Stable Baseline Correction of Digital Strong-Motion Data
by Hung-Chie Chiu

Abstract Most baseline errors of analog strong-motion data still exist in high-resolution data. In this study, we identify the major baseline errors of digital strong-motion data and propose a three-step algorithm to correct these errors. The major baseline errors found in these digital data consist of constant drift in the acceleration, low-frequency instrument noise, low-frequency background noise, the small initial values for acceleration and velocity, and manipulation errors. This three-step algorithm includes fitting the baseline of acceleration by the least squares, applying a high-pass filter in acceleration, and subtracting the initial values in velocity. A least-squares fit of a straight line before filtering can effectively remove the baseline drift in acceleration. Then, the filtering removes the linear trend and other low-frequency errors that exist in the acceleration. Finally, the subtracting of the initial velocity removes the linear trend of displacement. Among these three steps, only the filtering in the second step may introduce a side effect. Compared to the Volume II routine developed by Trifunac and Lee (1973), this three-step processing significantly reduces computational efforts and side effects resulting from unnecessary manipulation of data. This algorithm has been successfully tested on several types of digital strong-motion data. Several independent validations show that the proposed algorithm is stable.

Introduction

Low-frequency signals including acceleration, velocity, and displacement waveforms are as important as the high-frequency acceleration for many studies in seismology and earthquake engineering. For example, the velocity signals are associated with the kinetic energy of seismic waves, displacements provide the information on deformation, the displacement of ground motion is preferred in the study of earthquake sources, and the low-frequency seismic waves have major contribution to the responses of high-rise buildings and large structures such as dams and bridges. Unfortunately, these low-frequency seismic waves are easily contaminated by baseline errors. Most ratios of baseline error to the seismic signal are negligible in acceleration, but they become larger and larger in velocity and displacement waveforms. A displacement waveform integrated directly from the raw accelerograms without applying any preprocessing may deviate greatly from a zero baseline. In fact, most of these baseline errors are much larger than the ground displacement itself and, as such, limit the usefulness of low-frequency signals. Therefore, baseline correction is an essential step in extracting more low-frequency information from strong-motion accelerograms.

It has generally been agreed that baseline errors of analog strong-motion records are derived from the recording and manipulation of records. Recording errors come from film or paper warping, background noise, recording system noise, baseline drift, and the baseline uncertainty due to an incomplete accelerogram in an analog recording (Trifunac, 1971; Trifunac and Lee, 1974; Hudson, 1979). Errors derived from the manipulations are due to the enlargement before the digitizing, digitizing from a finite thickness of seismic trace and filtering.

Recent developments in digital strong-motion accelerographs (16- or 24-bit recorder) have made great improvements in data quality. Some of the errors found in analog data do not exist in digital strong-motion data, for example, the warping of records and the digitization errors. Other errors, such as the uncertainty of the initial baseline, have been significantly reduced as well. However, a large offset still exists in high-resolution and high-sampling-rate digital data despite the improved data quality. Hence, baseline correction is still an important issue in the processing of digital data.

In the past two decades, many methods have been proposed for strong-motion data processing. Among these methods, the most popular is the Volume II routine developed by Trifunac and Lee (1973) and later revised in 1979 (Trifunac and Lee, 1979) and in 1990 (Lee and Trifunac, 1990) to include new developments in hardware and software. This routine has yielded several other versions, such as those used by the California Division of Mines and Geology (CDMG) (Porter, 1982) and by the U.S. Geological Survey (USGS) (Converse and Brady, 1992). Other methods...
have also been developed, for example, the method proposed by Sunder and Connor (1982). Most of these routines were mainly developed for the processing of analog data; each includes many steps for the correction of various errors. For example, Volume II requires at least four filter applications and one least-squares fit for a baseline correction. If iterations are desired, all of the procedures are repeated. For digital strong-motion data, many of the steps in these routines are redundant. Although the cost of the computing becomes cheaper and the increase of computational effort less important, side effects might be introduced with extra processing.

The SMART-2 (Chiu et al., 1994) data have much higher quality than analog data. However, to provide reliable data in a wide frequency band, the baseline correction algorithm used in analog data must be modified. For this article, about 1500 sets of 16-bit SMART-2 accelerograms and 100 sets of other digital data have been analyzed, and their baseline errors have been classified into four categories based on the source of errors. Although the individual pattern of these baseline errors are quite different, most of them affect the low-frequency seismic signal below about 0.1 Hz. Therefore, it is possible to apply a high-pass filter to remove most of these errors except for those from the initial velocity (velocity at the beginning of the record) that do not exist in the acceleration. This initial velocity has been given little attention in strong-motion data processing because it is usually small. However, it makes a large contribution to the final offset of displacement. In fact, the initial velocity causes a constant shift in velocity and a linear trend in displacement. In order to remove this error further processing either in velocity or in displacement is necessary. In this article, three-step algorithm is proposed to do baseline correction. Detailed analysis of baseline errors and the description of this algorithm are given. This algorithm reduces the numerical manipulation of the original accelerogram to a minimum; nevertheless, it gives very stable results.

The SMART-2 Data

The baseline-error analysis is mainly based on SMART-2 array data. The recording system of this array includes a triaxial force-balance accelerometer (FBA) and a 16-bit recorder. The sensor used in the SMART-2 array, the FBA-23 of Kinemetrics Inc., has a natural frequency of 50 Hz and a damping of 70% of critical damping. This sensor has a very flat amplitude response and a near-linear phase response from 0 to about 20 Hz. The deviation of the phase response from a linear phase is small, starting from 0° at 0 Hz and decreasing monotonically to 2.2° at 20 Hz. Overall, the response of this instrument is close to ideal over the frequency range from 0 to 20 Hz.

The recorder used in the SMART-2 array, an SSR-1 of Kinemetrics Inc., has a 16-bit resolution that is equivalent to 0.0305 gal/count for a 1 g sensor. The peak ground motions of most data selected in this study are over 10 gal, and the distortion due to the resolution of the recorder is negligible. This recorder also provides adjustable pre-event and postevent memories. In the SMART-2 array, 10 sec for the pre-event memory and 30 sec for the postevent memory were programmed, and, in most cases, this setting ensured that the first P arrival and later arrivals were well recorded.

Although the DC offset of accelerometers was adjusted to be less than 1 gal in each routine maintenance, a DC drift always exists in the SMART-2 data. The DC drift of the raw data used in this study was reduced by subtracting the mean value of whole record that does not entirely remove the DC but reduces it below one-half of a digital count.

These data include 1500 sets of SMART-2 data collected in 1992 and about 100 records of four other types (SSA-1 of Kinemetrics Inc., A800 and A900 of Terra Technology, and IDS of Teledyne) of strong-motion data. These data, covering the typical baseline errors found in the digital strong-motion data, are used in the baseline-error analyses and wide testing of the proposed algorithm.

The Origins of Low-Frequency Errors

Both low- and high-frequency errors are present in digital strong-motion data, but only the low-frequency error affects the baseline. According to their origins, low-frequency errors are classified into instrument noise and constant drift, background noise, initial value, and manipulation errors.

Instrument Errors and Constant Drift

Five typical sources of error come from the instrument: imperfect instrument response, insufficient resolution, insufficient sampling rate, electronic noise, and baseline drift.

The deviations of the instrument response from the flat amplitude response and the linear phase are small in the low-frequency but large in the high-frequency signals. Therefore, the imperfect response of a sensor has a small influence on the baseline correction. Although the instrument correction is not important for low-frequency seismic waves, all the data used in this study have been corrected for the instrument response.

The limited resolution is another source of instrument error. The digital data have been curtailed for those values that are less than one digital count by rounding off, which produces a residue and causes some uncertainty as to the true baseline. The upper bound of the drift due to this rounding off is one-half of a digital count. However, the balance between the rounding up and rounding down will keep the true drift much less than the upper bound. For the SMART-2 data, the resolution of the recording system is about 0.0304 gal/(cm/sec/sec); the upper bound of the drift of the baseline does not exceed 0.0152 gal.

A simple numerical test can demonstrate the existence of this error. A sine wave with an amplitude of 15 gal and 40 sec long is sampled using the same sampling as the SMART-2 data, which have the unit of 0.0304 gal (one digital count). The signal amplitude is rounded up by one digital count if its value is larger than one-half of a unit; otherwise,
The sensor and other unknown reasons cause an additional baseline for the SSR-1 recorder during maintenance. No baseline due to the material fatigue of the sensor. The presence of background noise makes it difficult to set the zero baseline drift. These two types of drift produce the final drift in the accelerograms. These nonzero baselines produce a linear trend on a velocity seismogram and a parabolic baseline on a displacement seismogram. The parabolic baseline is the basic shape of the baseline error that comes from the constant drift of acceleration. A variety of baseline errors can be produced by various combinations of the initial velocity and the background noise. Some selected baseline errors are shown in Figure 2. In order to explore baseline errors in more detail, all DC components have been removed from the plots in this figure. All these baselines have different shapes, and even the three components of the same recording may have different shapes. Fortunately, all these baseline errors are related to the low-frequency noise that can be significantly reduced by applying a high-pass filter.

Background Noise

A random waveform and wide distribution in the frequency content are also features of background noise. The frequency content and the characteristics of background noise are strongly site dependent. Ocean waves and various cultural activities are the main sources of these noises. The acceleration of background noise is much smaller than that of the seismic signal, but the effect of noise on the displacement cannot be ignored. Background noise contributes to the nonzero initial value that causes an accumulated baseline error. As a result, background noise also has a large effect on the baseline error.

The noise level in the area of the SMART-2 array is about 0.3 cm/sec/sec. This noise includes the instrument and the background noise of the site. The comparisons of the noise and seismic signal for typical SMART-2 data are shown in Figure 3. Noise is extracted from the first 9 sec of
the pre-event recording, while the earthquake indicates the whole accelerogram that includes both seismic signal and noise. From the top to the bottom in Figure 3 are the corresponding Fourier amplitudes of the N–S, vertical, and E–W components. The background noise in all three components distributes uniformly in the whole frequency band, implying that the noise is close to a white spectrum. This figure also illustrates a low signal-to-noise ratio in both the low and high frequencies. Therefore, a high-pass filter is necessary to reduce the noise in the baseline correction.

Initial Values

The causality of seismic waves requires zero acceleration, velocity, and displacement before the arrival of seismic waves. In reality, these initial values are not zero because of the presence of electronic noise and the background microtremor. These initial values may cause a large final offset in the displacement waveform; a small initial acceleration might be magnified in the integrated displacement. For example, a 0.01 cm/sec/sec offset in a 60-sec accelerogram will have 0.6-cm/sec final offset in velocity and 18-cm final offset in displacement. Besides, the data processing causes an additional modification on the initial value. One example is given later.

The initial velocity does not explicitly appear in the acceleration since the derivative of the constant initial velocity vanishes. Therefore, to reduce errors caused by the initial velocity, another step is required. Let \( \ddot{x}(t) \) represent the time series of acceleration. The Fourier expansion of \( \ddot{x}(t) \) is

\[
\ddot{x}(t) = \frac{a_0}{2} + \sum_{n=1}^{N} \left[ a_n \cos(2\pi f_n t) + b_n \sin(2\pi f_n t) \right],
\]

where \( a_n \) and \( b_n \) are coefficients corresponding to the even and odd functions of \( x(t) \). The integration of \( \ddot{x}(t) \) from 0 to \( t \) gives

\[
\int_0^t \ddot{x}(t) dt = \ddot{x}(t) - \ddot{x}(0) = \frac{a_0 t}{2} + \sum_{n=1}^{N} \frac{1}{2\pi f_n} \left[ a_n \sin(2\pi f_n t) - b_n \cos(2\pi f_n t) \right] + \sum_{n=0}^{N} \frac{b_n}{2\pi f_n}.
\]

The second summation in (3) corresponds to the initial velocity. If this summation does not vanish, the initial velocity will not be zero. Equation (3) not only indicates the existence of an initial velocity, it also provides an easy and stable estimation of initial velocity. The verification of equation (3) is shown in Figure 4. On the top of Figure 4 is the filtered acceleration. The integrated displacement obtained from this acceleration is shown in Figure 4b. A clear linear trend is seen in this displacement waveform.

The initial velocity estimated by the last term in (3) is 0.000242452 cm/sec. The corrected displacement using this initial velocity is shown in Figure 4c. This displacement waveform is almost the same as the result from an independent correction (Fig. 4d) constructed by subtracting a least-squares fitting line from the displacement. The performance of the baseline correction based on (3) was successfully tested on more than 200 sets of the selected data.

Manipulation Errors

Data processing removes some types of errors that come from the recording; but at the same time, it introduces new
errors. Filtering, windowing, and tapering are typical forms of data manipulation that may introduce side effects to modify the processed waveform as well as the baseline. A small change in the waveform does not significantly modify the integrated displacement, but a small baseline drift causes a large final offset in displacement.

In summary, most of the low-frequency errors found in analog data still exist in digital data and cause significant baseline errors, despite the fact that the quality of the digital data has been greatly improved. These baseline errors may be grouped into two categories: The first type of errors are of order two (parabolic) or lower in the displacement that arise from the baseline drift and the initial values in both velocity and acceleration. These errors relate to the long-period noise and can be accumulated when the acceleration is integrated to velocity or displacement. The second type of errors are high-order random errors. These errors are not accumulated in the integrated velocity or displacement waveforms.

The Proposed Algorithm for Baseline Correction

Based on the characteristics of the baseline errors, a simple algorithm is proposed for baseline correction of digital strong-motion records. This three-step algorithm includes least-squares fitting in acceleration, high-pass filter-
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116.33
-116.33
0.3157
-0.3157
0.2873
-0.2873
0.2867
-0.2867
0

(A) Filtered acceleration
(B) disp. of (A)
(C) Corrected disp. (Vo correction)
(D) Corrected disp. (lsq in disp.)

Figure 4. The filtered acceleration (a) and its integrated displacement (b). The final displacement corrected by the initial velocity (c) and the least-squares fit in displacement (d).

The filtered acceleration and its associated displacement are shown in Figures 5c and 5d, respectively. This step slightly shifts the baseline, but the baseline errors are significantly reduced (Fig. 5d). In this particular case, the accelerogram in Figure 5c still has a residue of baseline error that causes a parabolic baseline in the displacement (Fig. 5d). Nevertheless, this residual error can be removed during filtering in the second step.

The discussion is divided into two parts: the first part deals with the processing steps and the second part focuses on the filtering in the second step. The first part explains why the proposed algorithm is effective in removing the baseline errors. The second part discusses the filtering in the second step and its impact on the waveform.

For the processing of most digital strong-motion data, all three steps in the proposed algorithm are necessary. Removing the large offset of linear trend before filtering avoids distortion at the ends of records, applying a band-pass filter is needed to recover ground displacement when the displacement of noise is not negligible, and subtracting of initial velocity cannot be skipped because the initial velocities in most cases are not zero. On the other hand, these three steps have been shown to be enough for correcting the baseline errors. The iterations in Volume II are not required in this three-step algorithm.

The proposed algorithm not only minimized the processing steps but also the side effects of data manipulation. Among these three steps, filtering in the second step is the only procedure that may modify the waveform. The subtraction of least-squares-fit line from the velocity to remove the drift of the baseline. A second approach is to use the second approach is ineffective because the offset is too small compared to the velocity. Therefore, the low signal-to-noise ratio will reduce the accuracy of the initial velocity estimation. The corrected displacement based on the estimation of the second approach is shown in Figure 5g. The baseline error still persists. Both the first and third approaches give reliable estimations on the initial velocity. The corrected displacement waveforms based on the first and third approaches are shown in Figures 5h and 5i. No visible baseline errors were found in these displacement seismograms.

Discussion

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reduce the effect of the baseline drift in acceleration. In the first approach, the mean acceleration of the whole record was subtracted from the original record. Instead of using the whole record, one can use the pre-event recording to obtain the mean. The integrated displacements based on these two methods are shown in Figures 6a and 6b, respectively. Both show a large final offset. The displacement corresponding to the least-squares fitting is given in Figure 6c. All three of these displacement waveforms still exist in long-period baseline errors. After filtering, the major error becomes a linear trend which come from the initial velocity. Different final offsets as shown in Figures 6d through 6f indicate that different manipulations may give various initial velocities. Although the small difference is still present among the displacements of the filtered accelerations, the final displacements in Figures 6g through 6i are almost identical after the correction of step 3. It indicates that these three methods can be used to remove the offset in the first step.

When filtering data, one must choose causal or zero phase. Since the filtering is the only step in this algorithm that modifies the waveform, the selection of the filter and the determination of a long-period limit are important. Brady
Figure 6. Numerical tests for three types of correction for the baseline drift. The first one can be done by subtracting the mean value of acceleration from the whole record. The second approach uses the first 9 sec of the pre-event recording to obtain the mean. The integrated displacements based on these two methods are shown in (a) and (b). The displacement corresponding to the least-squares fit is given in (c). The displacements of the filtered accelerations corresponding to (a) through (c) are shown in (d), (e), and (f), and the final corrected displacements are given in (g), (h), and (i).

(1988) suggested several criteria for selecting a long-period limit. Various criteria may apply to different cases. In this study, I chose the zero-phase Gaussian filter and determined the long-period corner by examining the spectral plot of earthquake and background noise. If pre-events are not available, a trial-and-error approach to select a proper frequency band becomes practical.

Since the initial velocity does not contribute to the acceleration, the modification in velocity in the third step does not change the acceleration. If the least-squares approach is chosen to remove the linear trend in displacement, the estimated initial velocity should be substituted back to the velocity.

No standard data are available for checking the stability of the proposed algorithm. However, the following several independent validations are given to show that the three-step algorithm is stable.

A digital accelerogram was processed using both the three-step algorithm and the Volume II routine. Three pairs of seismograms shown in Figure 7 are the processed accelo-
erations, velocities, and displacements. The top plot in each pair is the result of the three-step algorithm, while the bottom one is obtained from the Volume II routine. For this particular case, the results of the Volume II routine are poor. The distortions at both ends are due to the filtering applied to the velocity that are not small at the tail. On the other hand, the three-step algorithm only applies filtering once in acceleration. The corresponding displacement seems to be reasonable.

The second comparison between the three-step algorithm and the Volume II routine is shown in Figure 8. An SMA-1 analog accelerogram was digitized using a scanner digitization system (Hsu et al., 1991). The processed accelerations, velocities, and displacements based on the Volume II routine and three-step algorithms are shown in Figures 8a to 8f. The same high-pass filter was applied in both routines, and its cutoff and roll-off frequency are 0.12 and 0.1 Hz, respectively. Both the acceleration and velocity waveforms are almost the same. The displacement waveforms are almost the same before 6 sec but are slightly different after 6 sec. The three-step algorithm seems to give more reasonable results because the displacement waveforms keep oscillation about the zero baseline. If we change the filter to be cut off at 0.08 Hz and to roll off at 0.06 Hz, the difference between them becomes larger. The corresponding displacement waveforms are shown in Figures 8g and 8h. The three-step algorithms still keep the same waveform in the first 6 sec, but the waveforms corresponding to the Volume II algorithm are carried by a low-frequency noise and deviate from the baseline. Both the second parts of waveforms were carried by about a 10-sec low-frequency wave, and this low-frequency wave is weaker in Figure 8h. These results implied that the three-step algorithm can also apply to analog data and works as well as the Volume II routine. It was expected.

Figure 7. A digital accelerogram was processed using the three-step algorithm and the Volume II routine. Three pairs of seismograms shown in this figure are the processed accelerations, velocities, and displacements. The top plot in each pair is the result of the three-step algorithm, while the bottom one is obtained from the Volume II routine.
Figure 8. The accelerations, velocities, and displacements of an SMA-1 data processed by the Volume II routine [(a), (c), and (e)] and the three-step algorithm [(b), (d), and (f)]. The cutoff and roll-off of high-pass filters in (a) through (f) are 0.10 and 0.12 Hz, and in (g) and (f) are 0.08 and 0.06 Hz.

that the difference of these two algorithms will be in the low-frequency range. The three-step algorithm reduced many manipulations so as to introduce fewer side effects. Results in Figures 8g and 8h also show that the three-step algorithm seems to be more stable than the Volume II algorithm.

The three-step algorithm can be applied to the truncated accelerograms without any modification. To demonstrate the performance of this algorithm to an incomplete accelerogram, a truncated accelerogram is simulated from a normal recording (Fig. 9a). The truncated record (Fig. 9b) is made by cutting off the tail of the seismogram in Figure 9a at 44 sec. The velocity and displacement waveforms corresponding to Figure 9a are shown in Figures 9c and 9e, while truncated waveforms are given in Figures 9d and 9f. The truncated velocity and displacement waveforms remain unchanged except at its tail (about 1 sec long). The modified tail is due to the effects of the filtering on the large value around the truncated point. In general, excepting the very short tail, the truncated waveforms do not affect the baseline correction of this method. If the ground motions are not small around the truncated point, adding a taper at the end of the truncated record can reduce this effect.

Since the long-period displacement waveforms are less affected by the local site effects, two close stations are expected to have similar waveform. The separation of two SMART-2 stations S42 and S43 is about 230 m. The acceleration and displacement waveforms at these two stations
are shown in Figure 10. The almost identical displacement waveforms imply that the processed displacements are stable.

The long-period surface waves, as shown in Figure 11, provide another good data set for checking the stability of baseline correction. The epicenter of the 15 December 1993 event and stations S07 and S13 lie on a straight line. The epicentral distances are 45 and 27 km, respectively. The accelerogram at S07 was truncated during recording because the acceleration dropped below the threshold. Although the surface waves had been truncated, the similar waveform of surface waves again show that the data processing is stable.

The proposed algorithm cannot directly recover the permanent displacement (Iwan et al., 1985) because of the high-pass filtering in step 2. Approach 3 in step 3 is not proper in this case either because the final displacement is not zero. However, by skipping step 2 and selecting the first approach in step 3, a permanent displacement, which is relatively larger than the background noise, is possible to be recovered. To recover a small permanent displacement, a quiet site and a high-resolution recorder (24 bit or higher) are necessary.

This algorithm has been tested mainly for the SMART-2 data obtained from the SSR-1/FBA-23 recording unit. Nonetheless, it can be applied to any type of digital data. About 100 other types of data both 12 bit (SSA-1 of Kinematics Inc. and A800 of the Teledyne Geotech) and 16 bit (A900 of Teledyne Geotech and IDS of Terra Technology Corp.) have been successfully tested. All of these data show that this algorithm is stable. In addition, about 20 digitized analog data had been tested. Results of these integrated displacement waveforms are also satisfactory.

Conclusion

We have identified the major baseline errors of digital data and developed a stable algorithm to process digital data. The baseline error of digital strong-motion data has been analyzed, and a three-step algorithm is proposed for the baseline correction of the digital data. The proposed algorithm has minimized the steps that are necessary for correcting the baseline errors of the digital strong-motion data. This algorithm has been successfully tested for several types of data that include analog, 12-bit, and 16-bit accelerograms.
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Figure 10. The acceleration and displacement waveforms recorded at two close SMART-2 stations in the 1 September 1992 event. Station $S42$ is 230 m away from station $S43$.

Figure 11. The acceleration waveforms was recorded in the 15 December 1993 event at stations $S07$ and $S13$. The epicenter of this earthquake and these two stations lie on a straight line, and the epicentral distances of S07 and S13 are about 45 and 28 km, respectively. The surface wave at S07 was truncated because the acceleration dropped below the threshold. The reference waveform at S13 was shifted 15.84 sec for easy comparison.

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