A Quantitative Approach for Estimating Coseismic Displacements in the Near Field from Strong-Motion Accelerographs

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Abstract The translational accelerations recorded by strong-motion seismometers are often contaminated by baseline offsets that prevent recovering the ground displacements by double integration. Detailed analysis of the K-NET95 strong-motion seismometer, and the improvement of the visual display of the recorded accelerations’ Fourier transform by addition of long zero pads to the acceleration records, made it possible to distinguish the origins of the long-period noise that contaminate the translational accelerations recorded in the near field of two studied earthquakes, the 2004 Niigata-ken Chuetsu earthquake and the 2007 Niigata-ken Chuetsu-Oki earthquake, Japan. They are the residual rotation of the instrument (residual tilt) or the $1/f$ digital semiconductor noise. The quantification of these two terms allows us to discuss the low-frequency content of the records and to describe when it is possible to obtain realistic displacement time histories. It happens when the residual tilt is removed in the time-domain or when the $1/f$ semiconductor noise overshadows the translational acceleration records up to sufficiently small frequencies. As a check of the method, displacement time histories obtained from acceleration records are compared with nearby 1-Hz GPS data. Good similitudes are obtained in the near field for collocated instruments.

Online Material: Figures showing acceleration, velocity, and displacement time series, and acceleration spectra for 18 records.

Introduction

The determination of coseismic displacements from strong-motion accelerographs is needed for a number of important purposes including tsunami prediction, estimation of ground strain, design of lifelines, and design of structures and deep foundations, especially where structures are located close to capable faults (e.g., Park et al., 2004) and the design ground motions must consider both permanent and oscillatory displacements.

Recovering displacement from acceleration records is interesting because of the large number of accelerometers deployed. This is, however, a challenging task: displacement time histories can theoretically be obtained by double integration of accelerograms recorded by strong-motion seismometers, but they usually show drift larger than expected for true ground displacement (Fig. 1).

The origin of the drift had been investigated, and detailed studies of the specific components of the strong-motion seismometers had been performed. The baseline offsets have been attributed to mechanical or electrical hysteresis in the sensor (Iwan, 1985; Shakal et al., 2001), cross-axis effects due to misalignment of nominally orthogonal sensors (Trifunac et al., 1973; Todorovska, 1998), analog-to-digital converter error (Boore, 2003), electronic $1/f$ noise (Kinoshita et al., 1997; Kinoshita, 1998; Javelaud et al., 2005), or ground tilt and rotation (Graizer, 1991; Trifunac and Todorovska, 2001; Boore, 2001; Javelaud et al., 2005, 2010; Kalkan and Graizer, 2007).

Rather, coseismic oscillatory and residual displacements are needed. Various processing methods have been developed to remove the baseline offsets: making baseline adjustments such as simple step function, pulse followed by a step function (Iwan, 1985; Boore, 2001; Boore et al., 2002; Wang et al., 2003; Paolucci et al., 2008); parabola or other functions removed from accelerograms; filtering (Trifunac, 1971; Trifunac et al., 1973; Graizer, 1979; Graizer et al., 2002; Boore et al., 2002; Boore, 2003; Boore and Bommer, 2005); or a combination of both (Trifunac, 1971; Boore et al., 2002; Boore and Bommer, 2005).

In this paper we focused our study on one single strong-motion seismometer, K-NET95. We investigated the performance of this instrument (theoretically and experimentally) and analyzed the contents of the acceleration time series that

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it delivers. Our main object was to answer the following questions: first, can we obtain reliable displacement time histories from acceleration records? If yes, on which circumstances? Second, can we obtain information about the rotation of the seismometer (tilt) during the earthquake, and especially the remaining rotation of the instrument (residual tilt), from acceleration records?

The choice of the K-NET95 had been motivated by the large number of instruments deployed, over 1600 uniformly covering all Japan, and by the release of its characteristics (full details in Kinoshita et al., 1997; summary in Kinoshita, 1998) that enable a detailed study of the instrument. K-NET95 is used in both K-NET and KiK-net seismic networks (Fujimura et al., 2004). K-NET (Kyoshin Network) consists of 1000+ strong-motion sensors settled on the ground surface and KiK-net (Kiban-Kyoshin Network) of 675 sets of boreholes and surface strong-motion seismometers. K-NET and KiK-net seismometers are basically the same. The main difference is that the data released by the KiK-net network have a sampling frequency of 200 Hz, while the K-NET records have a sampling frequency of 100 Hz (Fujimura et al., 2004). The data used in this study were recorded during the 2004 Niigata-ken Chuetsu earthquake, Japan \((M_w, 6.6, 23\text{ October 2004, epicenter at } 37.29^\circ\text{N, } 138.87^\circ\text{E})\) and the 2007 Niigata-ken Chuetsu-Oki earthquake, Japan \((M_w, 6.8, 16\text{ July 2007, epicenter at } 37.56^\circ\text{N, } 136.61^\circ\text{E})\), which produced large sets of strong-motion records, including near-field ground motions. Both were shallow crustal earthquakes with reverse faulting. The two Japanese nationwide networks K-NET and KiK-net released, for each mainshock, nearly 900 digital, three components, strong-motion records. General information about these two earthquakes, which generated crustal movements in the land area around the source region, can be found in Asano and Iwata (2009), Tabuchi et al. (2008), and Miyake et al. (2010). Unless specified otherwise, the strong-motion data come from these two networks K-NET and KiK-net. A few records from the Japanese Meteorological Agency have also been used.

In outline, this paper begins with a practical study of the shape and geographical distribution of the baseline offsets that contaminate the acceleration records. The example of the 2004 Niigata-ken Chuetsu earthquake, Japan, is detailed, and the shape of the baseline offsets estimated from the velocity trends derived from acceleration records. The second part discusses the response of the accelerometer from theoretical and experimental studies and the origin of the observed baseline offsets. The nature of the different sources of noise, which collectively contribute to the noise in the final digital data, are estimated and modeled. Residual rotation of the instrument (residual tilt) and 1/f digital semiconductor noise are the two main sources of long-period noise that contaminate the acceleration records delivered by the instrument and distributed on the K-NET and KiK-net network web pages. The third part of the paper describes a proposed processing scheme, based on the preceding observations and analysis. A tool to retrieve the residual tilt and remove it from the acceleration records, and a method to estimate the importance of the 1/f semiconductor noise on the records are proposed. Both are based on the use of classical signal processing tools, applied consecutively to the improvement of the Fourier spectra’s visual display by addition of long zero pads. The last section compares the displacement time histories obtained using strong-motion records of the 2007 Niigata-ken Chuetsu-Oki earthquake with those of 1 Hz-GPS, as a check of the proposed method.

Shape and Spatial Distribution of Baseline Offsets Evaluated from Acceleration Records of the 2004 Niigata-ken Chuetsu Earthquake, Japan

The shapes of baseline offsets that contaminate the acceleration records are investigated from the trends of the velocity time histories, obtained by simple integration of the acceleration recorded by strong-motion seismometers, after removing the pre-event mean.

Figures 2 and 3 show the spatial distribution of velocity time histories, in the near field of the 2004 Niigata-ken Chuetsu earthquake. They reveal three main features. First, the velocity shows linear trend but not everywhere. Second, the steeper slopes are observed near the epicenter: the variation of the scale used to plot the velocity can be used as a good
first indicator. Also, the slope $A$ of the linear trends, determined by using the processing scheme detailed later in this paper, is given for each record in Figures 2 and 3. It can be observed that slope $A$ tends to decrease when the epicentral distance increases (Figs. 2 and 3), which is summarized in Figure 4. Third, far from the epicenter there is no more linear trend but shapeless trends. Such shapes can also sometimes be observed near the epicenter of the earthquake and for the vertical components of the acceleration records.

These observations show that there are at least two different sources of baseline offsets. In the next section, the performance of the K-NET95 strong-motion seismometer’s response is investigated, with an aim at finding the origin of the observed baseline offsets.

Performance of the K-NET95

Description of K-NET95 and Noise Model

The K-NET95 strong-motion seismometer consists of five building blocks as follows (Kinoshita et al., 1997; Kinoshita, 1998): a seismometer, an amplifier included in the sensor, an analog antialias filter for the analog-to-digital converter, an analog-to-digital converter, and a digital anti-alias and decimation filter. Brief descriptions of the characteristics of each follow.

Seismometer. The sensor (Kinoshita et al., 1997), type V403BT, is a triaxial force-balance accelerometer with a natural frequency of 450 Hz and a damping factor of 0.707 (standard values). Its resolution is better than 0.1 mGal ($10^{-3}$ cm/s$^2$). The seismometer’s sensitivity is $3.0014$ V/g.

A force-balance accelerometer is basically an inertial seismometer that compensates the unknown inertial force acting on its suspended mass with a known force (Aki and Richards, 2002; Wielandt, 2002).

The response of the seismometer, in the frequency range of interest, is flat to acceleration. Strictly speaking, the response of the accelerometer is frequency dependent (Animi and Trifunac, 1983, 1995; Aki and Richards, 2002). However, when using a damping ratio $\zeta = 0.707(1/\sqrt{2})$, the amplitude response of V403BT (Fig. 5) is nearly constant up to 150–200 Hz. K-NET and KiK-net instruments release data sampled at 100 and 200 Hz, respectively. It is thus possible to retrieve information from their records up to 50 and 100 Hz (Nyquist frequency) in the frequency domain. From zero to those frequencies, the amplitude response varies from 1 to 0.9999 and
0.9988, respectively, and can be assumed to be constant and equal to 1. The phase varies from 0 to $-0.00009\cdot 0^\circ$ and $-0.000018\cdot 3^\circ$, respectively, from 0 to 50 and 100 Hz. We do not correct for the response of the sensor because the amplitude response is flat to acceleration, and we neglect the phase shift.

The equation of motion (NIED, 2000; Trifunac and Todorovska, 2001; Graizer, 2005; Graizer, 2006a, 2006b) of a horizontal strong-motion transducer can be written as follows. The right side of the equation is derived from the equation of a pendulum-like transducer.

EW: $y_1'' + 2\omega_o\zeta y_1' + \omega_o^2 y_1 = -x_1'' + g \sin \psi_2 - \psi_3' r_1 + x_2'\theta_1$,  

(1)

NS: $y_2'' + 2\omega_o\zeta y_2' + \omega_o^2 y_2 = -x_2'' + g \sin \psi_1 - \psi_1' r_2 + x_1'\theta_2$.  

(2)

For a vertical seismometer

UD: $y_3'' + 2\omega_o\zeta y_3' + \omega_o^2 y_3 = -x_3'' + g(1 - \cos \psi_3) - \psi_3' r_3 + x_2'\theta_3$,  

(3)

where $x_i''$ is ground acceleration in $i$th direction, $y_i$ the recorded response of the seismometer, $\omega_o = 450$ Hz, and $\zeta = 0.707$, the natural frequency and the fraction of critical damping of the transducers.

Figure 3. Spatial distribution of velocity time histories obtained by simple integration of acceleration recorded during the 2004 Niigata-ken Chuetsu earthquake, and estimated slope A of the velocity trend (part 2 over 2: the seismometers are more distant from the epicenter).

Figure 4. Slope of the velocity time histories (A in Gal) versus epicentral distance, 2004 Niigata-ken Chuetsu earthquake.
The expressions $g \sin \psi_i$ and $g(1 - \cos \psi_i)$ are, respectively, the horizontal and vertical contribution to the response from tilt, where $g$ is the gravitational acceleration and $\psi_i$ a rotation of the ground surface about $x_i$ axis. When the ground is tilted by an amount of $\psi_i$, the response of the system is exactly identical with a horizontal acceleration of magnitude $g \sin \psi_i$ or a vertical acceleration of magnitude $g(1 - \cos \psi_i)$. The difference of sensitivity to tilt between the horizontal and vertical seismometers is sometimes used (Kalkan and Graizer, 2007; Graizer and Kalkan, 2008) to identify the corner frequency at which the long-period contamination due to tilt occurs in the horizontal components.

The expression $x_i \theta_i$ is the contribution to the response from cross-axis sensitivity. Cross-axis sensitivity is the sensitivity of a transducer to motion perpendicular to its principal axis. For K-NET95 we are not aware of any measurements of cross-axis sensitivity. However, Kinoshita et al. (1997) measured the overall cross talk of the instrument by using a shaking table. These measured values of cross talk provide a global quantification (mechanical and electrical) of signal leakage from one channel to another channel. At frequencies ranging from 1 to 10 Hz, the cross talk is less than 1%. It is smaller at lower frequencies. We do not correct for the cross-axis sensitivity, because it is much smaller than the translational acceleration, especially at low frequencies. It may, however, not be neglected for applications requiring detailed information about the very high frequency content of the acceleration records.

**Analog Antialias Filter.** This analog high-cut filter consists (Kinoshita, 1998) of a two-stage resistor-capacity filter with time constants of 1/12 600 s and 1/62 600 s. We simulate the filter’s response. It is flat to 1000 Hz, and the phase shifts are 0 to 100 Hz: from 0 to 50 Hz (K-NET) and 100 Hz (KiK-net), the amplitude response varies from 1 to 0.9997 and 0.9987, respectively, and the phase varies from 0 to $-1.72^\circ$ and $-3.43^\circ$, respectively. Therefore, both the amplitude and phase can be assumed to be constant.

**Analog-to-Digital Converter.** The analog-to-digital converter (ADC) consists (Kinoshita et al., 1997; Kinoshita, 1998) of a 1-bit sigma-delta modulator (Mitra and Kaiser, 1993) and a digital decimation filter. It can be approximated to a 24-bit type converter.

The effect of the ADC noise on the final displacement is estimated. Basically the ADC converts the output of the amplifier (3.0014 V/g) into integers. The maximum measurable acceleration of K-NET95 is 2000 Gal. This means that at each sampling time, for each analog input ranging from $-6$ V to $+6$ V corresponds an integer value among the $2^{24} = 16777216$ possible ones. The smallest input voltage change that causes the output value of the ADC to increase or decrease by one unit, known as the least significant bit value or $Q$, is (Scherbaum, 2001)

$$Q = \frac{\text{Full Scale Voltage}}{2^\pi},$$

for an $n$-bit ADC.

Assuming that the conversion induces a uniformly distributed white noise (Scherbaum, 2001), the standard deviation of the noise is

$$\sigma_n = Q/\sqrt{12}. $$

**Figure 5.** Variation of the amplitude response with damping and frequency. V403BT response is the simulation where $\zeta = 0.707$. 

![Diagram](image.png)
Double integration of this white noise is a random variable with zero mean and nonzero standard deviation. The standard deviation of the final displacement ($\sigma_{\text{final}}$; Boore, 2003) is

$$\sigma_{\text{final}} = \left( \frac{T^2 \Delta t}{3} \right)^{1/2} \sigma_a,$$

where $T$ is the duration of the time series and $\Delta t$ is the sampling interval.

K-NET95 has a $Q$ value of $7.15 \times 10^{-7}$ V/count, which is $2.34 \times 10^{-4}$ Gal/count. With this value, equations (5) and (6) give $\sigma_{\text{final}}$ of 0.020 cm and 0.014 cm for the K-NET and KiK-net instruments, respectively, after integration of 300 s. Thus, this model of the analog-to-digital converter shows that the ADC noise can be neglected.

**Digital Antialias Filter.** The digital high-cut filter is a three-pole Butterworth filter with a corner frequency of 30 Hz. This filter was designed by applying the bilinear transform to an analog Butterworth filter (Kinoshita, 1998). We used the same procedure to simulate the filter’s response, whose amplitude is shown in Figure 6.

The effect of the digital antialias filter on the displacement is investigated. A simple model (Fig. 7) that simulates the amplitude response of a high-cut filter (Fig. 7a) is used. It separates its amplitude response into an all-pass filter (Fig. 7b) and a boxlike function (Fig. 7c). The boxlike function has an amplitude of 0 up to 20 Hz, then it linearly increases up to 80 Hz (KiK-net) where it reaches a value of 1. Above 80 Hz, the amplitude is 1. This function is subtracted from the all-pass filter.

The effect of the boxlike function on the velocity is calculated. Let $B(f)$ be the boxlike function in the frequency domain and $b(t)$ its inverse Fourier transform in the time domain. Thus,

$$B(f) = \int_{-\infty}^{+\infty} b(t) e^{-j2\pi ft} dt,$$

Figure 6. Simulation of the amplitude response of the digital antialias filter.

Figure 7. Simple model used to investigate the influence of the digital antialias filter on displacement.

when $f = 0$, $B(0) = \int_{-\infty}^{+\infty} b(t) dt$, where $\int_{-\infty}^{+\infty} b(t) dt = \int_{0}^{t_{\text{end}}} b(t) dt$ is the residual velocity obtained at the end of the record $t_{\text{end}}$ by single integration of $b(t)$. Moreover, $B(0) = 0$ by definition, as can be seen in Figure 7. Thus, $B(0) = \int_{0}^{t_{\text{end}}} b(t) dt = 0$, and adding or subtracting such a boxlike function has no effect on the residual velocity and then on the residual displacement. This simple model shows that the presence of the digital antialias filter has no effect when double integrating the acceleration to obtain the displacement.

**Other Sources of Noise.** As all seismographs using semiconductor circuits, the K-NET95 output acceleration data are contaminated at low frequencies by $1/f$ noise (Kinoshita et al., 1997; Kinoshita, 1998).

What Are We Really Recording?

According to the previous explanation, the K-NET95 acceleration time series delivered on the network web page contains, for each component, three kinds of information: the translational acceleration itself $x'$, $1/f$ noise at low frequencies, and information about tilt.

In this section, we first investigate the presence of $1/f$ noise in the record and describe how to determine its level for each accelerometer. We then experimentally confirm the tilt effect on the acceleration record and discuss it in terms of transient and residual tilt.

**Characterization of the $1/f$ Noise at Low Frequency.** The presence of $1/f$ semiconductor noise within modern strong-motion seismometers is described by Kinoshita et al. (1997) and Kinoshita (1998). After checking its presence in the Kinematics K2 Altus series, an instrument similar in that respect to the K-NET95 and available for test in the laboratory, we then describe a practical method to determine the $1/f$ noise level of each accelerometer used in the K-NET and KiK-net networks.
The performance of the K2 strong-motion seismometer is evaluated by comparing its theoretical response to the observed one. Kinemetrics Inc. (see Data and Resources) determined an empirical model of its K2 sensor: two pairs of conjugate poles were found to represent well the instrument’s transfer function. The amplitude of the instrument’s overall response is simulated according to the Kinemetrics’ model and shown in Figure 8.

Each accelerograph’s response can be tested by using ambient vibration noise records. Figure 9a shows a 240-s acceleration time history recorded in the laboratory. Figure 9b is its Fourier acceleration spectrum. The comparison of this spectrum with the Fourier amplitude spectrum of the microtremors recorded simultaneously by a sensitive velocimeter shows that the K2 instrument recorded the natural response of the building from 1 to 20 Hz. Above 20 Hz, the noise rapidly decreases in amplitude: the ground acceleration (input of the instrument) is high-cut filtered by the instrument’s response (Fig. 8). At low frequencies, up to 0.5 Hz, 1/f digital semiconductor noise predominates (slope −1 in a log–log plot). The real amplitude response of the accelerometer is therefore the sum of its theoretical response and of 1/f noise at low frequency (Fig. 10).

From our experience, the 1/f noise level varies according to each sensor and with time. It must therefore be determined for each accelerometer’s component before processing the records.

Practical Determination of the 1/f Noise. The response of each accelerometer and the 1/f noise level can be evaluated by using ambient vibration noise records. These records are very similar to the pre-event part of the mainshocks (same amplitude), but of longer duration: we usually use 100 s long records. Such records can be found among the large number of aftershocks recorded by the K-NET and the KiK-net networks. Figure 11 shows the acceleration power spectrum of the ambient vibration noise recorded at the bottom of an observation borehole at the KiK-net NIGH04 station. The spectrum shows the characteristics of electrical instruments
(Smith, 1999). At low frequencies, up to 0.1 Hz, digital 1/f semiconductor (Kinoshita, 1998) noise predominates.

Between 0.1 and 20 Hz, the signal consists of white noise. Above 20 Hz, the noise rapidly decreases in amplitude (digital antialias filter). At very high frequencies, the analog/digital converter noise predominates. It is therefore possible to precisely estimate the 1/f noise level.

Effect of Tilting on the Seismometer’s Output. The response of the seismometer to tilt is first experimentally confirmed. Then the effect of tilt (transient and residual) on the displacement time histories derived from acceleration is evaluated.

Experimental Effect of Tilting on the Seismometer Output. Theoretically, when the ground is tilted by an amount of $\psi$, the system’s response is exactly identical with a horizontal acceleration of magnitude $g\sin\psi$ or a vertical acceleration of magnitude $g(1 - \cos\psi)$.

We experimentally rotated the Altus K2 strong-motion seismometer around its $X$ axis. The angle of rotation was $1.10^\circ$. Figure 12 shows the acceleration recorded before and after the tilting of the instrument, the latter lasting from the sixteenth to the twenty-second second of the record. According to equation (2), the acceleration offset caused by the rotation and recorded by the $Y$ axis should be $980\sin(1.10^\circ) = +18.81$ Gal, which is identical, at the experimental rotation error, to what can be observed in Figure 12, Y component. Inversely, an angular rotation of $-1.10^\circ$ would give an output of $-18.81$ Gal.

Therefore, any rotation of the strong-motion instrument is recorded simultaneously to the translational ground acceleration. The acceleration time series delivered by the instrument includes the record of the instrument’s rotation during the transient part of the shaking (transient tilt), but it also includes any residual rotation (residual tilt) that will be recorded as a constant value lasting until the end of the record.

Effect of Transient Tilting on the Acceleration Record. Published comparisons of oscillatory displacements from 1-Hz GPS instruments with those derived from nearby K-NET and KiK-net accelerograms, after accounting for a baseline offset using the pre-event signal, show very good similitudes (figure 2 in Miyazaki et al., 2004; chapter 4 in Clinton, 2004). The results shown later in this paper (especially at the Ojiya stations where the instruments are only 600 m apart) confirm the observations. We therefore assume that the effect of the transient ground tilt on the displacement can be neglected.

Effect of Residual Tilting on the Acceleration Record. Any residual tilt is recorded by strong-motion seismometers as a constant value lasting until the end of the record. To get insights on the effect of this addition of low amplitude but long duration information, it is convenient to model the residual tilt. The simplest method to simulate the residual tilt is to consider a step function of amplitude $A$ and duration $T$, ending at the end of the record. When processing the data, finite length records are used. The step function becomes a boxlike function lasting until the end of the record. The Fourier transform of that boxlike function has an amplitude of

![Figure 10. The observed response of the accelerometer is the sum of its theoretical response and of 1/f low-frequency semiconductor noise.](image)

![Figure 11. Power spectrum calculated from a noise record at Sekikawa NIGH04 station, underground seismometer, recorded soon after the 2004 Niigata-ken Chuetsu earthquake, Japan. The power spectrum representation allows comparison with Kinoshita’s original papers.](image)
\[ F(f) = AT \sin(\pi f T) \] It shows three main features. First, when the frequency \( f \) is equal to or is a multiple of \( \frac{1}{T} \), \( F(f) = 0 \). Then, \( F(f) \to AT \) as \( f \to 0 \). Furthermore, the envelope of the signal has a slope of \( 1/f \).

Summary. The analysis of the K-NET95 performance shows that its output contains four different elements of information. They are the translational acceleration and the tilt of the ground, both of them being modified during the recording process by the response of the seismometer (theoretical response, and the addition of electronic \( 1/f \) noise at low frequencies). Therefore, the content of the acceleration time series must be discussed in terms of the four different elements’ relative importance.

The low-frequency content of the acceleration record is always dominated by either \( 1/f \) semiconductor noise or by residual tilt. Two main cases can be distinguished according to the relative position, in the frequency domain, of the translational acceleration, \( 1/f \) semiconductor noise and residual tilt.

The first case happens when \( 1/f \) semiconductor noise dominates the low-frequency content of the record, overshadowing both the translational acceleration and any residual tilt. An example of this situation is shown in Figure 13. In this case, it is usually not possible to recover the displacement time histories, unless the frequency at which the \( 1/f \) noise stops to dominate the record is so small that the \( 1/f \) noise would not affect the displacement time histories for durations of interest.

The second situation happens when the residual tilt dominates the low-frequency content of the record, overshadowing both the translational acceleration and the \( 1/f \) semiconductor noise.

Based on this analysis of the K-NET95’s performance, the next section proposes a processing scheme for both situations. It first starts with the selection of the most suitable signal processing tools to carry out the Fourier transform of the record and to improve the visual display of the Fourier spectra at low frequencies.

**Processing Scheme**

**Zero Order Correction**

We apply the usual condition that the acceleration is zero before the earthquake shaking starts: the pre-event mean of the acceleration record is subtracted from the whole record.

**Fourier Transform and Zero Padding**

The long-period (low frequency) information contained in the acceleration records is investigated. So far, we studied

![Figure 12](image_url) **Experimental rotation** of a K2 Altus strong-motion seismometer around its X axis, and effect on the seismometer output.

![Figure 13](image_url) **Power spectrum calculated from a record at Sekikawa NIGH04 site, underground seismometer, during the 2004 Niigata-ken Chuetsu earthquake. The power spectrum representation allows comparison with Kinoshita’s original papers.**
the response of the instrument. We now consider the modifications that the change from continuous-time signal (input of the instrument) to discrete-time signal (output of the instrument) is implying on the Fourier transform and discuss how to best apply the Fourier transform on the records.

During the recording process, the infinite continuous-time signal, input of the instrument, is transformed to a discrete-time signal. Finite length records of seismic events are stored. In terms of the Fourier spectra, this corresponds to a transformation from a continuous-time Fourier transform to a discrete-time Fourier transform (DTFT). The best Fourier transform that one can expect to obtain from the data released is the DTFT.

However, computers perform the discrete Fourier transform (DFT) of finite length records, such as the acceleration records distributed by the networks. The DFT computes the Fourier amplitudes only at a finite number of frequencies, $f_k$ (Oppenheim and Schafer, 2010). It implies a loss of information. Indeed, if the sampling spacing between the frequencies $f_k$ is not small enough, important information of the DTFT spectrum located between the frequencies $f_k$ does not appear in the computed Fourier spectrum. It is therefore necessary to reduce the interval between the frequencies $f_k$ as much as possible, when performing the DFT, to calculate the Fourier amplitudes of the DTFT at frequencies sufficiently dense so the computed Fourier spectra is indistinguishable from the DTFT itself.

In signal processing, the frequency spacing of the discrete Fourier transform is $\Delta f = \frac{1}{NT}$, where $\Delta f$ is the sampling interval and $N$ is the number of data. When $N$ increases, $\Delta f$ decreases; it is therefore possible to compute the record’s Fourier amplitudes at closer frequencies by addition of zero pads before taking the DFT (Oppenheim and Schafer, 2010). The addition of a high degree of time-domain zero is a usual step in classical signal processing. It does not add information nor improve the ability to resolve close frequencies (which depends, for example, on the sampling frequency). Adding zeroes before and after the acceleration time series results in a smaller frequency spacing of the computed Fourier transform, allows the user to recover the record’s DTFT, and simply allows him to make the most use of the available data.

Acceleration time histories are first padded with zeroes. Figure 14 shows the Fourier transform of the acceleration recorded at station NIG019 (east–west component, 2007 Niigata-ken Chuetsu-Oki earthquake) after adding a variable number of zeroes. It can be seen there that the Fourier amplitude spectrum without zero pads is very jagged at low frequencies due to the small number of sampling defining the curve there. This situation is improved by increasing the number of zero pads in the acceleration record before taking the discrete Fourier transform. Adding zeroes to make the record $2^{23}$ samples long results in a smaller frequency spacing of the Fourier transform. It provides more details at low frequency for the purpose of this method, without taking much computing time (from 1 s to 2 s with current computers). This tool reveals the characteristics of the long-period information contained in acceleration record.

Case 1: At Low Frequencies, the $1/f$ Semiconductor Noise Overshadows the Translational Acceleration and the Residual Tilt

During the 2004 Niigata-ken Chuetsu earthquake, NIGH04 station was 111 km from the epicenter of the mainshock. The acceleration power spectrum of the mainshock recorded at station NIGH04 is shown in Figure 13, as well as the $1/f$ noise model determined from the noise record (Fig. 11).

At low frequencies, the $1/f$ digital noise predominates. Let $A_{\text{sec}}(f)$ and $A_{\text{noise}}(f)$ be the sum in the frequency domain of $A_g(f)$ and $A_{\text{noise}}(f)$, where $A_g(f)$ is the true ground translational acceleration and $A_{\text{noise}}(f)$ is the sum of the digital $1/f$ and white noises. The same relation holds for the velocity $V(f)$. The velocity $V(f) = V_g(f) + V_{\text{noise}}(f)$, where $V_g(f)$ is the true ground velocity and $V_{\text{noise}}(f)$ is the sum of a digital $1/f^2$ and $1/f$ noise. By definition of the Fourier transform, for a 300 s record,

$$v(t) \leftrightarrow V(f) = \int_{-\infty}^{+\infty} v(t)e^{-j2\pi ft}dt = \int_{0}^{T=300\text{ sec}} v(t)e^{-j2\pi ft}dt, \quad (8)$$

when $f = 0$,

$$V(0) = \int_{0}^{T=300\text{ s}} v(t)e^{-j2\pi 0t}dt = \int_{0}^{T=300\text{ s}} x(t)dt = [x(t)]_{T=300\text{ s}} = \text{displacement}(t=300\text{ s}). \quad (9)$$

Thus, the residual displacement is equal to the Fourier amplitude of the velocity at zero frequency. Because $V(0) = V_g(0) + V_{\text{noise}}(0)$, where $V_g(f) \ll V_{\text{noise}}(f)$, instrumental noise completely overshadows the Fourier amplitude of the ground acceleration at low frequencies. It is therefore not possible to recover the exact residual ground displacement in such cases.

However, if the frequency at which the $1/f$ noise stops to dominate the record is small (i.e., $V_g(f) \ll V_{\text{noise}}(f)$ is true only at very low frequencies), it is possible to obtain stable displacement time histories over the duration of engineering interest. As an example shown in Figure 15, the double integration of the acceleration recorded by the underground KiK-net NIGH12 station during the 2004 Niigata-ken Chuetsu earthquake leads to a stable residual displacement of 14 cm. The frequency at which the $1/f$ noise stops to dominate the record (0.004 Hz determined from the Fourier acceleration spectra) is so small that the $1/f$ noise does not affect much the displacement time histories.
Case 2: At Low Frequencies, the Residual Tilt Overshadows the Translational Acceleration and the $1/f$ Semiconductor Noise: Example of the NIG019 Station, East–West Component

After adding zero pads, we find that in this case the low-frequency content of the acceleration time history (Figs. 14, 16) is similar to the Fourier spectra of a step function (Fig. 16a,b).

The amplitude $A$ and duration $T$ used to define a step function in the time domain (Fig. 16a) can be extracted in the frequency domain from the Fourier transform of the step function (Fig. 16b): by definition, the Fourier amplitude at zero frequency is $A\cdot T$, and the frequency when the Fourier amplitude is zero for the first time is $1/T$. Therefore, $A$ and $T$ of a step function can be uniquely derived from its Fourier transform. It is important to note that $A$ and $T$ are not handpicked at random, but really extracted from the Fourier transform.

In Figure 16, we compare the acceleration record and its Fourier transform (Fig. 16c,d), with a simple step function and its Fourier transform (Fig. 16a,b). It can be seen that in the frequency domain, the low-frequency part of the record (Fig. 16d, in the box) is identical to a step function (Fig. 16b). We therefore observe that the acceleration record (Fig. 16c) is contaminated by a step function, whose amplitude and starting time can be determined uniquely from the Fourier spectra of the acceleration record. In this example, we obtain the following values from the Fourier transform of the acceleration record (Fig. 16d): $A\cdot T = 11.7177 \text{ Gal s}$ (Fourier amplitude at zero frequency) and $1/T = 0.0036467 \text{ 1/s}$ (frequency when the Fourier amplitude is zero for the first time). Thus, $T = 1/(1/T) = 274.2186 \text{ s}$, $A = A\cdot T/T = 0.042731 \text{ Gal}$ and the starting time of the step function ($t_s$) = duration of the record $- T = 300 \text{ s} - T = 25.7814 \text{ s}$. In Figure 17, the superposition in the frequency domain of the acceleration record and the step function of characteristics $A$ and $t_s$ shows extremely good match at low frequencies.

Subsequent processing is applied in the time domain. A step function of amplitude $A = 0.042731 \text{ Gal}$ and of starting time $t_s = 25.7814 \text{ s}$ is subtracted from the acceleration record (Fig. 17a,b). Note that we corrected the acceleration time series from a step function starting at $t_s$ (until the end of the record). While zero pads are added after the acceleration record, it is strictly speaking a rectangular box of amplitude $A$, starting at $t_s$, until the end of the record (300 s in K-NET case).

Double integration of the corrected acceleration time history shows no more drift: the displacement is perfectly stable after the shaking (Fig. 17c,d). The residual displacement is estimated at $-3.2 \text{ cm}$.

This proposed processing scheme is applied in the next section to acceleration records of the 2007 Niigata-ken Chuetsu-Oki earthquake, Japan.
tories obtained from acceleration records are compared with 1-Hz GPS data, when collocated, as a check of the method.

Example of the 2007 Niigata-ken Chuetsu-Oki Earthquake

The K-NET and KiK-net acceleration time histories recorded in the near field during the 2007 Niigata-ken Chuetsu-Oki earthquake were processed according to the scheme described in the preceding section. The records of two Japanese Meteorological Agency (JMA) instruments are also added by extension of the method.

In the present section, we first detail the processing steps applied to accelerograms recorded near the epicenter of the earthquake (map in Fig. 18), then compare the displacement time histories obtained from acceleration records with 1-Hz GPS data, when collocated. Finally, we draw a map of the residual displacements obtained by the two methods.

Figure 15. Acceleration, Fourier amplitude of the acceleration, acceleration derived velocity and displacement time histories of the 2004 Niigata-ken Chuetsu earthquake, NIGH12 downhole accelerometer, north–south component.

Figure 16. Comparison of (a), (b) step function and (c), (d) acceleration record in both time and Fourier domains. Example from the NIG019 station, east–west component.
Summary of Processing Steps Applied

The accelerograms recorded at the stations shown in Figure 18 have been processed. Each accelerogram, its Fourier transform, velocity, and displacement time histories as well as the processing steps applied are given in Figures S1–S18 in the electronic supplement to this paper. The processing details of the acceleration times series are summarized in Tables 1 and 2.

In Tables 1 and 2, “no correction applied” does not mean that the residual tilt is equal to zero, but that it is so small that other sources of noise, especially the 1/f semiconductor noise, predominates at low frequencies.

Stable displacement time histories are obtained in processing case 1 (4 records) and case 2 (8 records). However, for intermediate situations (5 records), stable residual displacements are usually not obtained, and so an estimation of the displacement is given.

Note that at two stations, the processing scheme could not be applied. A retaining wall collapse had been reported at station NIG018 by NIED (2007), altering the acceleration record. Also, one record, JMA Kashiwasaki, north–south component, shows more than one slope in the velocity time history. An additional pulse can be observed in the acceleration time series at about 40 s.

Comparison of Displacements Obtained from Acceleration Records with 1-Hz GPS Data

The processing scheme’s efficiency is tested: the displacement time series obtained by processing strong-motion records are compared with nearby 1-Hz GPS data as a check of the method.

During the earthquake, the K-NET NIG019 OJIYA station and the 1-Hz GPS OJIYA station recorded the event. Both stations are 600 m distance apart. Displacement time histories calculated from processed acceleration records were compared with the 1-Hz GPS data (Fig. 19). For the east–west and the north–south components, the seismic displacement and the 1-Hz GPS displacement time histories show extremely good similitude for both the residual and the oscillatory parts of the displacements.

In Kashiwasaki, two strong-motion accelerograms, NIG018 and JMA Kashiwasaki, as well as two 1-Hz GPS stations, K1 and K2, recorded the event. The area is in the very near field of the earthquake and was subjected to very large displacements. It is known for having experienced soil related problems including liquefaction: at GPS station K2, tilt of the antenna pillar (Tabuchi et al., 2008) had been reported; also, at NIG018 station, collapse of a retaining wall around the station was reported (NIED, 2007). The data of these two instruments were removed from the set of records used. The records remaining at hand, that is, the displacement time histories obtained from the JMA seismometer and the K1 1-Hz GPS station (situated 3.5 km apart), were compared. For the east–west component, we found a good agreement for the residual displacement at about 14 cm. From the JMA seismometer, the amplitude of the oscillatory displacement reached almost 80 cm. There is a good agreement between the acceleration-derived displacement and the 1-Hz GPS displacement. The differences can be due to the quickly varying field of displacement in the area and to

Figure 17. (a) Superposition of the acceleration record and the step function of amplitude A (not on scale) and starting time t[s] used to correct the acceleration record. (b) The superposition in the frequency domain of the acceleration record and a step function of amplitude A and starting time t[s], determined in (a), shows extremely good match at low frequency. (c), (d) Uncorrected and corrected velocity and displacement time histories. The corrected displacement history is obtained by subtracting the step function from the acceleration record, then double integrating the corrected acceleration time history. The displacement is stable after the earthquake.
possible misorientation of the instruments during their installation. Regarding the north–south component of the acceleration record, a pulse at 40 s made the processing scheme impossible to apply.

At Takayanagi, the JMA accelerometer and the 1-Hz GPS station are 1.2 km apart. They show similar residual displacement and good similitude during the oscillatory part of the displacement, considering the distance between the stations.

For the other two stations, the displacements obtained by the two methods show very good similitude considering that the distance between the two sensors is several kilometers.

Comparison of Coseismic Residual Displacement

In the near field of the 2007 Niigata-ken Chuetsu-Oki earthquake, residual displacements calculated as suggested previously were compared with displacements measured at

Table 1

<table>
<thead>
<tr>
<th>Station</th>
<th>East–West Component</th>
<th>Residual Displacement (cm)</th>
<th>Processing Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIG017</td>
<td>0.0048</td>
<td>≈ -2.0</td>
<td>Intermediate</td>
</tr>
<tr>
<td>NIG018</td>
<td>0.04273</td>
<td>-3.2</td>
<td>Case 2</td>
</tr>
<tr>
<td>NIG019</td>
<td>No correction applied</td>
<td>-2</td>
<td>Case 1</td>
</tr>
<tr>
<td>NIG020</td>
<td>No correction applied</td>
<td>-2.3</td>
<td>Case 2</td>
</tr>
<tr>
<td>NIG021</td>
<td>0.00963</td>
<td>-0.2</td>
<td>Case 1</td>
</tr>
<tr>
<td>NIG022</td>
<td>No correction applied</td>
<td>-2.1</td>
<td>Case 1</td>
</tr>
<tr>
<td>NIGH12</td>
<td>0.0048</td>
<td>≈ -1.5</td>
<td>Intermediate</td>
</tr>
<tr>
<td>JMA Takayanagi</td>
<td>0.2366</td>
<td>-1.8</td>
<td>Case 2</td>
</tr>
<tr>
<td>JMA Kashiwasaki</td>
<td>-1.0365</td>
<td>-13.8</td>
<td>Case 2</td>
</tr>
</tbody>
</table>
surrounding GPS stations. When GPS and seismometer stations are collocated (a few hundred meters apart), the residual displacements obtained by the two methods are almost identical. At other locations where accelerometers and GPS stations are a few kilometers distance apart, residual displacements obtained by processing seismometer records are consistent with displacements measured by GPS stations.

**Discussion and Conclusions**

This paper proposes a simple method based on the addition of long zero pads to investigate the low-frequency content of acceleration time histories recorded by the strong-motion seismometer K-NET95 and delivered on the Japanese K-NET and KiK-net networks’ web pages. It points out that the translational acceleration is contaminated at low frequency by $1/f$ electronic noise and by the residual tilt. The shapes of the baselines offsets that contaminate the acceleration records (observed, for example, in the section Shape and Spatial Distribution of Baseline Offsets Evaluated from Acceleration Records of the 2004 Niigata-ken Chuetsu Earthquake, Japan for a typical earthquake) can be related to the predominance of residual tilt (linear trend in the velocity time history) or $1/f$ noise (shapeless trend in the velocity time history) at low frequencies.

We find that in some circumstances, it is possible to obtain reliable estimates of the displacement time histories from acceleration records. This happens when the low-frequency content of the acceleration record is dominated by $1/f$ electronic noise up to very small frequencies (case 1 in

<table>
<thead>
<tr>
<th>Location</th>
<th>A (Gal)</th>
<th>Residual Displacement (cm)</th>
<th>Processing Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIG017</td>
<td>0.0092</td>
<td>2.1</td>
<td>Case 2</td>
</tr>
<tr>
<td>NIG018</td>
<td>–</td>
<td>Problem of wall stability</td>
<td>–</td>
</tr>
<tr>
<td>NIG019</td>
<td>–0.0472</td>
<td>2.3</td>
<td>Case 2</td>
</tr>
<tr>
<td>NIG020</td>
<td>–0.0023</td>
<td>1.8</td>
<td>Case 2</td>
</tr>
<tr>
<td>NIG021</td>
<td>–0.0095</td>
<td>≈3.0</td>
<td>Intermediate</td>
</tr>
<tr>
<td>NIG023</td>
<td>0.00068</td>
<td>0.6</td>
<td>Intermediate</td>
</tr>
<tr>
<td>NIG028</td>
<td>No correction applied</td>
<td>0.8</td>
<td>Intermediate</td>
</tr>
<tr>
<td>NIGH12</td>
<td>No correction applied</td>
<td>1.2</td>
<td>Case 1</td>
</tr>
<tr>
<td>JMA Takayanagi</td>
<td>–0.1449</td>
<td>6.8</td>
<td>Case 2</td>
</tr>
<tr>
<td>JMA Kashiwasaki</td>
<td>2.7449</td>
<td>See text</td>
<td>Double slope</td>
</tr>
</tbody>
</table>

**Figure 19.** Accelerometer displacement time series vs. nearby 1-Hz GPS data recorded during the 2007 Niigata-ken Chuetsu-Oki earthquake, Japan.
the Processing Scheme section) or by constant residual tilt (case 2 in the Processing Scheme section).

Other situations, including large $1/f$ noise contaminating the translation acceleration, make it impossible to retrieve accurately the displacement time histories (processing scheme, intermediate situation in Example of the 2007 Niigata-ken Chuetsu-Oki Earthquake). This study therefore shows the importance of the deployment of instruments with as low as possible $1/f$ electronic noise. The recent replacement of K-NET95 by K-NET02 seismometers, instruments with lower electronic noise, is providing great improvement in the determination of displacement time histories.

Another limitation of the method appears when seismograms contain motions from more than one event or from late pulse such as the JMA Kashiwasaki, north-south component record, as this may create multiple baseline offsets. Also, the method requires a minimum original data’s length. K-NET and KiK-net usually release 300 s long signals recorded at a sampling frequency of 100 Hz or 200 Hz, which give good results when processed according to the proposed method.

Regarding the tilt, we observed that the transient tilt usually has no significant effect on the derivation of the displacement time histories, whereas any residual tilt of low amplitude but long duration seriously alters the velocities and displacements. We propose a systematic method to estimate the residual tilt (case 2 in the Processing Scheme section) from acceleration records.

Data and Resources

Seismograms were provided by the National Research Institute for Earth Science and Disaster Prevention (Tsukuba, Japan) available through the K-NET at www.k-net.bosai.go.jp (last accessed March 2011) and KiK-net at www.kik.bosai.go.jp (last accessed March 2011) networks, and by the Japanese Meteorological Agency, while GPS measurements were provided by the Geographical Survey Institute, Ministry of Land, Infrastructure and Transport, Ibaraki, Japan. The K2 user’s manual (K2 and Makalu User’s Manual, Document 302200) is available from Kinematics Inc. at www.kinematics.com (last accessed May 2010).

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