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Baseline correction for near-fault ground motion recordings of the 2008 Wenchuan *Ms*8.0 earthquake

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Abstract: In this study, both records of a digital accelerometer and a seismograph at a far-field station for the 2008 *Ms*8.0 Wenchuan earthquake were analyzed, and a pulsive noise model for acceleration record was found. By comparing with the result of a rotary-table tilt test, we concluded that the noises in the acceleration records were caused by ground tilt as a result of rotational ground motion. We analyzed the key noises that may cause baseline offset, and proposed a baseline-correction scheme for preserving the long-period ground motion in accordance with specific pulse positions. We then applied this correction method to some near-field strong-motion acceleration records. The result shows that this method can obtain near-field ground displacements, including permanent displacements, in agreement with GPS data, and that this method is more stable than other methods.

Key words: strong ground motion; baseline correction; permanent displacement; rotational motion; tilt

1 Introduction

Modern strong-motion acceleration instruments have the advantages of high accuracy, broadband and low noises. However, their records still contain baseline offsets[1-3], although small, can produce exaggerated displacements by double integration of the recorded acceleration. Thus baseline corrections are necessary. The traditional baseline correction procedure uses a high-pass filter[4], which tends to filter out signals together with noises, and thus losing long-period ground motions, which are important to engineering studies. Later correction methods can retain long-period signals[2,5], but have not been applied widely for lack of some valid noise model to match them. Furthermore, in many cases the derived displacements are very sensitive to the parameters used in the correction[3].

Generally speaking, the displacement obtained from velocity data by single integration is more stable and conclusive than that derived from acceleration data by double integration, for the long-period error is smaller[6].

Many factors can lead to baseline offset, including ground tilt and rotation, mechanical or electrical hysteresis in the transducer system, background noises and analog-to-digital convertion. Trifunac and Todorovska[7] concluded that the permanent ground displacement could not be computed without knowledge of the rotational components of strong motion. Although special instruments are needed to record rotational components of earthquake motion, ground tilt can be estimated by applying a low-pass filter to the digital strong-motion recording[8].

In this paper, we report on a study of baseline correction for the acceleration data recorded for the *Ms*8.0

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Wenchuan earthquake on 12 May 2008 through estimation of ground tilt, while keeping the long-period signals of ground motion, including permanent displacement. We tried to find a crucial noise model by comparing data from an accelerometer and a seismometer located near each other.

2 Data

More than 420 digital strong-motion accelerograms were recorded for the Wenchuan earthquake by China National Strong Motion Observation Network. Most of the sensors installed at the network stations were SLJ-100 force-balance accelerometers[1]. The effective-frequency band was from 0 to 80 Hz, and the sampling frequency was 100 or 200 sps[9]. The seismographic velocity records we used were downloaded from the China Earthquake Network Center (http://www.csndmc.ac.cn/newweb/data.htm). But only records (including both acceleration and velocity data) obtained from the Quanzhou station can be used. The static GPS data we used came from Zhang et al[10], who also applied high frequency (1 Hz) GPS data to obtain dynamic ground deformation. However, due to power failure caused by the strong earthquake shaking, only high-frequency GPS data of 65 seconds were recorded[11].

The strong-motion stations and the GPS stations are shown in figure 1. The strong-motion station 051PXZ is only 100 meters from the GPS station PIXI, where the ground motions of the main shake were recorded relatively well. Therefore, it is important to compare the displacements obtained by GPS with those obtained from the accelerogram.

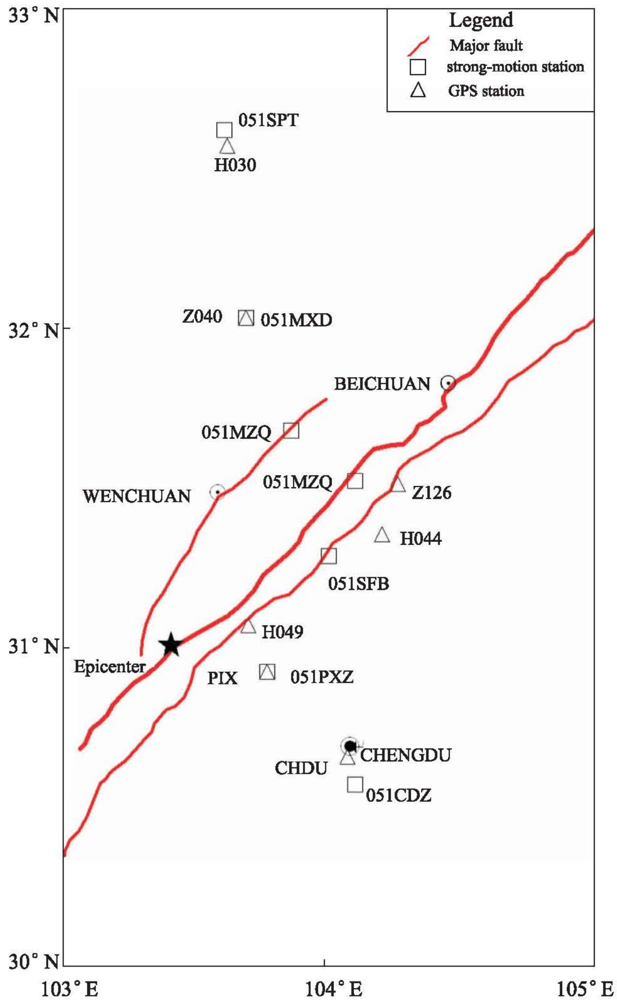

Figure 1 Sketch of Longmenshan thrust belt, strong-motion stations, and GPS stations

3 Correction schemes

3.1 Previous methods

With the development of digital accelerographs, the strong-motion records with high precision and broad-band have been widely used. Seismologists attempt to apply these records to obtain the residual ground deformation and the fault rupture process by inversion. Since baseline offsets always exist in the records, these deflects must be corrected before the result is utilized.

A correction method widely applied was proposed by Iwan et al[2], who ascribes the source of the baseline offsets to some minute mechanical or electrical hysteresis in the transducer system that occurred when the acceleration exceeded about 50 cm/s^2. To correct for this offset, Iwan et al[2] proposed that two baselines showd be removed: a_m between times t_1 and t_2, and a_f from time t_2 to the end of the record (t_e in this paper); they selected t_1 and t_2, respectively, to be the times of first and last occurrences of acceleration that exceeds 50 cm/s^2. The level a_f is determined by a least-squares fit to the tail part of the velocity trace:

$$v_f(t) = v_0 + a_f t \tag{1}$$

Then, a_m is given by

$$a_m = v_f(t_2)/(t_2 - t_1) \tag{2}$$

Boore[5] considered it not suitable to select t_1 and t_2 this way, and suggested to allows t_1 or t_2 to be a free parameter. However, the numerical tests indicated that the derived displacements were very sensitive to the selection of parameters. Another option discussed by Boore, which is called v_0 correction, is to choose t_2 as the time when the velocity-fitting line reaches zero:

$$t_2 = -v_0/a_f \tag{3}$$

In order to determine a_f, fitting to the final portion of the velocity record is necessary for any correction method. But different a_f and v_0 are obtained by choosing different starting time for the fitting (t_{FIT}). Akkar et al[12] proposed the following method to determine t_{FIT}: first choosing t_{FIT} to be an increment Δ less than t_e and find a_f by fitting the velocity. Then, reducing t_{FIT} by Δ to determine a new a_f, and plotting the ratios of consecutive slopes ($a_f, i+1/ a_f, i$) against t_{FIT}. The time, at which these ratios attain a relatively constant level of unity, is taken as the value of t_{FIT}. Akkar et al selected increments of 1 sec, but we have found that, even using increments of 0.1 second for t_{FIT}, the errors in the permanent displacements derived from such corrected acceleration can be several centimeters. Boore et al[3] proposed a correction scheme that involves fitting a quadratic term to the velocity. We carried out many numerical tests according to this method, and found the results showing evident fluctuations for the tail parts of the displacement traces. Figure 2 shows, as an example, the displacements obtained from various correction methods for the east-west component of acceleration recorded at station 051PXZ. Also shown in figure 2 are the 1-Hz GPS data of displacement after removing the pre-event average value. It is obvious that there are tremendous differences between the results of using different correction methods, and between results of selecting different parameters for the same method.

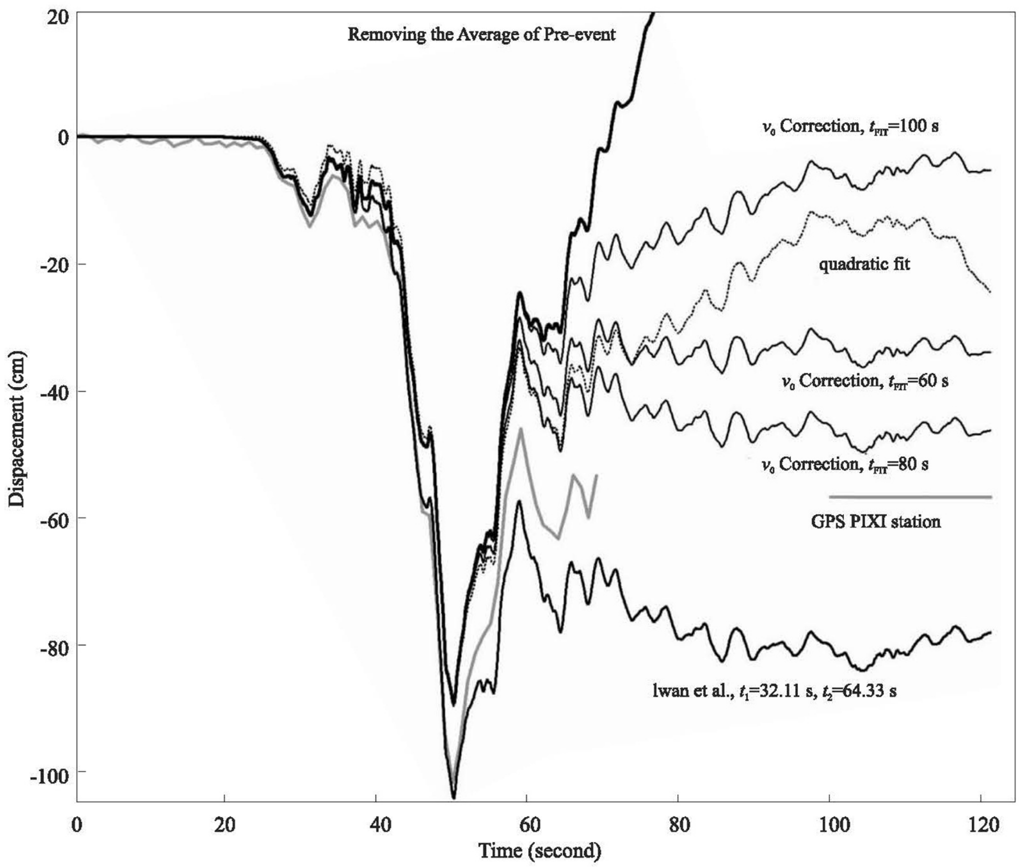

Figure 2 Displacements obtained by the double integration of the east-west component of acceleration recorded at the 051PXZ station for the 2008 Wenchuan earthquake. Also shown are modified displacements by using a variety of baseline corrections.

3.2 Causes of baseline offsets

Many researchers analyzed the causes of baseline offsets in digital strong-motion acceleragrams[2,3,13,14]. Since interference to instrument from ground deformation is smaller at a larger epicentral distance, we chose the station Quanzhou, which is 1640 km away and has both acceleration and velocity records, as a reference.

As shown in figure 3(c), the baseline of displacement at this station can be fitted by a piecewise linear function. From this function, the baseline functions of velocity and acceleration can be derived by single and double differentiations, respectively. In such an approach, the velocity baseline becomes a step function, and the acceleration baseline, some discrete pulses. The problem now is how to determine the beginning and end points of the subsections accurately, since it is quite subjective in finding the trend of displacement trace. After several trials and adjustments, we chose time T_1, T_2, T_3, T_4 and T_5 shown in figure 3(c) for correction. The baselines of acceleration, velocity and displacement derived from this correction are shown in figure 6. The displacement trace obtained from the corrected SLJ-100 acceleration is in good agreement with that from the CTS-1 velocity time series, as shown in figure 4.

What are the causes of the baseline offsets in the SLJ-100 records? If the offsets are regarded as noises, then the sources should be identified. A noise model in acceleration can be deduced from differentiation of the displacement function. The noise model for acceleration shown in figure 6 is very simple, consisting of several equal-interval alternating pulses. Of course, it is hard to find these pulses directly from ordinary acceleration records. However, by examining the results of a rotary-table tilt test conducted with Lee in 1993 and published by Gaizer in 2006[8] (Fig. 5), we found that not only baseline offset of acceleration records but also high-frequency pulses may be caused by tilt, when it reaches some peaks. In this test, since the largest table tilt was about 9 degrees[8], the noise amplitude was much bigger than the input signal.

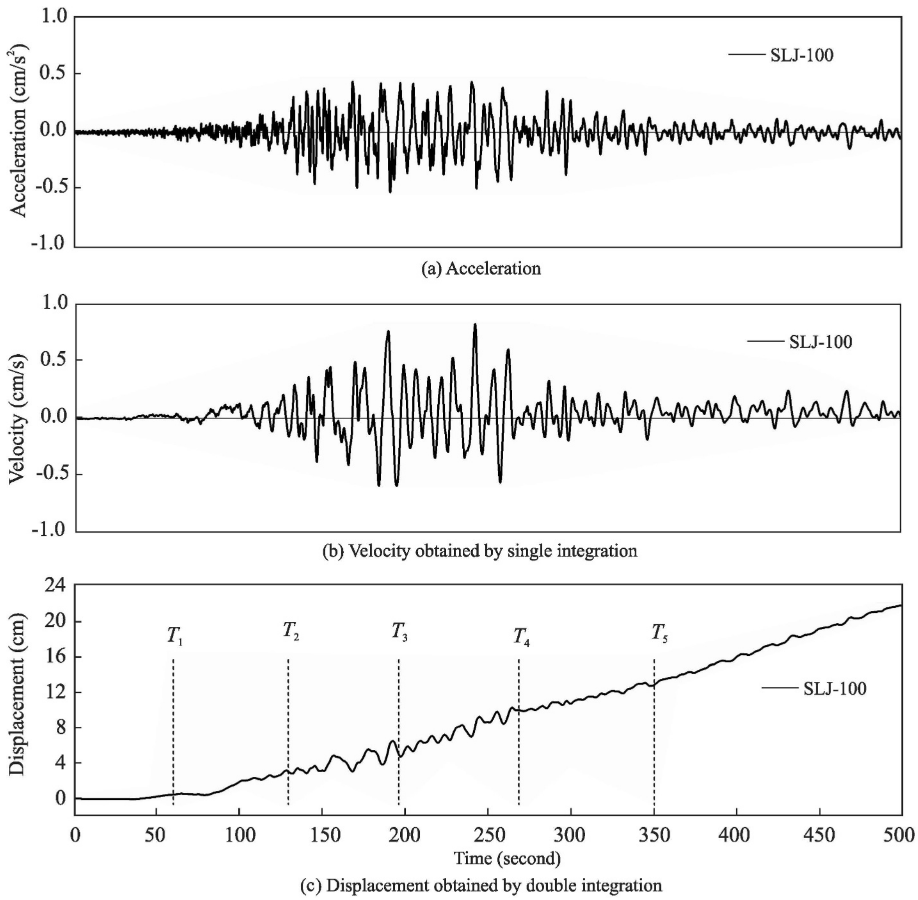

Figure 3 The NS component of strong – motion recorded at Quanzhou station

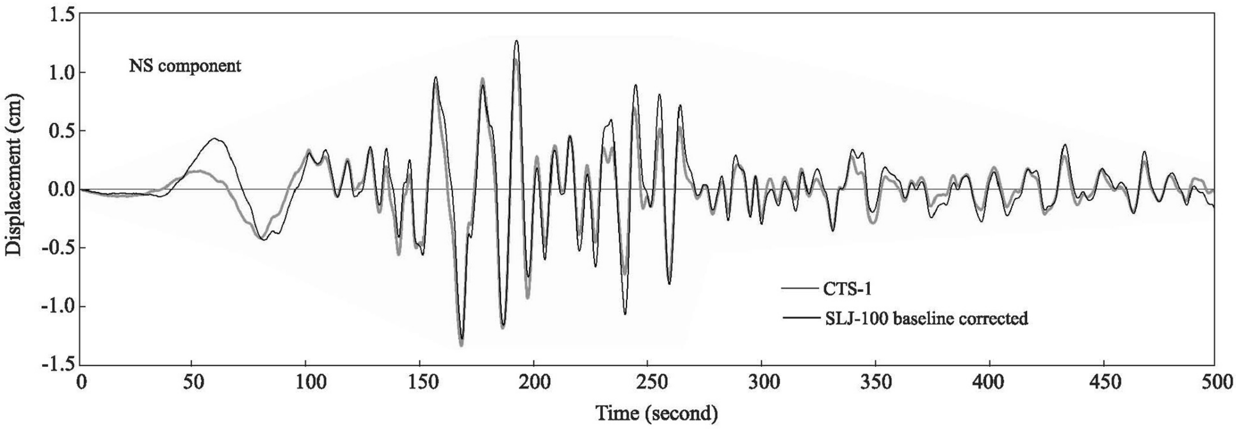

Figure 4 Displacement traces obtained from the CTS-1 velocity and the SLJ-100 acceleration after applying baseline correction to the records at Quanzhou station

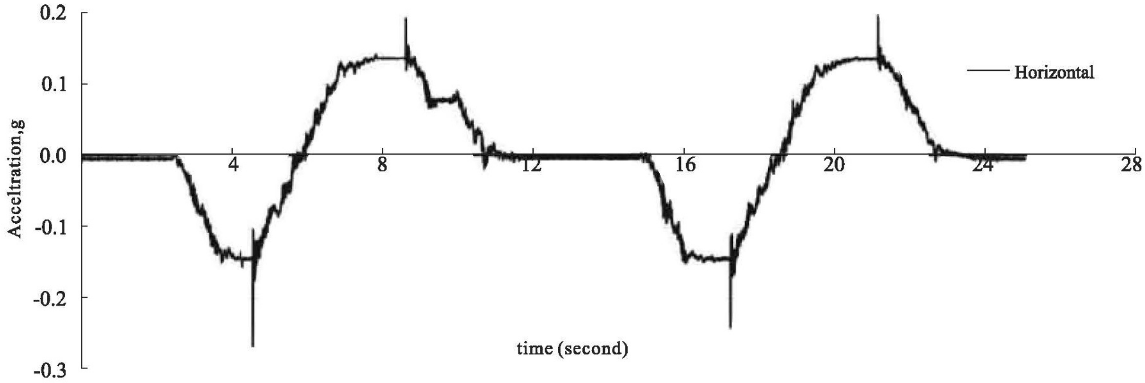

Figure 5 Partial results of a rotary-table tilt test in the laboratory[8]

In order to prove that the pulsive model noise in the SLJ-100 acceleration record is caused by ground tilt, it should be compared with observed tilt data. Gaizer[8] proposed an algorithm for tilt identification, including calculation of amplitude-spectra ratio between horizontal and vertical components, determination of characteristic frequency and application of low-pass filter.

We attempted to use this method to identify ground tilt in the SLJ-100 acceleration records. However, the difference between the spectra of horizontal and vertical components in low-frequency is too small to choose the characteristic frequency. Hence we used the velocity spectrum to determine the characteristic frequency. Theoretically, the spectrum decreases with the decreasing frequency in low-frequency, but in the case of uncorrected SLJ-100 acceleration record, it increased with the decreasing of frequency for frequency less than 0.012 Hz. So the characteristic frequency was determined to be 0.012 Hz. Then, we applied a low-pass filter to filter out all frequencies higher than 0.012 Hz, and postulated that the filtered signal divided by acceleration of gravity is the tilt[14] (Fig. 6(a), where units of tilt are changed from radian to degree for the direct viewing).

Figure 6(a) indicates that high-frequency pulses are produced when tilt reaches some peaks, which is in agreement with the test result shown in figure 5. Noises in velocity and displacement derived from integration of the pulsive-noise model of acceleration are shown, respectively, in figure 6 (c) and (d). We may conclude that the ground tilt caused not only the baseline offset of the acceleration records but also the pulsive noises. If the ground tilt is very small (no residual tilt), then its effect on its own baseline may be ignored, but the pulsive noise may cause obvious offsets in displacement baseline. Trifunac et al[7] concluded that the long-period information (e. g., permanent ground displacement) cannot be calculated without the knowledge of the rotational components of strong motion. According to our results, even when the rotational

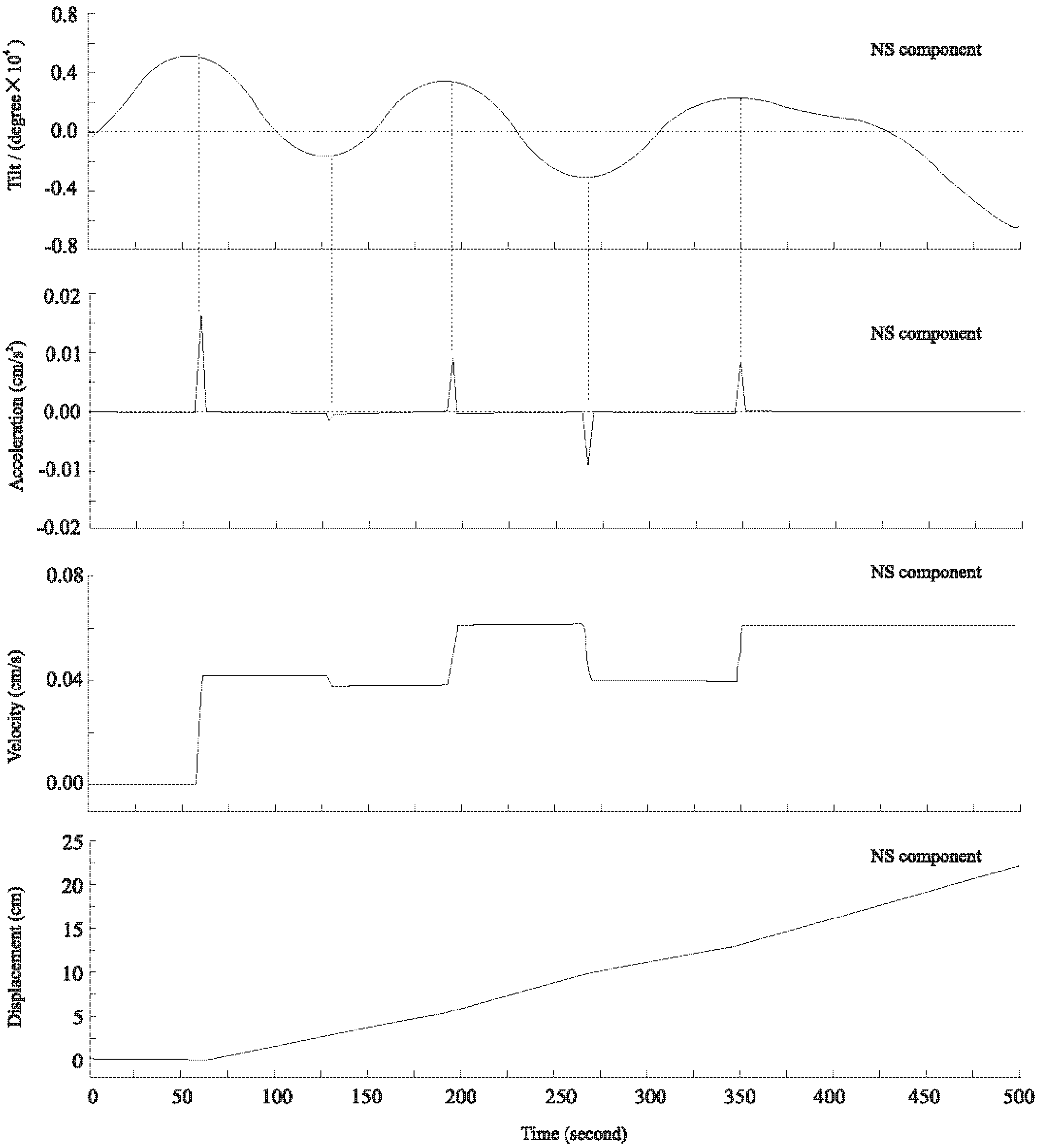

Figure 6 Tilt and the corresponding noises in NS component of SLJ-100 record at Quanzhou station

motion is available, the above-mentioned noise should still be subtracted from the acceleration records in order to recover the true ground displacement.

Based on this analysis, the ground tilt may be computed by applying a low-pass filter to the acceleration record before the baseline correction, and the time points at which the noise pulses occur may be determined, thus the previously-mentioned problem may be resolved. In this way, the EW component of the SLJ-100 recorded from the Quanzhou station was corrected, and the corrected displacement was found to be consistent with the CTS-1 record (Fig. 4).

3.3 Proposed algorithm for baseline correction

Based on baseline characteristics of the digital strong-motion acceleragrams, we propose here a simple algorithm for baseline correction. The scheme includes the noise identification and the least-squares fitting in velocity, as outlined below:

(1) Choosing a suitable corner frequency (f_c), and using a low-pass filter with f_c to obtain a long-period signal.

(2) Calculating velocity by integrating the filtered acceleration, determining the correlative parameters by the least-squares fitting to the tail part of the velocity function, and then determing the positions of the peaks of the filtered acceleration. We think that the filtered signals contain not only the noises which may cause baseline offsets, but also the long-period motions and permanent displacements, which are of concern in en-

gineering.

(3) Removing the offsets from the acceleration data, then obtaining velocity and displacement by integration.

We illustrate this correction process by taking the horizontal component of acceleration recorded at the near-field 051PXZ station as an example. We first obtained the amplitude spectra of the three components of acceleration in order to choose corner frequency, In view of energy leakage of fast Fourier transform (FFT), we adopted Parzzen window to achieve smoothing. The f_c so determined is 0.08 Hz, the reason being that the spectrum of horizontal component is far higher than that of the vertical at frequencies lower than f_c and its declining rate becomes evidently slowdown while the frequency is less than f_c.

Then, we applied a low-pass Butterworth filter with the the chosen f_c to the acceleration records. In order to avoid the phase shift, the same filter was applied twice in opposite directions. The low-frequency acceleration and velocity were derived by integration are shown in figure 7.

The starting point for fitting (t_{FIT}) was easily determined according to these curves, that is, t_{FIT} is the starting point of the relatively stable section for the acceleration and the seemingly linear trend section for the velocity. Level a_f was obtained by the least-squares fitting to the velocity from t_{FIT} to t_e, and t_2 determined as the intersection point (near t_{FIT}) of the fit line and the velocity curve.

Note that the parameters a_f and t_2 are less sensitive to the selection of t_{FIT}. The baseline of the acceleration record from the start of strong shaking to t_2 is influenced by not only the ground tilt but also the pulsive model noise, as mentioned previously. Graizer[8] assumed that the filtered acceleration could reflect ground tilt, but from the velocity traces shown in figure 7, it may be seen that the large velocity pulse is the cause of permanent displacement. Therefore, the filtered acceleration contains long-period earthquake motion.

According to this analysis, the acceleration pulses occur at t_a, t_b, t_c, etc. Although the magnitude of each pulse is not known at present, the integration of all pulses on the time axis can be estimated as $v_f(t_2)$. Thus, we averaged these acceleration pulses as a_m according to equation (2) in which t_1 was chosen as the occurence time of the first obvious pulse with the same direction as the offset. The model of this method is similar to that provided by Iwan et al[2], but the causes of baseline offsets considered are different. In the correction scheme proposed by Iwan et al[2] and that modified by Boore[3], t_1 and t_2 were chosen subjectively, but in this scheme they were determined by noise position; also, t_1 was constrained between arrival time of S

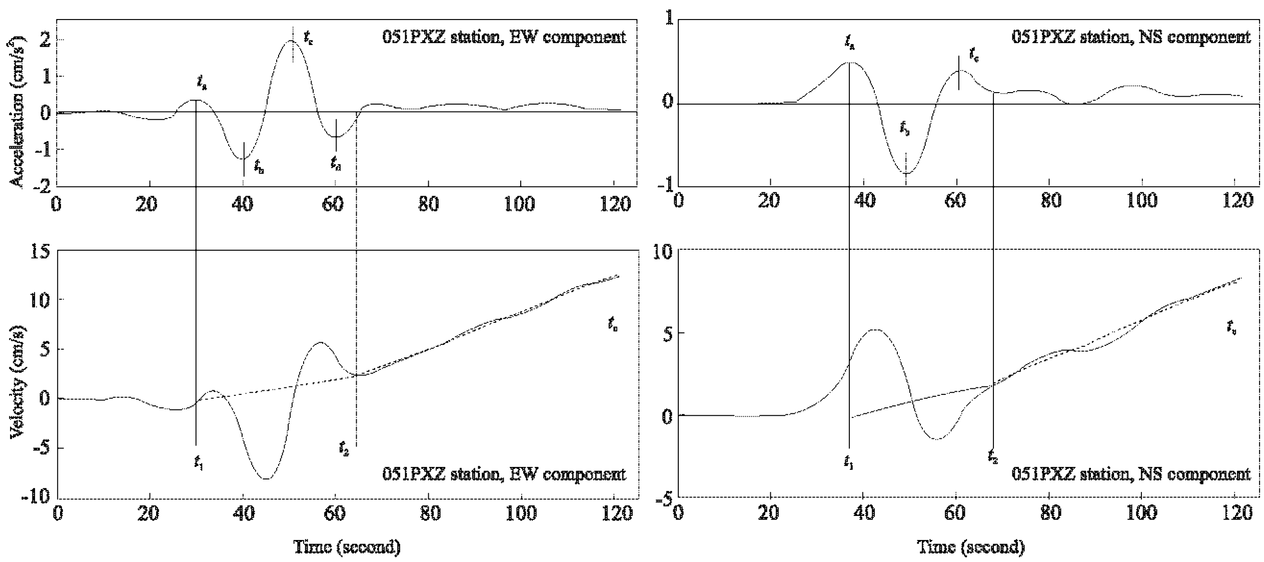

Figure 7 Baseline correction scheme. The top traces are obtained by low-pass filtering of the original acceleragrams of 051PXZ station; the bottom traces are derived from the integration of them, and the dashed lines are baselines of the uncorrected velocities to be subtracted.

wave (t_S) and t_2. As shown in figure 8, the displacements obtained from the corrected accelerations are very consistent with the GPS data. The present result is more precise than the result of Yin et al[11].

Under some condition, the amplitude of the pulsive noise can be estimated. Taking the east-west component of acceleration recorded at the 051SPT station as an example, there is no pulsive model noise between t_1 and t_2 in the filtered acceleration curve (Fig. 9(a)), thus the pulse can be calculated by $v_f(t_2)$:

$$0.5\ ba_p = v_f(t_2) \tag{4}$$

where b is the width of the pulse and a_p is the height. Removing this pulse from the corrected acceleration between $t_1 - 0.5b$ and $t_1 + 0.5b$ and a_f between t_2 and t_e gives the result shown in figure 10. This figure also shows data from a GPS station located 5.6 km south of the strong-motion station. As shown in figure 10, if the duration of the record is very long, then there is evident influence from the long-period background noise, especially during the last portion of displacement.

By applying this correlation scheme to the records of the near-field strong-motion stations shown in figure 1, we obtained the results shown in figure 11.

4 Conclusions

In a comparative analysis of the SLJ-100 acceleration records and the CTS-1 velocity records of the 2008 Wenchuan earthquake at the remote Quanzhou station, we found that it's possible to recover ground displacement from the corrected high-precision strong-motion records. The acceleration noises model we used was a series of equal-interval alternating pulses, which was derived from the noise model of the displacement obtained in our correction scheme. By comparing with the results of a rotary table tilt test[8], we conclude that the pulsive model noises were caused by rotational ground motion, which resulted in ground tilt. This result will be useful for correcting baselines of strong-motion acceleration records in general.

According to the positions of the noise pulses, we proposed a baseline correlation scheme similar to that

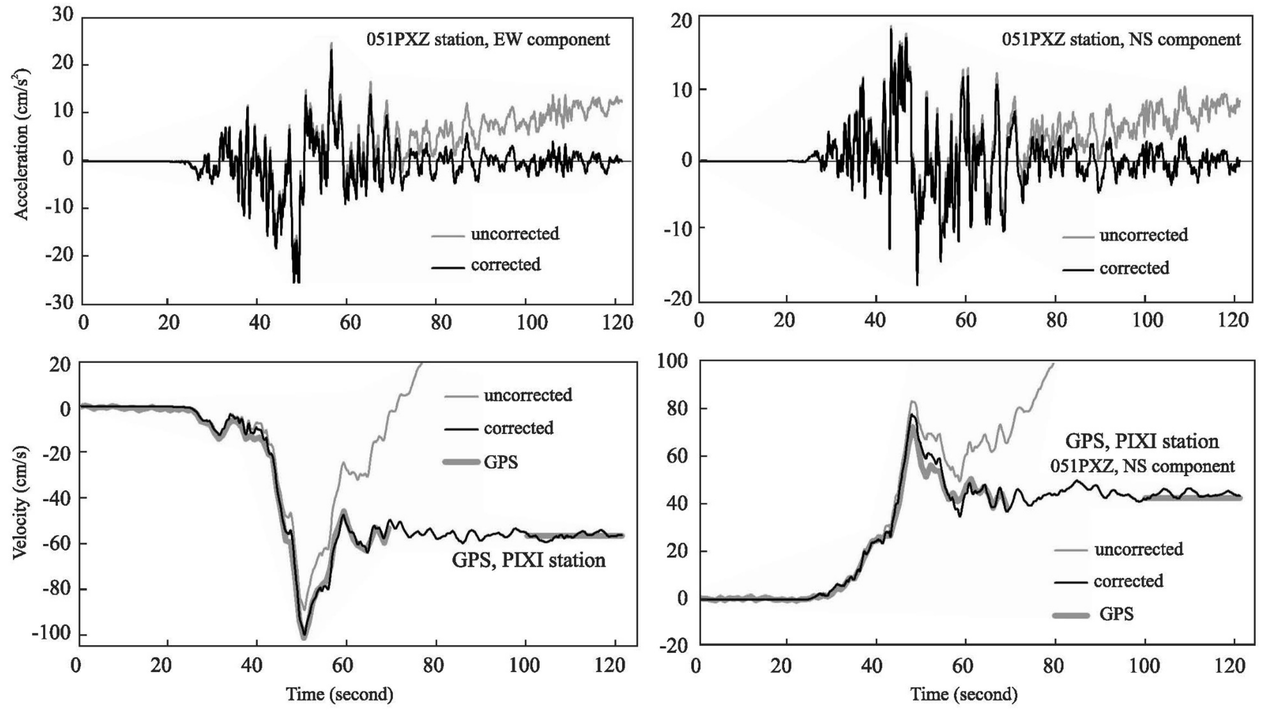

Figure 8 Velocities and displacements derived from the corrected accelerations of 051PXZ station.

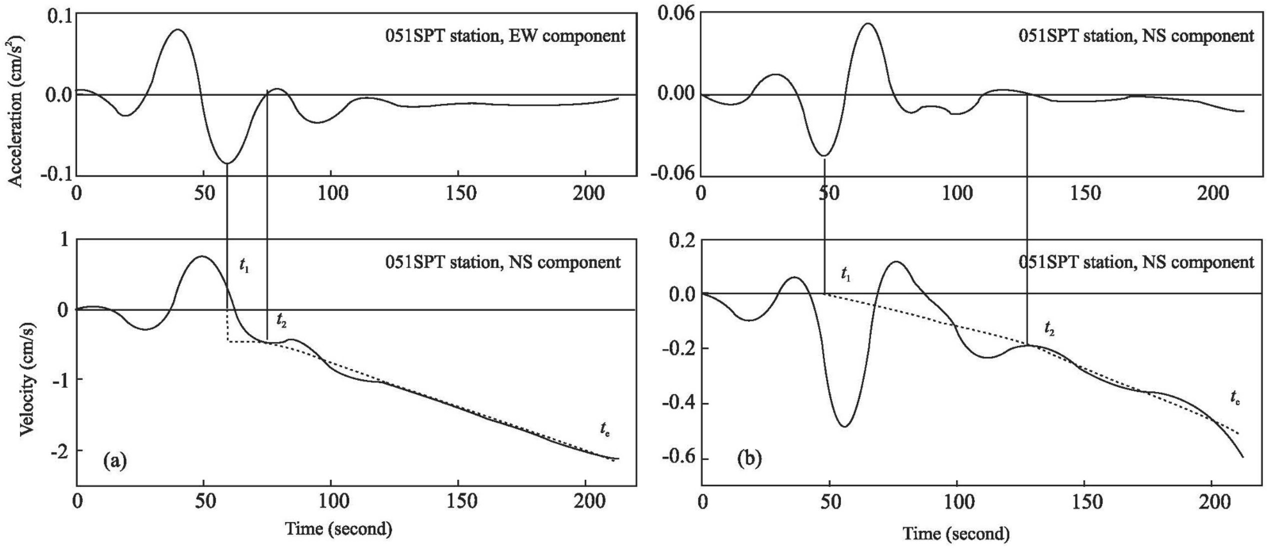

Figure 9 The same baseline-correction scheme as shown in figure 7 is illustrated with records of 051SPT station

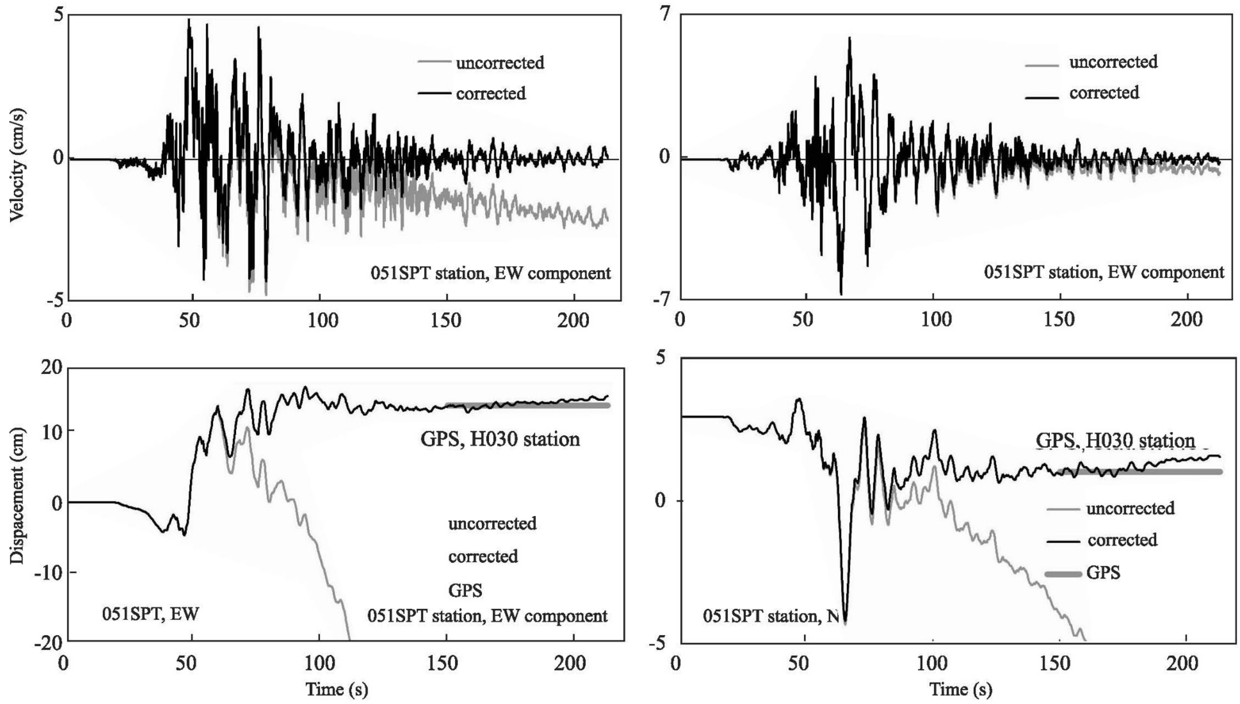

Figure 10 Velocities and displacements derived from the corrected accelerations of 051SPT station.

by Iwan et al[2], except that our correlation parameters are determined objectively. By applying this method, we corrected a set of near-fault strong-motion records of the 2008 Wenchuan earthquake with GPS data as reference. The results shows that the displacements obtained by the corrected strong-motion accelerations essentially coincide with those obtained from the GPS data.

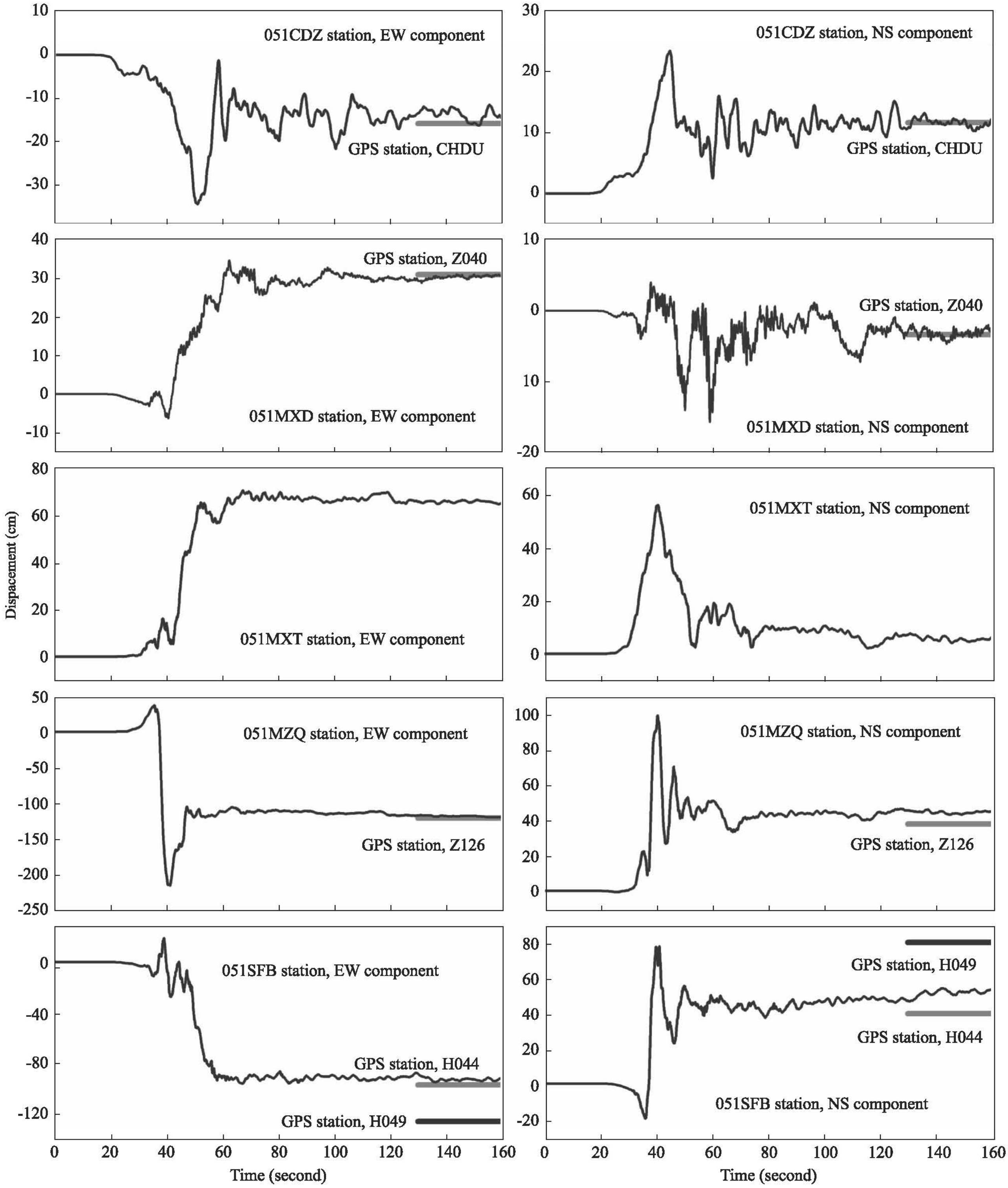

Figure 11 Displacements obtained by double integration of the corrected accelerations from several stations shown in figure 1 using this baseline correction. The results from GPS data are indicated by the marked straight lines

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