 24 seconds) and 0.0075 Hz (2 minutes 13 seconds).

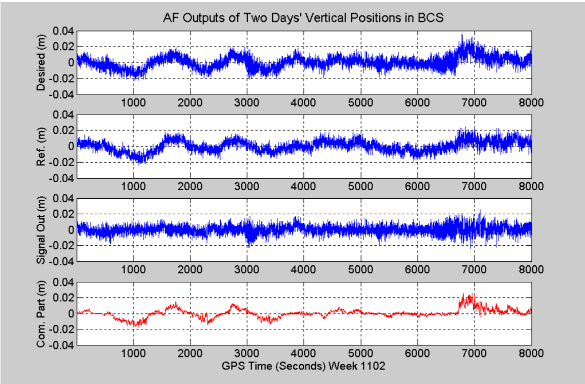

Fig. 13 GPS AF results using two day's position solution

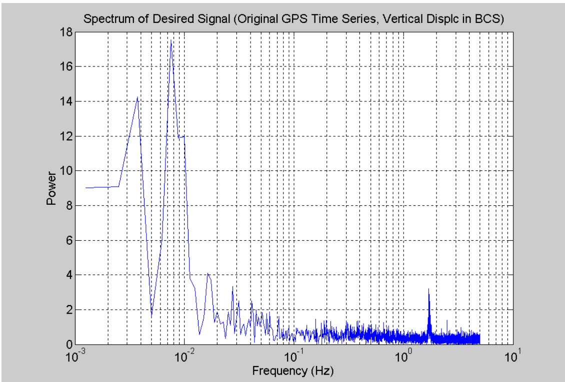

Fig. 14 Spectral distribution of desired signal

Figure 15 is the spectrum of the reference signal. There is no signature of 1.75 Hz vertical movement since there was no excitation caused by organised crossing, but the same frequency signature of multipath is almost filtered out through the AF procedure (Figure 16).

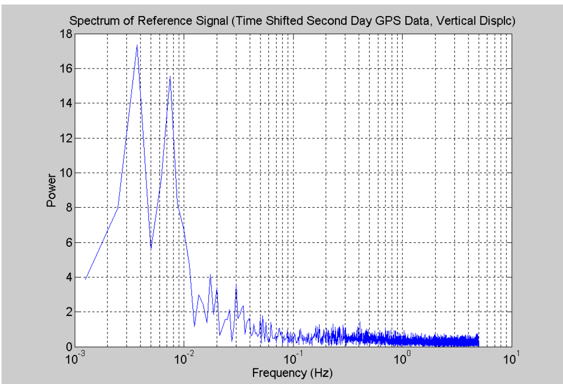

Fig. 15 Spectral distribution of reference signal

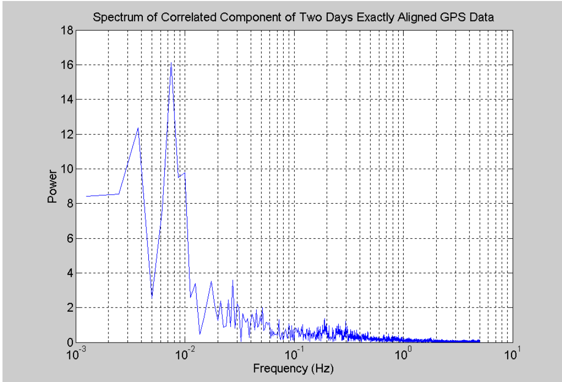

Fig. 16 Spectral of isolated multipath signature

Figure 17 is the output using the relative multipath free GPS position solution (the third row in Figure 13 which constitutes receiver random noise and real movement) as the desired signal and the calculated relative bridge displacement from accelerometer as the reference signal in the AF algorithm. The synchronisation between the data sets of GPS and accelerometer is realised in the software whose detail is introduced by Meng (2002). The outputs of Figure 17 are the receiver noise time series (third row) and relative bridge movement (fourth row). Figure 18 illustrates the results of using untreated positioning solution from GPS directly to compare with the relative bridge movement sensed by the accelerometer. It shows that it is possible to isolate multipath from the real bridge movement but the detected real bridge movement is distorted at certain periods due to the error is too big to be adapted.

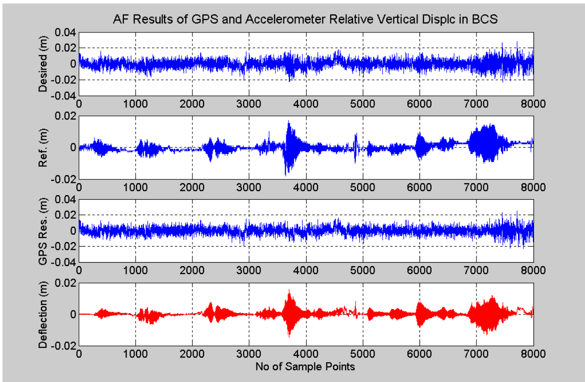

Fig. 17 Acceleration aided AF result with multipath free GPS position

Further analysis has been made on the frequency distributions of the input and output signals to and from acceleration aided AF system by spectral analysis. Figure 19 is the spectrum of the desired signal, which is the third row in Figure 13. It is evident that significant power reduction of multipath is realised through the AF procedure. Figure 20 is the spectrum of the reference signal of the relative displacement from resampled accelerations. It is obvious that the resample procedure does not change the spectrum distribution of acceleration.

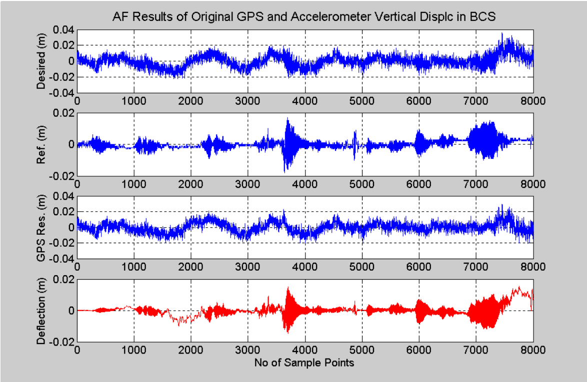

Fig. 18 Acceleration aided AF result with untreated position

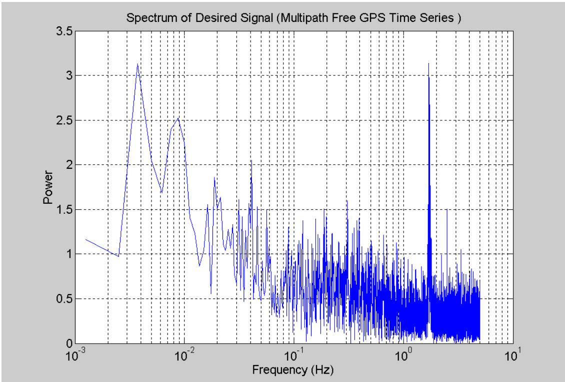

Fig. 19 Spectrum of desired signal (treated GPS data)

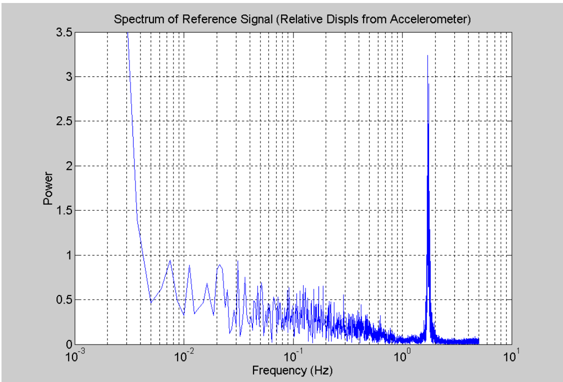

Fig. 20 Spectrum of reference signal (relative displacement derived from acceleration)

GPS receiver noise is the uncorrelated output via the AF procedure and its spectrum is illustrated by Figure 21. It provides an opportunity to further analyse the statistical nature of GPS receiver noise. Figure 22 is spectrum of the final integrated relative displacement (Figure 17 fourth row) from the two sensors. It illustrates that the instrument related errors have been removed successfully through the above data processing procedure. It needs to be pointed out that by this proposed sensor system, the detectable frequency is limited to the sampling frequency of GPS receivers and other signatures are left undetectable due to the unfiltered GPS noises and the weak power of these real vibration frequencies. Further reseach is needed to identify the reason why the frequencies identified by accelerometer and within the meaurable range of 10 Hz GPS receivers have been filtered out.

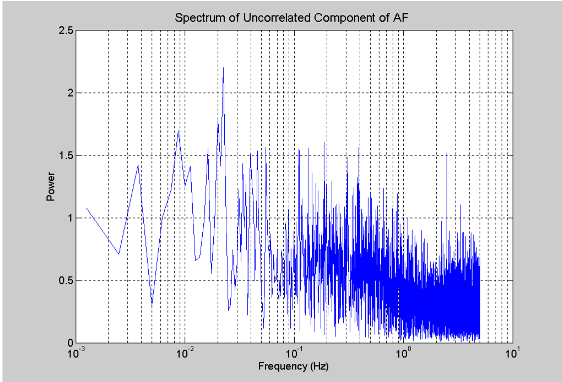

Fig. 21 Receiver random noise signature

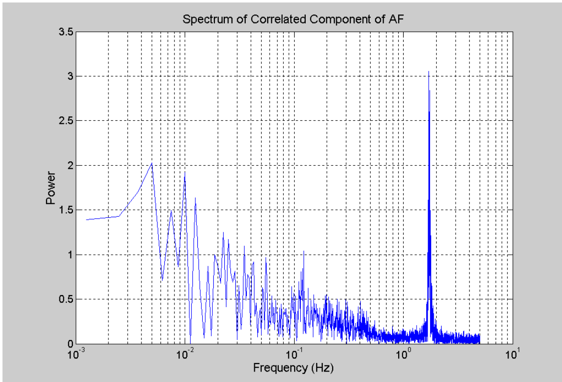

Fig. 22 Spectrum of the integrated system

5 Summary

Fundamental of a recursive adaptive filtering (AF) approach is reviewed first in the paper. Important issues such as filter length of an AF system, convergence of AF algorithm, and time series alignment are addressed. The focus is on the time series alignment and the consequence of misalignment of time series to the positioning solutions. The exact day-to-day time shifts of the whole satellite constellation are estimated with the GPS positioning solutions. A cross-correlation algorithm is used to detect the match point of two time series. The calculated results reveal that the time shifts between X, Y, and Z are different. The AF result differences by aligning two days' time series using normal time shift (4 minutes) and exact time shift have been compared. Two centimetre differences in residual noise and multipath are evident in the positioning solution from single frequency antenna AT501 and one centimetre for chokering antenna AT 504.

By using AF as an error suppression tool the authors demonstrate an acceleration aided AF approach to isolate real bridge movement from noise 'polluted' GPS positioning solutions. The moving average (MA) algorithm has been applied to the original acceleration to calculate the relative displacement by double integral and cope with the long period drift caused by acceleration double integral. Spectral analysis is applied as a signal diagnosis tool to check the efficiency of the AF algorithm in the data processing. The results illustrate that through the AF procedure, the errors from both sensors have been removed and real bridge movements have been isolated. It is possible to achieve millimetre positioning accuracy in 3D after the removal of receiver noise and residual multipath by the proposed approach. However, the comparison of the frequencies detected from the original accelerometer data which are within the detectable frequency band of 10 Hz GPS receivers and those from the proposed integrated sensor system of dual frequency GPS receivers and triaxial accelerometer demonstrates that some of the detectable components were filtered out. The possible reason for this is that these detectable frequencies have been removed during MA procedure which is illustrated very clear in the relative displacement illustrated by Figure 20. Since there are no such components in the relative displacements calculated from accelerations with those from GPS measurements, only the mode shape charaterised the same vibration of the first natural frequency is detected by AF technique. Further research is needed to investigate the possible reasons for this and associate data processing techniques.

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