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BASELINE CORRECTION MADE EASIER USING AN AUTOMATED METHOD BASED ON THE WAVELET TRANSFORM

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ABSTRACT

This paper presents a novel and automated method of correcting baseline shifts in seismic acceleration records. The method focuses on the recovery of the low frequency 'fling' from the acceleration record. The recovery of the fling makes double time integration to displacement much easier. Basically the wavelet transform can be described as a cascade of octave filter banks, down-sampling to lower frequency sub-bands until the sub-band containing the low frequency fling is reached. The algorithm also implements a de-noising scheme, which removes low and higher frequency outliers thereby improving the signal-to-noise ratio. The wavelets used for this analysis are bi-orthogonal, these have linear phase, though other wavelets perform as well. On recovering the low frequency fling and double time integrating, offsets in frequency and linear and quadratic trends in displacement are manifest, but at low frequencies these are straightforward to correct. The resulting trends are in the main due to instantaneous tilts and the method is able to recover these tilts. The algorithm simply locates the zero crossing point in the velocity time history and performs a simple correction. The events used in this paper are from the 1999 Chi-Chi event and the 2008 Iceland event. The method also lends itself to estimating instantaneous tilts.

Introduction

Strong ground motions at near-fault sites may contain long period, pulse type waves which induce substantial permanent ground deformation. Standard filtering methods [Trifunac et al., 1971] cannot extract such permanent displacements of the ground from acceleration time-histories. The problem occurs during the double time integration of the acceleration record when trying to recover the velocity and displacement time series. Shifts and offsets in the latter portion

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of the time history cause linear and/or quadratic trends in the displacement time history making estimates of any permanent displacements difficult. These baseline distortions are due to a variety of possible causes amply described in [Graizer, 1979, 2005, 2006], [Boore 2001, 2003], and [Boore and Bommer, 2005]. Methods for correcting baseline shifts already exist. [Graizer, 1979] was the first to advocate a baseline correction procedure by fitting a segment of the record in a time interval. [Iwan *et al* 1985] used a two-point method later modified by [Boore, 2001] and [Boore and Bommer 2005]. [Chiu 1997] high-pass filtered before integration, [Wu, 2007] also used a modified [Iwan, 1985] method on the Chi-Chi event. [Boore and Akkar, 2009], discuss and propose a Monte-Carlo based, baseline-correction scheme and used noise models to model the variations in baseline. Most of these methods assume that changes in the acceleration baseline occur in a finite time interval, $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$, where $\boldsymbol{t_2 > t_1}$. However, these methods do not recover the low frequency fling, nor are they easily automated and usually require some expert opinion. The scheme proposed and described in detail in [Chanerley, Alexander 2010], [Chanerley, Alexander, Halldorsson 2009], [Chanerley and Alexander, 2008, 2007] is automated and uses the discrete wavelet transform and de-noising, [Debauchies 1992], [Donoho 1995], [Chanerley and Alexander 2007], which recovers a low-frequency fling, with usually some baseline shift. The method then automatically locates at a zero crossover point, one time point on the low frequency velocity fling profile, and zeros the acceleration from that point. The method then re-integrates the acceleration profile down to displacement to give an almost theoretical, acceleration and velocity fling profile, as specified by the conditions in [Grazier, 2005], without any baseline drifts and a ramp like displacement. In addition and as an aside the method lends itself to determining estimates of residual and mean tilt angles as well as instantaneous tilt transients, which contribute to baseline shifts when expediting the double time integration.

The Discrete Wavelet Transform and De-noising

It's easiest to consider the wavelet transform [Debauchies, 1992] as a cascade of octave filter banks. The filters are quadrature mirror filters (QMF), whose frequency responses are mirror images about $\pi/2$. An example is shown in Figures (1) and (2) exhibiting linear phase and showing that the frequency response mirror images about $\pi/2$. The case shown is for bi-orthogonal wavelet(s) *(bior1.3)* these wavelet filters are symmetric and have linear phase, which make them important for the sort of processing necessary for seismic correction. Other wavelets such as *db1*, *db2, db10* and others give similar results to those published in [Chanerley, Alexander, 2010], [Chanerley, Alexander, Halldorsson, 2009]. These QM filters are also known as perfect reconstruction filters, such that the original signal after filtering and down-sampling into sub-bands as shown in Figure (3) can then be re-constructed to the original signal, by up-sampling and filtering. The signal is also de-noised during the process [Donoho 1995]. In the application used here, it is the decomposition into sub-bands which is the more significant property since the low and high frequency sub-bands were kept separate for ease of integration in order to obtain the lower and higher frequency velocity and displacement of the ground motion.

If for example we designate the low-pass prototype digital filter by $\boldsymbol{H}$, where $\boldsymbol{H}$ is a vector comprising coefficients $[\boldsymbol{h_0, h_1, h_2, h_3}]$ then the high-pass filter will have coefficients, denoted by the vector $\boldsymbol{G}$, multiplied by $(-1)^n$ giving [h_0, $-h_1$, h_2, $-h_3$]. Therefore because we are down-sampling by 2 each time, i.e. in octaves, we proceed in octave sub-bands as per Figure (1). However, because the discrete wavelet transform (DWT) is not translation invariant, the method uses the stationary or translation invariant wavelet (SWT) transform [10,12] and its corresponding complement the inverse stationary wavelet transform (iSWT). This essentially applies a range of signal shifts to allow for misalignment of the signal and wavelet features. Essentially this shifts, averages and un-shifts the data, i.e. Average [Shift → De-noise → Un-Shift].

The De-Noising Scheme

De-noising involves the setting of a threshold below which outliers are discarded. Basically, thresholding involves the setting to zero wavelet coefficients (i.e. the transformed data values), whose absolute values are below a certain threshold. This type of thresholding is called 'hard'. It leaves discontinuities in a signal, which could lead to unwanted and spurious oscillations. A 'soft' threshold scheme [Donoho, 1995] on the other hand still removes absolute values below a threshold, but it then gradually sets to zero the discontinuities, in effect smoothing and therefore is a better procedure to apply. The above description is the scheme applied to the seismic data in order to scale in a non-linear manner, down to the lower sub-bands which contain the low frequency fling components. More details can be found in [Chanerley & Alexander, 2010] and [Chanerley, Alexander, Halldorsson, 2009].

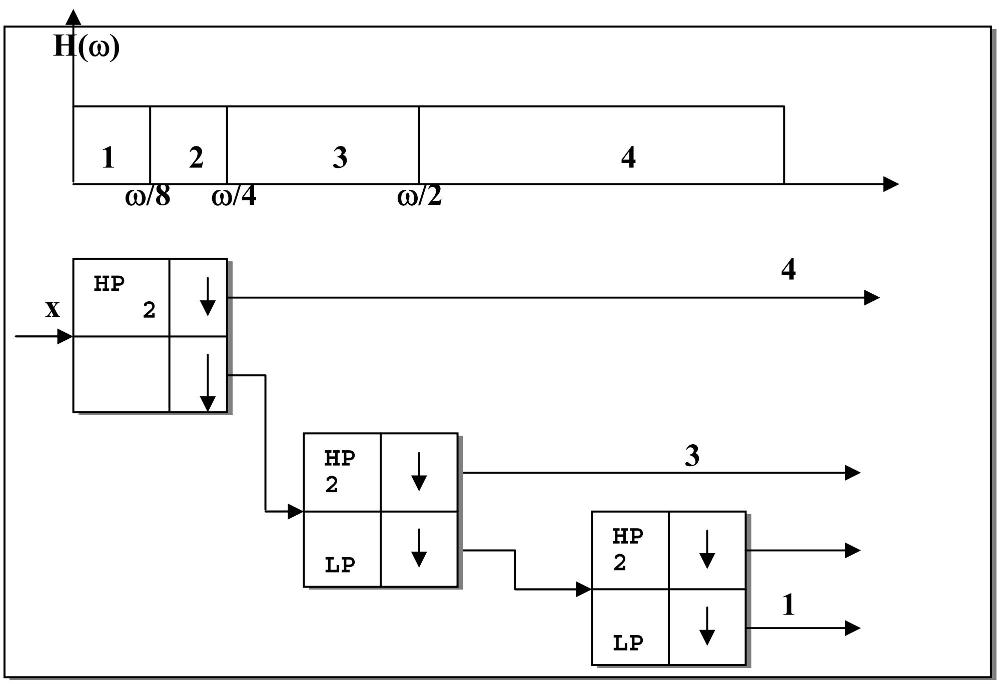

Figure 1: A 4- channel, analysis (decomposition) wavelet filter bank showing sub-band

Ideal Fling Models

The model flings are shown below in Figures (2, 3). Integration of the above equations gives the type A and type B profiles for velocity and displacement. The profile is type A where the acceleration is shown as a sine pulse, leading to a one-sided velocity pulse and ramp-like displacement. The displacement therefore retains its permanency and doesn't recover. The type B cosine profile leads to a two-sided velocity profile where the displacement recovers. The wavelet transform can extract type A profiles in the lower frequency sub-band and also type B profiles, though this latter profile tends to be in the higher frequency sub-band. The profiles are then summed and provide to an estimate of the local ground motion.

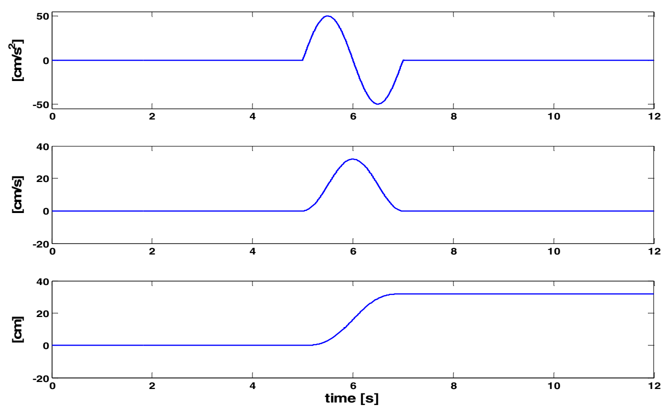

Figure 2: Sine model of type A fling profiles. Type A fling leaves a permanent displacement

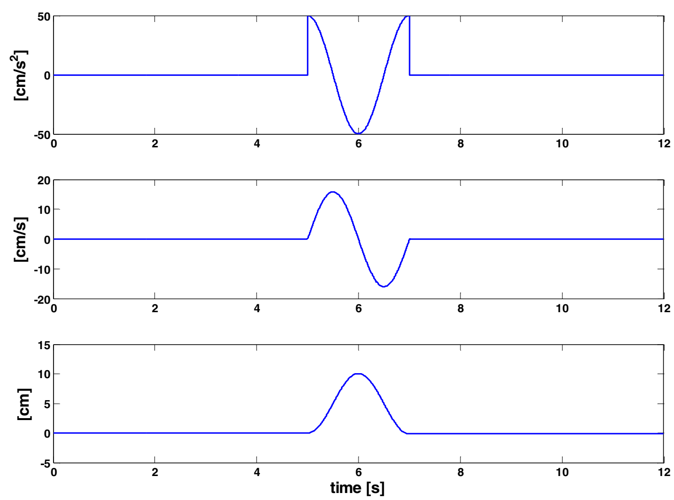

Figure 3: Cosine models of type B fling profiles. Type B fling leads to a recovery in displacement

Results

TCU068 Flings

Figures (4) show some examples of the low frequency flings obtained for the Chi-Chi 1999, TCU068 NS [Lee WHK, et al, 2001], component with and without baseline correction, more results and details are in [Chanerley, Alexander, 2010]. Without baseline correction the TCU068 NS component shows considerable deviation with a steep linear gradient in the displacement, caused by an almost constant velocity offset in the low frequency profile. This is automatically corrected by the algorithm which locates the time point at zero-velocity cross-over in the velocity profile and at that point, zeros the acceleration to make it as close to the model fling as possible as in Figures (2) and (3), without post-strong motion distortions, then double time re-integrate to displacement. From the correction the algorithm is also able to estimate the tilt angles for this and the EW component, by using a least squares method with which to estimate the residual and average angles of tilt [Chanerley, Alexander 2010]. Figure (5) shows the resultant profiles for TCU068NS and the low and higher frequency sub-bands at level 10. The vertical component was the easiest to correct since after application of the wavelet transform the low frequency fling was almost ideal. The correction for baseline shift in this case was barely palpable and it integrated straight down to displacement without any requiring any baseline correction. The fact that the vertical component shows very little offset, is consistent with the basic equations of pendulum motion as described in [Graizer, 2005], which for small tilt angles show that the vertical component is almost insensitive to tilts. A similar situation is manifest for TCU068 EW [Chanerley and Alexander, 2010] except that the sensors are facing in the opposite direction to ground motion, giving a negative type A profile. The table below shows the displacements

Table 1

Wavelet *bior1.3*		*Baseline zero velocity point*	Residual disp.
	i	T_i	$x_i\left(t_{end}\right)$
		[s]	[cm]
TCU068EW	1	45.7	-731
TCU068NS	2	45.67	555
TCU068V	3	56.84	300

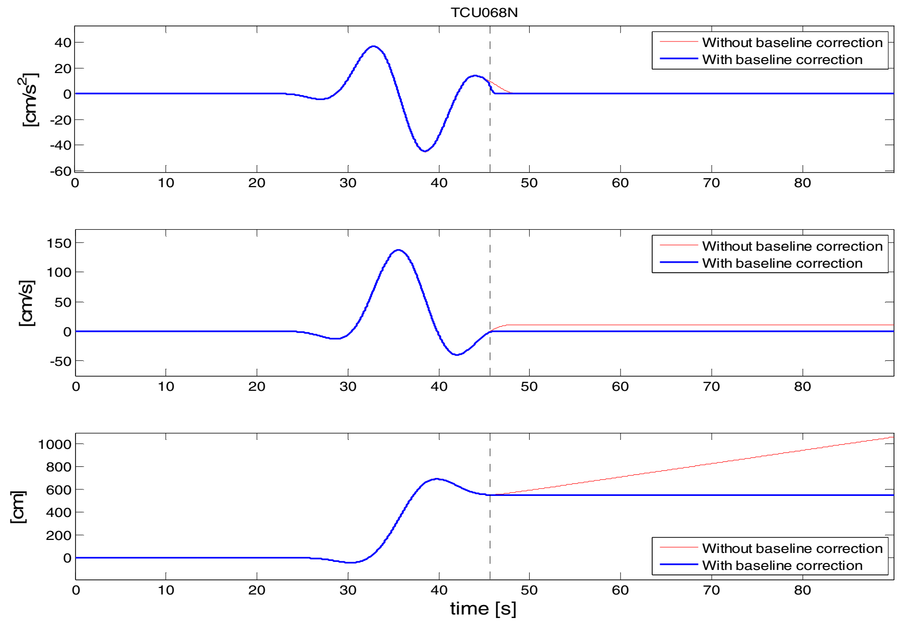

Figure 4, Baseline correction Lower frequency sub-band for TCU068NS component Recovered using bior1.3 at level 10

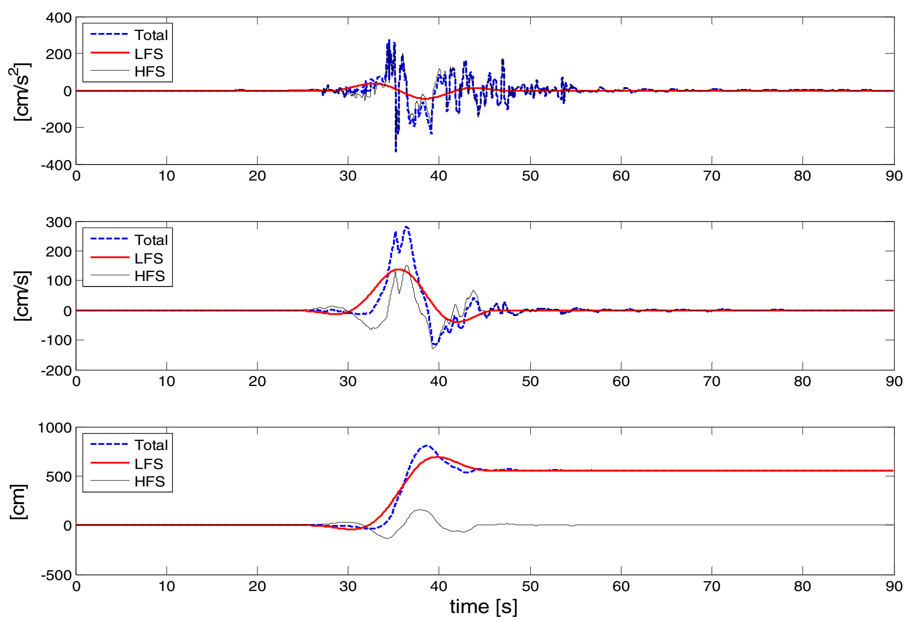

Figure 5, Comparison of lower and higher frequency sub-bands for TCU068NS at level 10, using *bior1.3*

TCU052 Fling

Results for TCU052 are summarized Table 2 and their time-history profiles shown in

[Chanerley, Alexander and Halldorsson, 2009]. The profiles are similar to those of TCU068NS, and the two stations are approximately 10km apart. Table 2 shows the resulting displacements and a comparison with GPS and the results given in [Wu & Wu, 2007]

Table 2

Wavelet *bior1.3*		Baseline point	Residual disp.	Disp offset	GPS:Wu (2.7km)
	i	T_i	$x_i\left(t_{end}\right)$		
		[s]	[cm]	[cm]	[cm]
TCU052E	1	40.05	-355	150	-342.3:-357.7
TCU052N	2	48.76	635	248	845.1 :687.9
TCU052V	3	56.93	337	59	397.2 :350.5

The ICEARRAY in Iceland

The ICEARRAY is the first small-aperture strong-motion array in Iceland, installed in the South Iceland Seismic Zone (SISZ) for the specific purpose of establishing quantitative estimates of spatial variability of strong-motions [Halldorsson et al., 2009]. At 15:45 UTC on 29 May 2008, a strong earthquake M_w = 6.3, took place in the district of Ölfus, South Iceland, in the western part of the zone [Halldorsson, Sigbjornsson, 2009]. During the earthquake the ICEARRAY produced high-quality, three-component data recordings at 11 stations, [Sigbjörnsson et al, 2009]. All stations were corrected for base line shift using the method published in [Chanerley, Alexander 2010] and some results were presented at the International Symposium on Strong-Motion Earthquake Effects [ISSEE, May 2009, ppt presentation: Chanerley, Alexander & Halldorsson.]. Some examples are shown in Figures 6 and 7.

Summary

This paper continues to demonstrate that the wavelet transform method of recovering the low frequency fling profiles makes double time-integration from acceleration to displacement easier and automatic. Once the wavelet transform algorithm has separated the low and higher frequency profiles and recovered the low frequency fling, the rest of the algorithm simply locates a time point, zeros the acceleration from that point and re-integrates to give the profiles shown in the Figures above. The success of this novel method lies in the fact that the wavelet transform and more specifically the wavelet filters, the non-linear scaling with de-noising provide a very reasonable method for automatically correcting seismic time-history records, and provides an alternative to some of the current methods used.

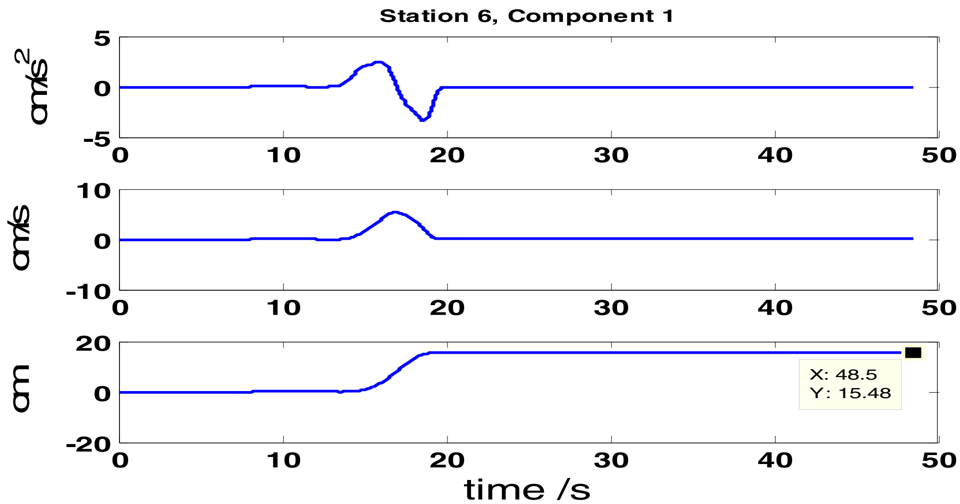

Figure (6), ICEARRAY station 6, horiz component 1, LF sub-band at level 9 using *bior1.3*

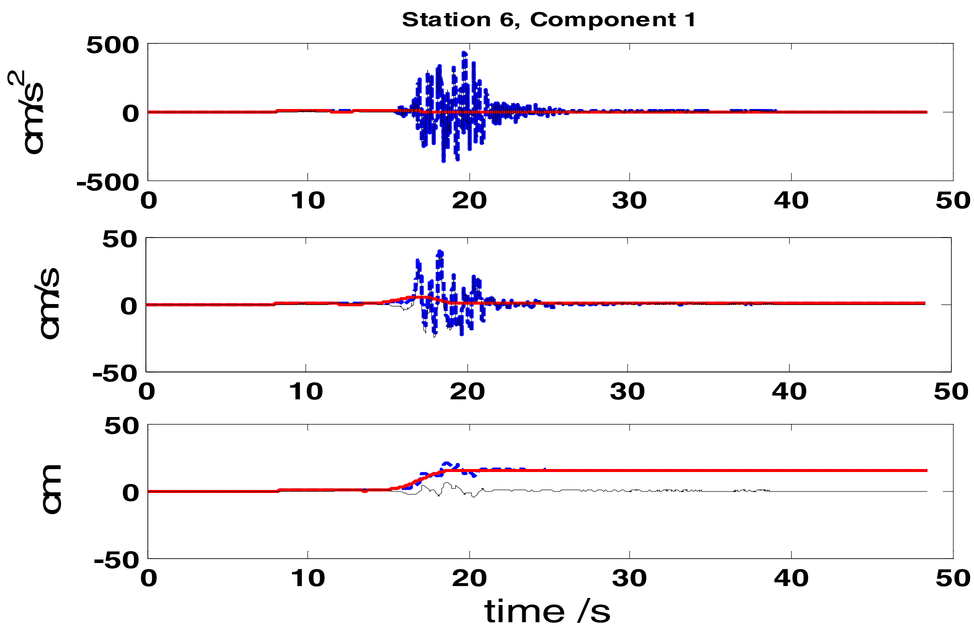

Figure (7) Showing the LF fling and HF profiles and the resultant profile of station 6, component

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