BILATERAL RECURSIVE RESTITUTION OF TRUE GROUND MOTION FROM NEAR-FIELD AND FAR-FIELD SEISMOGRAMS

V. Vavryčuk, A. Plešinger

Geophysical Institute, Czechosl. Acad.Sci., Prague)*

Summary: *A two-sided recursive inverse filtering procedure, originally proposed by R. Vích, is used to restore the true ground motion from digital records of inertial electromagnetic seismographs. Numerical simulations of far-field and near-field P-wave seismograms are used to test the performance of the procedure and to derive criteria for recognizing successful restorations. The procedure is applied to seismograms of local microearthquakes as well as of teleseismic events, and the restored signals are compared with those obtained by causal (one-sided) inverse filtering. In all cases the two-sided approach proved to have fundamental advantages: a higher accuracy of the approximation of the true ground motion, a faster convergence to the best attainable approximation, a lower sensitivity to incoherent noise, and a more reliable discrimination between veracious and dubious results.*

1. INTRODUCTION

A fundamental problem in studying the details of fault processes occurring in earthquake foci, whether they are based on local or on teleseismic observations of the radiated body waves, is the numerical restoration of the true ground motion from the available digital (or digitized analog) seismograms. Due to the noise components which are not related to the actual ground motion (spurious components caused by truncation of the seismogram, by the offset of its zero-line and by non-linearities of the seismograph system, intrinsic and externally generated instrumental noise, digitation noise caused by the limited dynamic range of the analog-to-digital conversion process) the exact deconvolution of a seismogram portion yields unrealistic, mostly unstable results. For the approximate solution of the problem a variety of different methods was developed, among them various kinds of frequency limited inverse digital filtering combined with pre-correction (removal of systematic noise components) of the seismogram [1—4], optimum inverse shaping filtering [5], re-iterative convolution [6], stabilized two-sided deconvolution [7], regularized inverse frequency filtering [8], and successive integration of the seismogram under regularizing a-priori assumptions [9].

A comparative application of methods [2—7] to hand-digitized analog seismograms of known ground motions, simulated by means of a shake-table, has shown that in cases of relatively long signals Vích's method of two-sided recursive deconvolution has essential advantages in the quality of the result as well as in the calculation speed [7, 10].

In the present paper, this method is applied to theoretical as well as actual digital seismograms of both near-field and far-field ground motions, and the results are compared with those obtained by causal recursive deconvolution.

2. TRANSFER FUNCTION OF THE SEISMOGRAPH SYSTEM

The following considerations concern the wide-spread class of conventional electronic seismograph systems in which an inertial seismometer with an electromagnetic

*) Address: Boční II/1401, 141 31 Praha 4.

(moving-coil) transducer is employed as the seismic sensor. The transfer function of such a system has the general form

$$G(s) = \frac{\mathscr{L}\{\text{system output}\}}{\mathscr{L}\{\text{ground motion}\}} = C \frac{s^3}{(s - s_1)(s - s_1^*)} A(s)\, F(s)\,, \tag{1}$$

where C is a real constant, s_1 and s_1^* are the poles of the transfer function of the seismometer $s_1, s_1^* = -2\pi f_s [\alpha_s \pm \mathrm{j}\sqrt{(1 - \alpha_s^2)}]$, α_s a dimensionless damping constant, f_s the natural frequency) and $A(s)$ is the transfer function of the electronic amplifier which can be of either the low-pass or band-pass type. In analog systems $F(s)$ represents the transfer function of the recording device (heat-pen or chart recorder, galvanometer of the photorecorder, filter and the voltage-to-frequency converter of a FM magnetic tape recorder, etc.), and in digital systems $F(s)$ is the over-all transfer function of the offset-removing high-pass and antialiasing low-pass filters.

For recording both local microearthquakes and distant earthquakes with the largest attainable dynamic range of seismic information, a broad-band flat-velocity response of the seismograph system is known to be the optimum (best pre-whitening) frequency response [11, 12]. In a system designed optimally in this respect, the amplifier has a constant gain in the frequency band $\langle 0, f_U \rangle$, where f_U is the highest seismic frequency to be recorded without attenuation, and either no offset-removing filter is used, or its corner frequency $f_{HP} < f_L$, where f_L is the lowest seismic frequency to be restored. In correctly designed digital systems $f_{LP} > f_U$ and $f_D \sim (4 - 5) f_{LP}$, where f_{LP} is the corner frequency of the anti-aliasing filter and f_D is the sampling frequency.

Further on we deal with the treatment of seismograms obtained from systems fulfilling the mentioned assumptions.

3. CONSTRUCTION OF INVERSE FILTERS

For the purpose of inverse digital filtering we have to construct a stable digital filter whose transfer properties simulate those of the inverse seismograph system. According to the preceding specifications the inverse transfer function to be simulated has the form

$$\tilde{G}^{-1}(s) = (s - s_1)(s - s_1^*)/Ks^3 = \sum_{i=1}^{3} a_i/s^i\,, \tag{2}$$

where K defines the sensitivity of the seismograph system and where $a_1 = K^{-1}$, $a_2 = -(s_1 + s_1^*)\, a_1 = 4\pi\alpha_s f_s a_1$, $a_3 = s_1 s_1^* a_1 = (2\pi f_s)^2\, a_1$.

Provided no offset-removing filter has been used, expression (2) defines the inverse transfer properties in the frequency range $f \in \langle 0, f_U \rangle$. If such a filter has been used, this range is restricted to $\langle f_L, f_U \rangle$. It would, of course, be easy to include also the inverse transfer function of this filter into (2), but this approach is physically ill-founded: to detect and remove a long-term offset in the stage of seismogram processing is more convenient than to suppress it together with useful long-period seismic information directly in the seismograph system and then to try to recover the seismic information.

A favourable method, allowing to construct a digital filter whose impulse response simulates that of the continuous system with high accuracy, is the approximate inverse Laplace transform of the continuous transfer function by means of the Z-transform [13]. This method is based on the evaluation of the Volterra integral equation using the trapezoidal rule for numerical integration. Applying the procedure described in Subsection 4.1.3 of [13] to expression (2), we obtain the discrete transfer function

$$\tilde{G}^{-1}(z) = z\, N(z)/(z-1)^3\,, \tag{3}$$

where

$$\begin{aligned} N(z) &= b_0 z^2 + b_1 z + b_2\,,\\ b_0 &= a_1\,,\\ b_1 &= -2a_1 + a_2 T + a_3 T^2/2\,,\\ b_2 &= a_1 - a_2 T + a_3 T^2/2\,,\\ T &= 1/f_D = \text{sampling interval}\,. \end{aligned}$$

$\tilde{G}^{-1}(z)$ has a triple pole at $z = 1$ which corresponds to the triple pole of $\tilde{G}^{-1}(s)$ at $s = 0$. Expressed in the frequency domain this means that the modulus of the inverse transfer function approaches infinity with the 3rd power of f for $f \to 0$. To regularize the mathematically incorrect inversion problem, we shift the triple pole at $z = 1$ slightly to a real position inside the unit circle $|z| = 1$, i.e. to $z_1 = 1 - \varepsilon$, where ε is "sufficiently small". The resulting inverse transfer function

$$\hat{G}^{-1}(z) = \frac{z\, N(z)}{[z-(1-\varepsilon)]^3} = \frac{b_0 z^3 + b_1 z^2 + b_2 z}{z^3 + c_1 z^2 + c_2 z + c_3}\,, \tag{4}$$

$$c_1 = -3z_1\,, \quad c_2 = 3z_1^2\,, \quad c_3 = -z_1^3\,,$$

represents a stable causal digital IIR (Infinite Impulse Response) filter which simulates the inverse seismograph system down to an arbitrarily low frequency f_ε and has a constant (finite) frequency response for $f \in (0, f_\varepsilon)$. This filter allows fast recursive signal restitution in the time domain, i.e. the causal filtering procedure is applie ddirectly to the digital (or digitized and pre-corrected analog) seismogram (see Section 4).

A disadvantage of the described approach is that the inverse transfer function is stabilized at the price of both amplitude and phase errors at low frequencies. It was also experienced that the causal transient response to the discontinuity at the beginning of the seismogram and the cumulative influence of systematic noise components in the seismogram may considerably deteriorate the quality of the restitution [10].

A method which preserves the advantage of recursive filtering and minimizes the discussed errors of causal deconvolution is the two-sided procedure proposed by

Vích [7]. In this case the discrete inverse transfer function (3) is formally supplemented by a mutually cancelling zero and pole at $z = 1$, and

$$\hat{G}^{-1}(z) = \frac{z-1}{z-1}\frac{z\,N(z)}{(z-1)^3} = \frac{N(z)}{(z-1)^2}\frac{z^2-z}{(z-1)^2}$$

is approximated by shifting the first pole pair sligthly inside and the other sligthly outside the unit circle $|z| = 1$. The resulting transfer function

$$\hat{G}^{-1}(z) = \frac{N(z)}{[z-(1-\varepsilon)]^2}\frac{(z-1)z}{[z-1/(1-\varepsilon)]^2} = \hat{G}_+^{-1}(z)\,\hat{G}_-^{-1}(z) \tag{5}$$

represents a two-sided filter consisting of a causal (memory) part $\hat{G}_+^{-1}(z)$ and a non-causal (anticipation) part $\hat{G}_-^{-1}(z)$,

$$\hat{G}_+^{-1}(z) = \frac{b_0z^2 + b_1z + b_2}{z^2 + d_1z + d_2}\,,\quad \hat{G}_-^{-1}(z) = \frac{e_0z^2 + e_1z}{f_0z^2 + f_1z + 1}\,, \tag{6}$$
$$d_1 = f_1 = -2z_1\,,\quad d_2 = e_0 = f_0 = z_1^2\,,$$
$$e_1 = -z_1^2\,,\quad (z_1 = 1 - \varepsilon)\,.$$

Two-sided processing of a seismogram (for the realization of the process refer to Section 4) completely eliminates the phase error of the restitution, and the additional zero at $z = 1$ efficiently reduces cumulative errors.

4. RECURSIVE INVERSE FILTERING

Let y_i, $i = 1, \dots, N$ be the digital (or equidistantly sampled and pre-corrected analog) seismogram. In the case of causal processing the restored input x_i, i.e. the approximation of the true ground displacement, is given by the recursive formula

$$x_i = b_0y_i + b_1y_{i-1} + b_2y_{i-2} - c_1x_{i-1} - c_2x_{i-2} - c_3x_{i-3}\,, \tag{7}$$
$$i = 1, \dots, N\,,$$

where b_0, b_1, b_2 and c_1, c_2, c_3 are the filter coefficients given, respectively, by (3) and (4).

In the case of two-sided processing, the causal part of the restitution procedure consists in recursive filtering of the sequence y_i from left to right, i.e.

$$\tilde{x}_i = b_0y_i + b_1y_{i-1} + b_2y_{i-2} - d_1\tilde{x}_{i-1} - d_2\tilde{x}_{i-2}\,,\quad i = 1, \dots, N\,, \tag{8}$$

and the non-causal part is performed by filtering of the resulting sequence $\tilde{x}_i$ from right to left using the recursive formula

$$x_j = e_1\tilde{x}_{j+1} + e_0\tilde{x}_{j+2} - f_1x_{j+1} - f_0x_{j+2}\,,\quad j = 1, \dots, N\,. \tag{9}$$

The filter coefficients are given by (3) and (6). The signal $\tilde{x}_i$ is the restored ground velocity, and (9) represents the process of stabilized numerical integration.

5. DECONVOLUTION OF THEORETICAL SEISMOGRAMS

To test the properties of the described restitution techniques, simple theoretical far-field and near-field seismograms were processed bilaterally as well as causally. For the generation of the theoretical signals the source moment function

$$M_0(t) = \begin{cases} t - [\sin(2\pi f t)\cos(2\pi f t)]/2\pi f & \text{for} \quad 0 \leqq t \leqq 1/2f\,, \\ 1/2f & \text{for} \quad t > 1/2f\,, \end{cases} \tag{10}$$

was used. This function corresponds to a smooth shear-dislocation, and its far-field term $\dot{M}_0(t)$ has the form of a single $\sin^2(2\pi f t)$ pulse of duration $\tau = 1/2f$. Using the formula for the displacement field of a double-couple point source in an infinite isotropic homogeneous medium ([14], p. 81), ground displacements at different distances from the source were computed and the resulting signals were passed through a recursive digital filter simulating the seismometer response. A source mechanism of strike 170°, dip 80°, rake −60° was assumed, and the filter was constructed using the

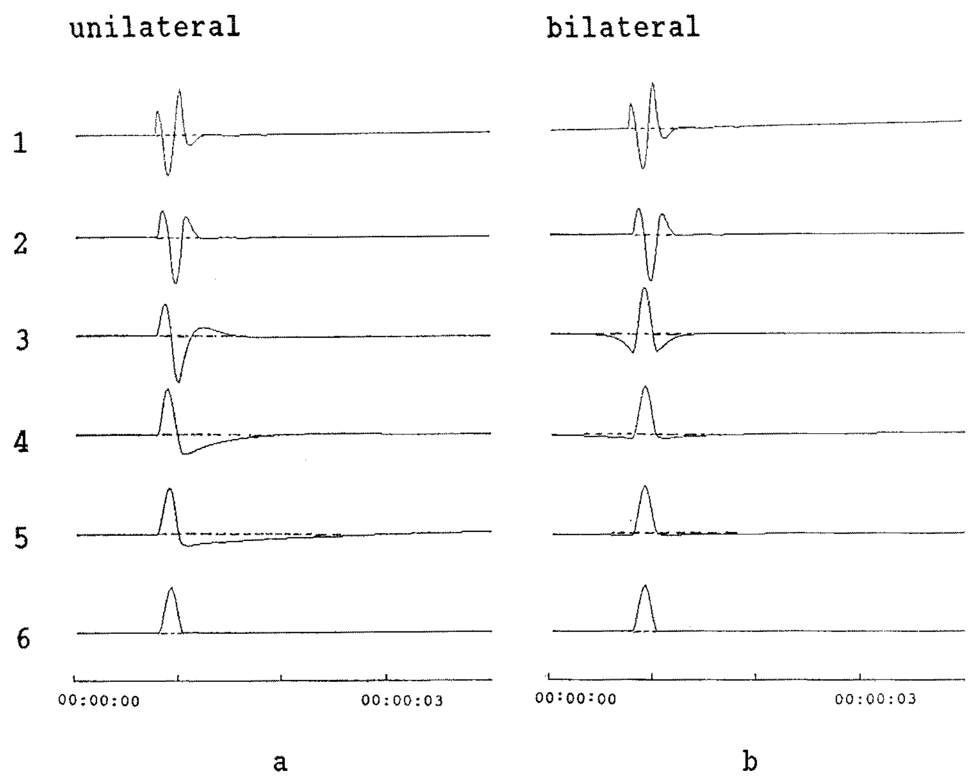

Fig. 1. Restitution of a simple theoretical far-field P-displacement pulse of duration $\tau = 0{\cdot}25$ s. Dynamic range 80 dB. 1 — seismogram ($T_s = 0{\cdot}25$ s, $\alpha_s = 0{\cdot}7$, 6th-order Butterworth filter, $f_{LP} = 30$ Hz, $f_D = 125$ Hz); 2 to 5 — restitution results for $T_L = 0{\cdot}25$ s, 1 s, 5 s, 10 s; 6 — true ground motion (TGM). The time marks indicate seconds.

method of modified impulse invariance [15]. The assumed mechanism corresponds to that of the main shock of the 1985/86 West Bohemian earthquake swarm [16].

Examples of the recursive restitution of the true ground motion (TGM) from theoretical seismograms generated in the described way are shown in Figs. 1 to 3. The uppermost signal is the response of the seismograph system to the TGM signal shown on the bottom trace. The signals inbetween are the results of the restitution of the TGM with a gradually decreasing ε, e.i. with an increasing corner period $T_L = 1/f_L$ of the inverse filter.

Figure 1 presents the results for a pure far-field pulse. This example demonstrates the superiority of two-sided processing: the TGM is already well approximated if $T_L = 20\tau$, whereas in the case of causal processing there still remains a significant spurious negative long-period component in the restored TGM if $T_L = 40\tau$. The effect of non-causal processing with a too low value of T_L is to produce a spurious earlier onset (see trace 3b). The absence of this phenomenon indicates successful

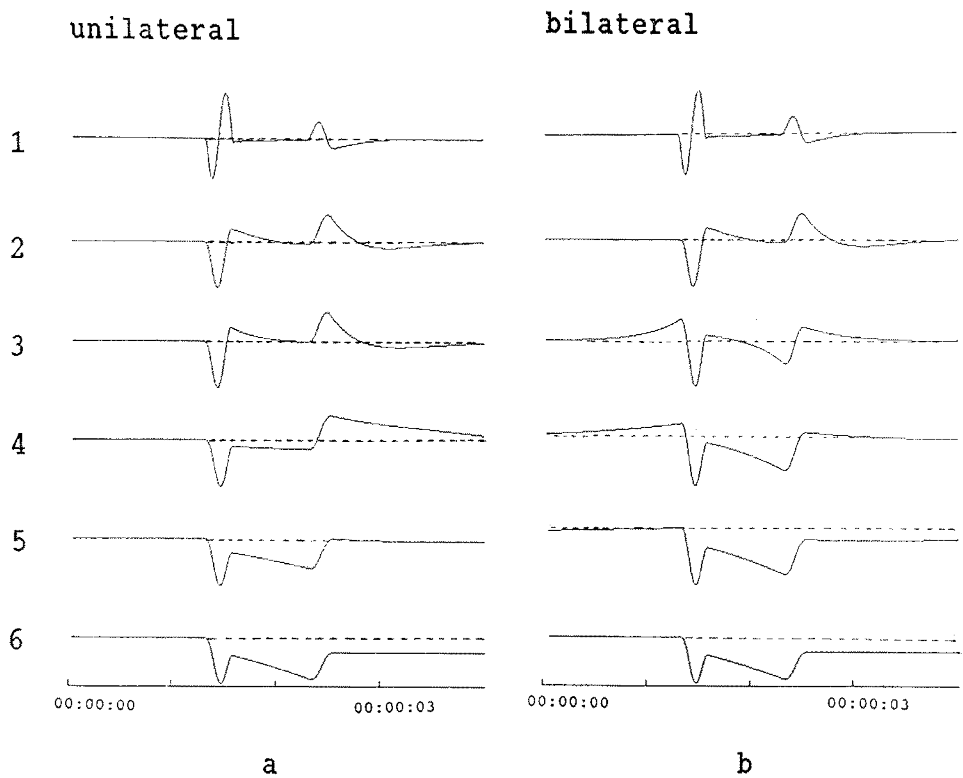

Fig. 2. Restitution of a theoretical signal containing intermediate-field and near-field terms (for source type and mechanism refer to text; back-azimuth 270°, take-off angle 160°, hypocentral distance $r = 8$ km). Dynamic range 80 dB. 1 — seismogram ($T_s = 1{\cdot}6$ s, other parameters identical with those of Fig. 1); 2 to 5 — restitution results for $T_L = 1{\cdot}6$ s, 3 s, 10 s, 40 s; 6 — TGM.

restorations (see traces 4b and 5b) and may serve as a criterion for the optimum choice of the approximation parameter ε.

The reliability of this criterion and the advantage of two-sided processing are more evident on the example of a seismogram containing also intermediate- and near-field terms (see Fig. 2). In no case of causal processing (see traces 2a to 5a) is the long-period near-field term (steady remnant displacement) restored well. Two-sided processing with a value of T_L large enough to produce no significant spurious anticipation component (see trace 5b) yields, on the contrary, a good approximation of the TGM inclusive of the remnant displacement.

Figure 3 demonstrates the influence of the round-off errors (noise caused by the limited dynamic range of the signal) on the result of the restitution. The limitation to 36 dB simulated in this example approximately corresponds to the dynamic range of a hand-digitized chart- or photo-record. The causal restitution (see traces 2a to 5a) obviously yields erroneous results. Trace 5a represents a typical example of noise-generated cumulative instability. Figure 3b demonstrates in a convincing manner the essential advantages of two-sided processing. The signal 5b, obtained by restitution down to a corner frequency of 0·025 Hz (T_L = 40 s), indicates that in this case the

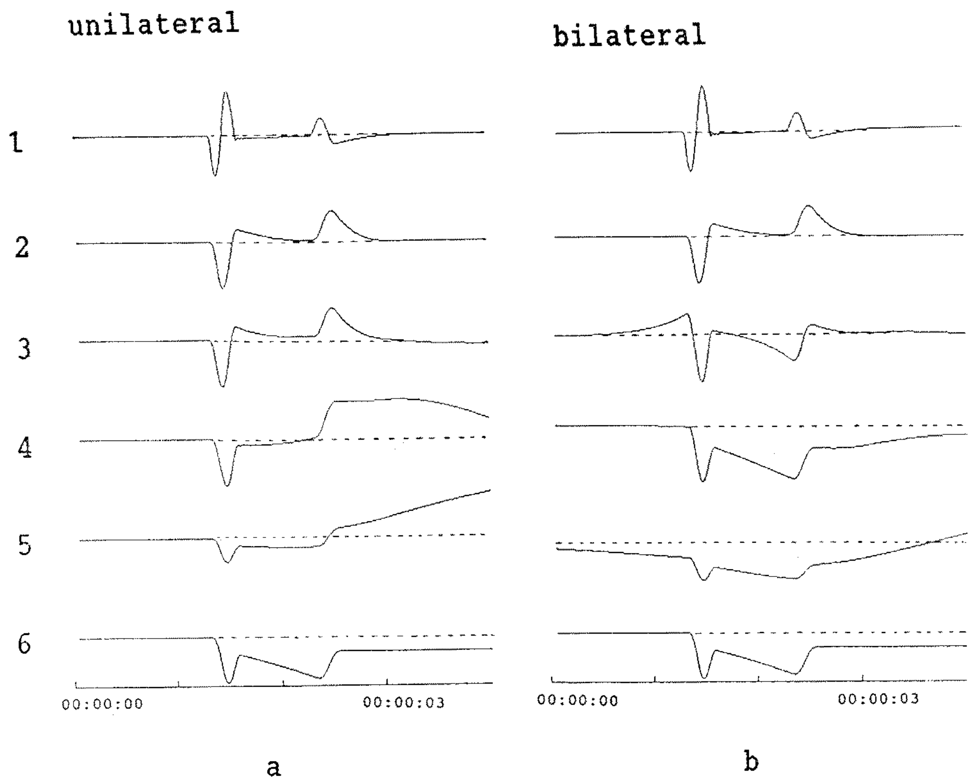

Fig. 3. Restitution of the same signal as in Fig. 2. Dynamic range 36 dB.

effect of the noise is to produce a spurious long-period component superimposed on the restored TGM. A still acceptably well restored signal (see trace 4b), representing the best approximation of the TGM in the given case, is obtained with a substantially worse approximation of the inverse seismograph (corner frequency 0·1 Hz, $T_L = 10$ s). The same fact follows from the comparison of this result with the best approximation obtained by two-sided processing of the equivalent 80 dB-seismogram (see trace 5b of Fig. 2). In this particular example a T_L of about 10 seconds thus obviously represents an optimum compromise between the mutually opposite requirements to approximate as exactly as possible the inverse seismograph and to suppress as efficiently as possible the destabilizing influence of the noise.

6. DECONVOLUTION OF ACTUAL SEISMOGRAMS

The approaches described in the previous sections have been used to process for various interpretation purposes records of different types of digital seismograph

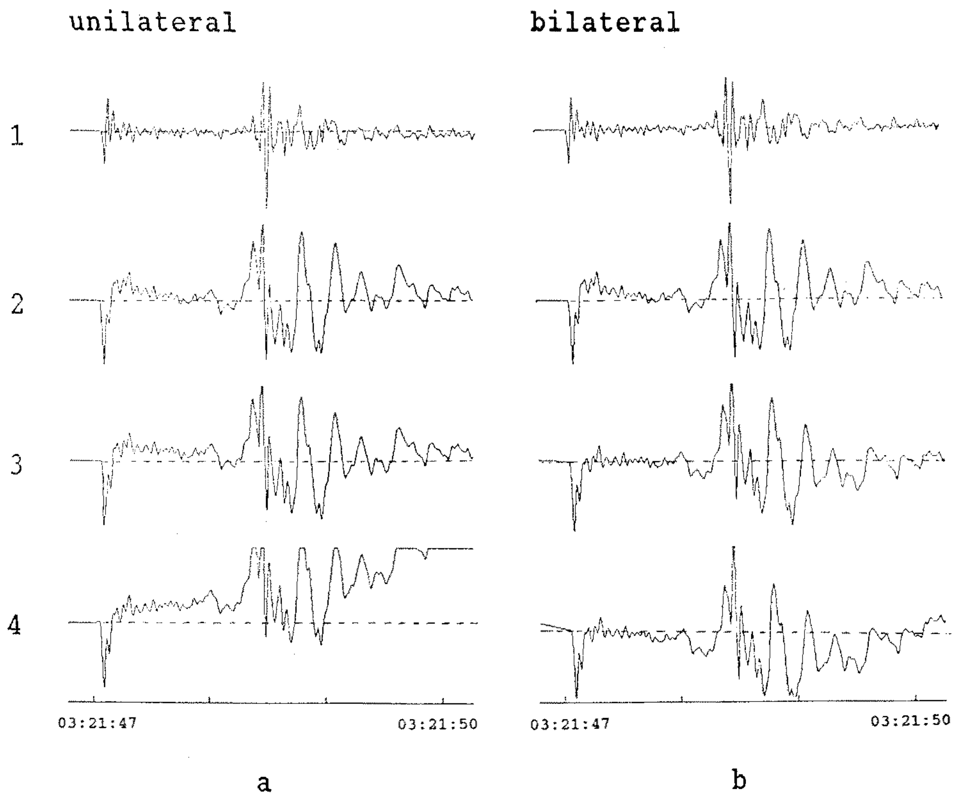

Fig. 4. Restitution of the TGM from the seismogram of a local earthquake of magnitude $M_L = 1{\cdot}8$ (West Bohemia, 8 January 1986, $H = 03{:}21{:}45{\cdot}3$, $r = 9{\cdot}9$ km). 1 — seismogram (Z-component, for seismometer parameters see text); 2 to 4 — restitution results for $T_L = 1{\cdot}6$ s, 5 s, 10 s.

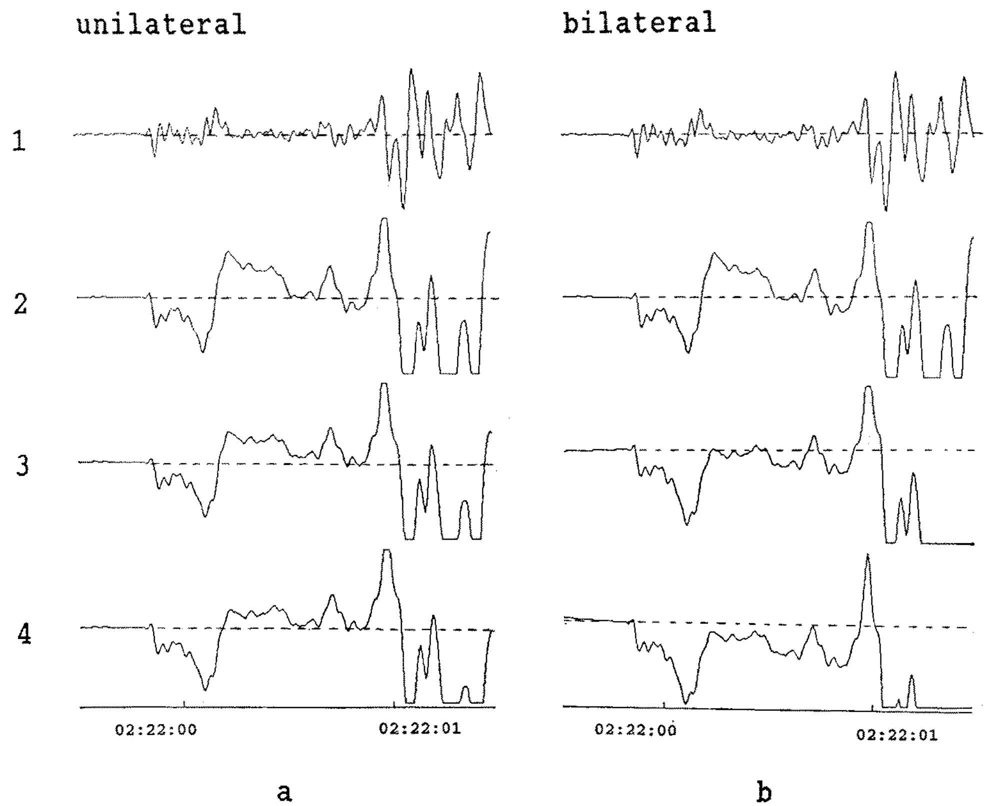

Fig. 5. Restitution of the TGM from the seismogram of a local earthquake of magnitude $M_L = 3{\cdot}4$ (West Bohemia, 23 January 1986, $H = 02{:}21{:}58{\cdot}3$, $r = 8{\cdot}6$ km), 1 — seismogram (Z-component, for seismometer parameters see text); 2 to 4 — restitution results for $T_L = 1{\cdot}6$ s, 5 s, 10 s.

systems, among them (i) systems for local observations in the West Bohemian/Vogtland earthquake swarm region, (ii) a short-period observatory system for recording weak regional and medium-size teleseismic events, and (iii) a standard broad-band (Kirnos type B) observatory system. In this section the performances of the procedures are demonstrated on examples of treating seismograms obtained from type (i) and (ii) systems.

In the systems of type (i) short-period SM-3 seismometers ($T_s = 1{\cdot}6s$, $\alpha_s = 0{\cdot}7$) have been employed and the amplified outputs of the velocity transducers have been recorded by a Lennartz PCM 5800 data acquisition system (dynamic range 120 dB, corner frequency of anti-aliasing filter $f_{LP} = 30$ Hz, sampling frequency $f_D = 125$ Hz). The systems were installed in the close vicinity of the epicenters of the 1985/86 West Bohemian earthquake swarm so that the seismograms could be expected to contain non-negligible low-frequency intermediate-field and near-field terms (for detailed description of the systems and recording sites see [17]). These terms are of principal importance for investigating the fault processes and in this context the restoration of the TGM became a fundamental requirement.

Figure 4 shows the result for an event with a local magnitude of $M_L = 1{\cdot}8$ and a focal depth of about 8 km, recorded at an epicentral distance of about 5 km. All the results of causal restitution and the worst approximation obtained by two-sided processing are characterized by the end of the P-pulse overshooting into the opposite polarity. According to the criteria discussed in Section 5 the best approximation of the TGM should be that shown on trace 3b. The results for a substantially stronger ($M_L = 3{\cdot}4$) event with almost the same hypocentral coordinates are shown in Fig. 5. At first glance trace 4b seems to contain a remnant displacement in the P-pulse but in view of the presence of the spurious anticipation component this displacement is most probably noise-generated (if the anticipation component were related to a ground movement, it should also be visible in the causally restored signal 4a). As in the preceding case, the best approximation thus is that shown on trace 3b.

A comparison of these results with those of the compatible numerical tests (see Figs. 1 and 2) indicates that the P-pulse for the $M_L = 1{\cdot}8$ event represents a pure

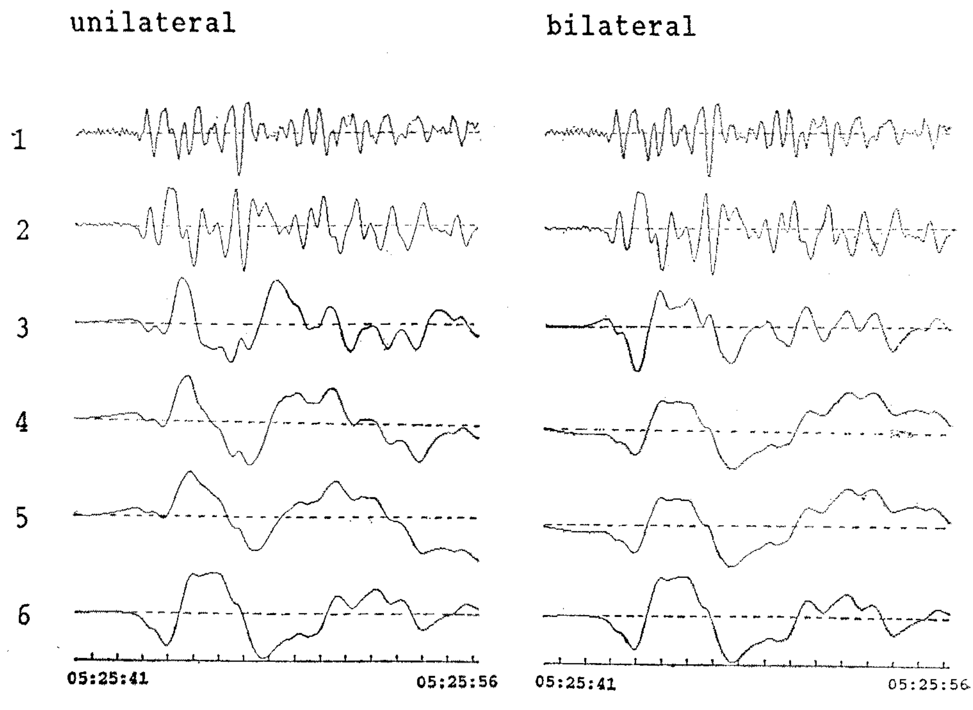

Fig. 6. Transformation of the short-period seismogram of a teleseismic event (Southern Xinjiang, 30 April 1987, $H = 05{:}17{:}37{\cdot}03$, $h = 8{\cdot}8$ km, $m_b = 5{\cdot}7$, $D_c = 43{\cdot}5°$). 1 — short-period seismogram (Z-component, for seismometer parameters see text); 2 to 5 — restitution results for $T_L = 0{\cdot}5$ s, 5 s, 10 s, 20 s; 6 — standard broad-band (Kirnos type B) seismogram ($T_L = 20$ s).

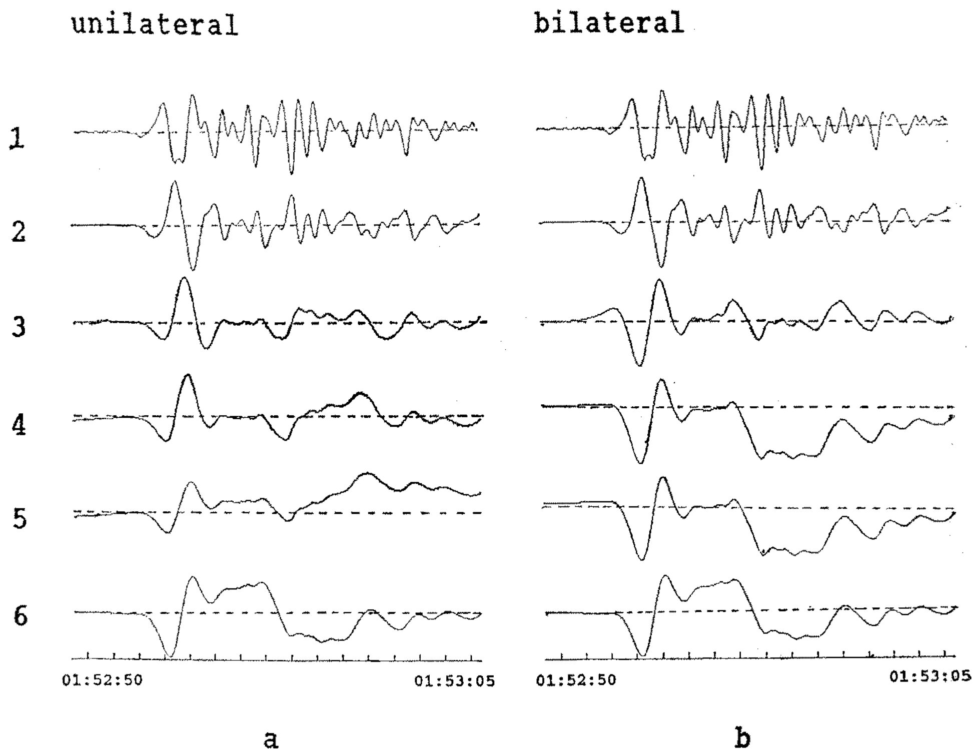

Fig. 7. Another example of short-period/broad-band transformation (Southern Iran, 29 April 1987, $H = 01{:}45{:}22{\cdot}63$, $h = 8{\cdot}1$ km, $m_b = 5{\cdot}9$, $D_c = 39{\cdot}2°$). 1 — short-period seismogram (*Z*-component, for seismometer parameters see text); 2 to 5 — restitution results for $T_L = 0{\cdot}5$ s, 5 s, 10 s, 20 s; 6 — broad-band seismogram.

far-field term and that the *P*-pulse for the $M_L = 3{\cdot}4$ event contains no near-field term. The shape of the former *P*-pulse corresponds to a comparatively simple fault process which lasted approximately 0·1 s, and that of the latter corresponds to a more complex fault process of a total duration of about 0·5 s. Assuming a fault propagation velocity of 3 km/s [18], the corresponding maximum source dimension, $x_{\max}$, amounts to 0·3 and 1·5 km, respectively. According to [19] the conditions for a pure far-field observation (negligible near-field and intermediate-field terms) are

$$r > 5\lambda\,, \quad x_{\max} < 0{\cdot}1\,\sqrt{(\lambda r)}\,, \tag{11}$$

where r is the distance from the source and λ is the dominant observed wavelength. In our case $r \sim 9{\cdot}5$ km, the *P*-wave velocity spectra of the two events peak near 5 and 1 Hz, respectively [18], and the average *P*-wave velocity in the region is 5·76 km/s [20]; hence we obtain $\lambda \sim 1{\cdot}1$ km for the weaker and $\lambda \sim 5{\cdot}8$ km for the stronger event. We can easily ascertain that for the weaker event both the conditions (11) are — in agreement with the observation — satisfied, and that for the stronger event the first condition is — in disagreement with the observation — not satisfied.

Type (ii) seismographs are the most common observatory systems used for the detection, localization and assessment of the body-wave magnitude of moderate-size regional and teleseismic events. In order to improve the accuracy of magnitude estimates, the use of several magnitude scales determined at different periods is necessary [21]. In this connection it is desirable to know to which longest period the actual teleseismic signal can be restored from records of such seismographs. To determine this, both the causal and two-sided procedures were applied to seismograms of the short-period digital seismograph system which is in service at the seismic station Kašperské Hory in South Bohemia ($T_s = 0{\cdot}5$ s, $\alpha_s = 0{\cdot}7$, $f_{LP} = 10$ Hz, $f_D = 31{\cdot}25$ Hz, dynamic range 120 dB), and the results of the restitution were compared with simultaneously recorded broad-band seismograms (type (iii) records, $T_s = 20$ s, the remaining parameters are identical with those of the short-period system).

The results for two teleseismic events of different magnitudes are shown in Figs. 6 and 7. The superiority of two-sided processing in the quality of the restitution is again clearly visible. The anticipation component is, however, in both cases masked by actual seismic noise so that the limit of stability of the restored signal remains the only criterion for the best attainable approximation of the TGM. The final approximations, corresponding to an expansion of the original pass-band 40-times towards longer periods, are accurate enough to enable the interpreter to determine the $(A/T)_{\max}$ parameter used for magnitude estimation with sufficient reliability. In this way, both the m_b and m_B magnitudes can be estimated from a single digital short-period record.

7. CONCLUSION

The comparison of results of causal and two-sided recursive inverse filtering of both theoretical and actual digital seismograms in the time domain has shown that the two-sided approach brings fundamental advantages: a higher accuracy of the approximation of the true ground motion, a faster convergence to the best attainable approximation, a lower sensitivity to incoherent noise, and a more reliable discrimination between veracious and dubious results. With regard to the small number of required arithmetic operations the recursive procedure is fast and, therefore, suitable for routine deconvolution of digital seismograms.

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