EET: Statistical attributes of pulse kinematics in complex deterministic strata

Gennady A. Ryzhikov and Marina S. Biryulina
University of Bergen, Department of Physics, Allégaten 55, N-5007 Bergen, Norway
E-mail: Gennady.Ryzhikov@fi.uib.no WWW: http://www.fi.uib.no/~antonych/

Introduction

A new approach to analysis of seismic records, corrupted with strongly interfering waves, is suggested. The problem of "decoding" coda in seismological records, as well as wide-offset data in seismic exploration, cross-well -, or marine reflection data with lots of multiples are well-known. *Energetic Envelopes -Transform***(EET)** is based on statistical aspects of pulse propagation in a deterministic media of an intricate layered structure. The reason to introduce the approach is that attempts to interpret the traces of interfering events in terms of such a deterministic kinematical parameter as travel time along of a few ray paths are not often successful: the powerful methods suitable for analysis of wave fields in a (simplified) medium model lose their strength under uncertainties in a real Earth structure knowledge. It is therefore attractive to make an attempt to find *statistical kinematical parameters,* which can help in a further refining the interpretation if necessary (and possible).
We illustrate the EE-transform by applying it to real seismological data from local network stations of Germany, Italy and Norway, and to real marine data from the area of a complicated sedimentological structure over rock strata. The outcome of the EE-transform is presented with Figures 1 and 2.

EE-Transform and Kinematics of Energetic Wavelets

The key to the strategy of EET is that an initial amplitude modulation of a pulse carrier, seen as an *envelope* undergoes to *diffusion* while propagating along a stratum. It gives an opportunity to interpret an individual record as a (short-scale) random realization of a (long-scale) diffusion process. Let us recall here the parabolic equation which involves non-local characteristics of a signal propagation in a stratified media.

The parabolic equation

Let a radial component of a sounding signal (a geometrical spreading factor $(2\pi r)^{1/2}$ is omitted) be represented with

$$\varphi(r,t) = \int_0^\infty A(\omega)\exp\{i[k(\omega)r - \omega t]\}\mathrm{d}\omega \tag{1}$$

where the dispersion is supposed to be nonlocal: e.g. it is caused by *geometrical* factors, such as thin-layer slabs or lateral variations of a layering. Assuming that the sounding signal has a dominant frequency ω_0, the parabolic approximation of the $k(\omega)$ has a form

$$k(\omega) \approx k(\omega_0) + k'(\omega - \omega_0) + \frac{1}{2}k''(\omega - \omega_0)^2 \tag{2}$$

Then φ can be rewritten

$$\varphi(r,t) \approx a(r,t)\exp\{i[k(\omega_0)r - \omega_0 t]\} \tag{3}$$

where the *wavelet* $a(r,t)$ is given by

$$a(r,t) = \int_0^\infty A(\omega_0 + \tilde\omega)\exp\{i\tilde\omega[(S_g r - t)] + i\frac{1}{2}\tilde\omega^2 r d^2\}\mathrm{d}\tilde\omega \tag{4}$$

with $S_g = k'(\omega_0)$, $d^2 = -k''(\omega_0)$.
Easy to check that $a(r,t)$ satisfies the *parabolic equation*:

$$i(\partial_r + S_g\partial_t)a(r,t) + \frac{1}{2}d^2\partial_t^2 a(r,t) = 0 \tag{5}$$

It follows from the Eq.5 that there are two time scales with respect to the modulating wavelet $a(r,t)$:
1. "conventional" time: the wavelet peak is moving along r with the average slowness S_g, and **2.** "inner" time: the wavelet becomes wider, there is a *diffusive broadening in the time domain* (or in the τ-domain, if to transform $\varphi(r,t) \to \varphi(p,\tau)$).
Note here, that we consider S_g as phenomenological parameter: it depends on the phenomenological dispersion (eq. 2). The latter can be derived theoretically provided the medium model is given (e.g., via representation of a wave field with normal modes). The "group slowness" S_g (eqs. 4 and 5) is a functional on a medium function and it involves, in particular, source-receiver locations as parameters. In other words, angular variations in layering can result in *an apparent anisotropy,* even though, perhaps, all off layer components are isotropic.

EET-operator design

Let a time record be $\varphi(\tau)$, and $|\varphi(\tau)| \equiv d(\tau)$, then the desired algorithm for *EET*-operator $\mathcal{E}$ should be:

$$d \to d^2 \equiv \hat{w} \xrightarrow{\mathcal{E}} \tilde{w} \tag{6}$$

(we omit the relevant grounds of the 1st part of the transform).
The strategy of the Energetic Envelope Transform consists of interpretation of an individual record $\hat{w}$ as a realization of a general diffusion process. In other words it is necessary to find the closest to the record $\hat{w}$ analog from a set of solutions of the parabolic equation $\{\tilde{w}\}$. The relevant algorithm consists in averaging of $\hat{w}(\tau)$ in a $\Delta\tau$-window with a proper chosen weight e.
Criterion on the operator $\mathcal{E}$ design:

$$\mathrm{Tr}\,[(I-\mathcal{E})\mathrm{e}^{\alpha\nabla_\tau^2}(I-\mathcal{E})^\dagger \;+\; \beta\mathcal{E}\mathcal{E}^\dagger] \;=\; \mathrm{Tr}\,[(I-\mathcal{E})^2\mathrm{e}^{\alpha\nabla_\tau^2} \;+\; \beta\mathcal{E}^2] \;=\; \min_{\mathcal{E}} \tag{7}$$

where ∇_τ stands for the derivative with respect to τ, and the exponential operator $\mathrm{e}^{\alpha\nabla_\tau^2}$ itself represents the convolution with Gaussian curve with "parameter of diffusion" α (see *diffusion regularization*, which we introduced in [1]).
$\mathcal{E}$ depends just on τ-difference, and thus the EE-transform is reduced to a simple convolution:

$$\tilde{w} \;=\; \mathcal{E}\hat{w} \;=\; e * \hat{w},$$

where $*$ denotes the convolution, and e defines the relevant "filter".

Two examples of EET-deeds.

To illustrate EET, we take two sets of seismic records.

• **Seismic exploration** (Fig. 1)
One of $p-\tau$ traces of real marine data is taken. Because of thin-layer slab over strong 2D-reflector (sediments over basalt) the respective wave-forms have no self-repetition.
Due to EE-Transform the desired self-repetitions of energetic wavelets are detected easily. Applying the strategy of Sharp Deconvolution [4], we remove all surface-related as well as intrabed multiples.

• **Seismology** (Fig. 2).
The 'raw' z-component high-frequency records from regional network stations φ (with digitizing frequency $\geq$ 40 Hz) are pre-filtered in the band 2-4 Hz and the resulting $\tilde{\varphi}^2$ is filtered then with **EE**-filter. The *EET* allows us to find some statistical parameters of a seismic wavefield which are nearly-invariant with respect to a local crustal structure. It is shown, that two main wavefield intensity components occur in the vicinity of the free surface, namely **P**-*Energetic Wavelets* **(P-EW)** and **S-EW**, which exhibit distinct group velocities being quite different from P_n, S_n or L_g phase velocities.
The exposed EW-kinematics shows that with respect to the seismic wave propagation it is possible to insert a *basic* reference model: slowly (*adiabatically*) varying stratified/gradient media, while a local crustal structure can be treated as random perturbations. The fairly robust EW-kinematics can be helpful for decoding of seismic records in the crust tomography. Besides an inversion of of EE-forms yields much more reliable (and cheap) estimates of seismic event epicenters [2], [3], which in its turn can provide with the more accurate crust images .

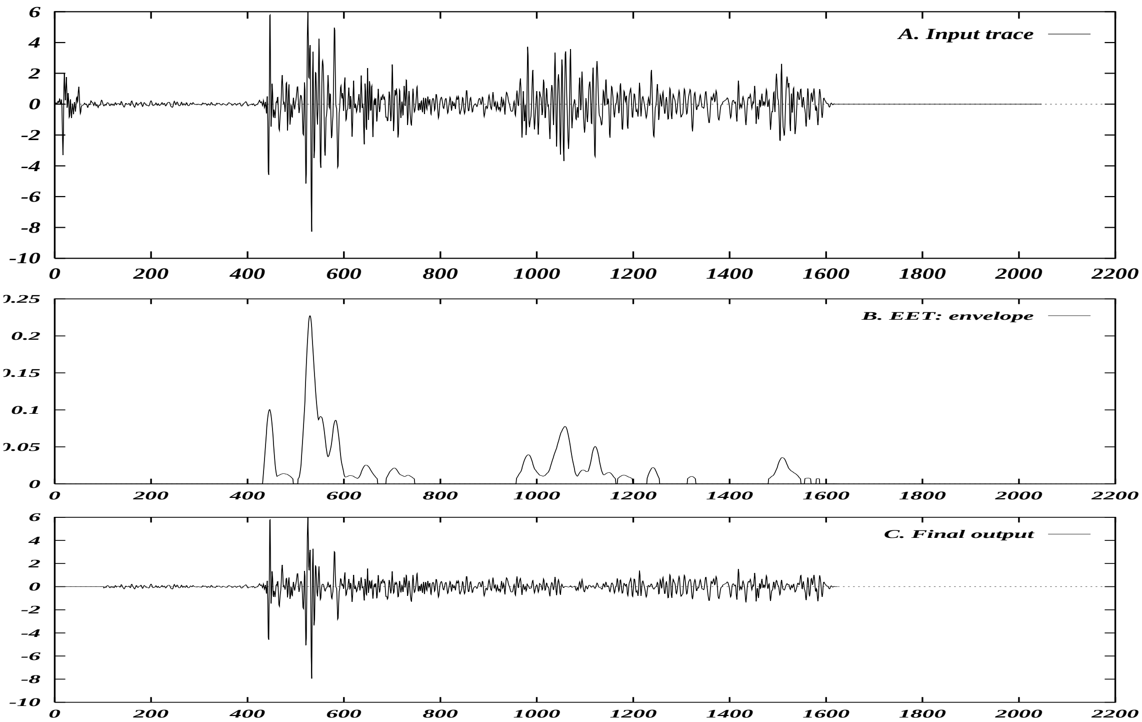

Figure 1: Example of elimination of multiples using energetic envelope transform: one of p-τ traces of real data corrupted with incoherent multiples is taken. Besides a sea-surface two main horizons generate multiples: a thin-layer slab forming a sea-floor and basalt beneath. • **A. Input trace;** • **B. EET output: Envelope;** • **C. Final output of Multiple Suppression via Envelopes (MSvE)**.

Conclusion

The suggested approach gives a way to extract statistical attributes of complicated wavefields preserving significant kinematical parameters. The relevant algorithm is very simple: it is just an averaging in a moving time-window. Due to very low frequencies of the envelopes the EET lets to reduce drastically seismic data banks in daily use.

Acknowledgements

The authors are grateful to M. Henger and G. Hartmann (Hannover), and R. Console and F. Mele (Rome) for providing us with real seismological data, and D.Lokshtanov (Norsk Hydro RC) for supplying the marine data set which could not be interpreted deterministically.

Our "seismology"-fragment of the research was partly supported by the US Air Force Office of Scientific Research, AFOSR Grant # F49620-94-1-0278. The "exploration geophysics"-part was stimulated by a short-term project with Norsk Hydro Research Center (D.Lokshtanov and A. Sagehaug).

Our special thanks to Prof. Jakob J. Stamnes, University of Bergen, Department of Physics: due to his help we got the opportunity to display the results of the research.

References.

[1] Ryzhikov, G.A., Biryulina, M.S. and Hanyga A.J., 1995, 3D nonlinear inversion by entropy of image contrast optimization: *Nonlinear Processes in Geophysics,* **2**, 228-240.

[2] G.Ryzhikov, M.Biryulina and E.Husebye, 1995, Automatic event location using local network data, in *Proc. of the 17th Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty, 12-15 09. 1995, Scottsdale, Arizona*, pp. 389-400.

[3] G.Ryzhikov, M.Biryulina and E.Husebye, 1996, A novel approach to automatic monitoring of regional seismic events, IRIS Newsletter, v.15, pp. 12-14.

[4] G.Ryzhikov and M.Biryulina, 1998, Sharp Deconvolution in Elimination of Multiples: 68th Ann. Internat. Mtg. Soc. Expl. Geophys., Expanded Abstracts, ST-18.3, p. 1983-1986.

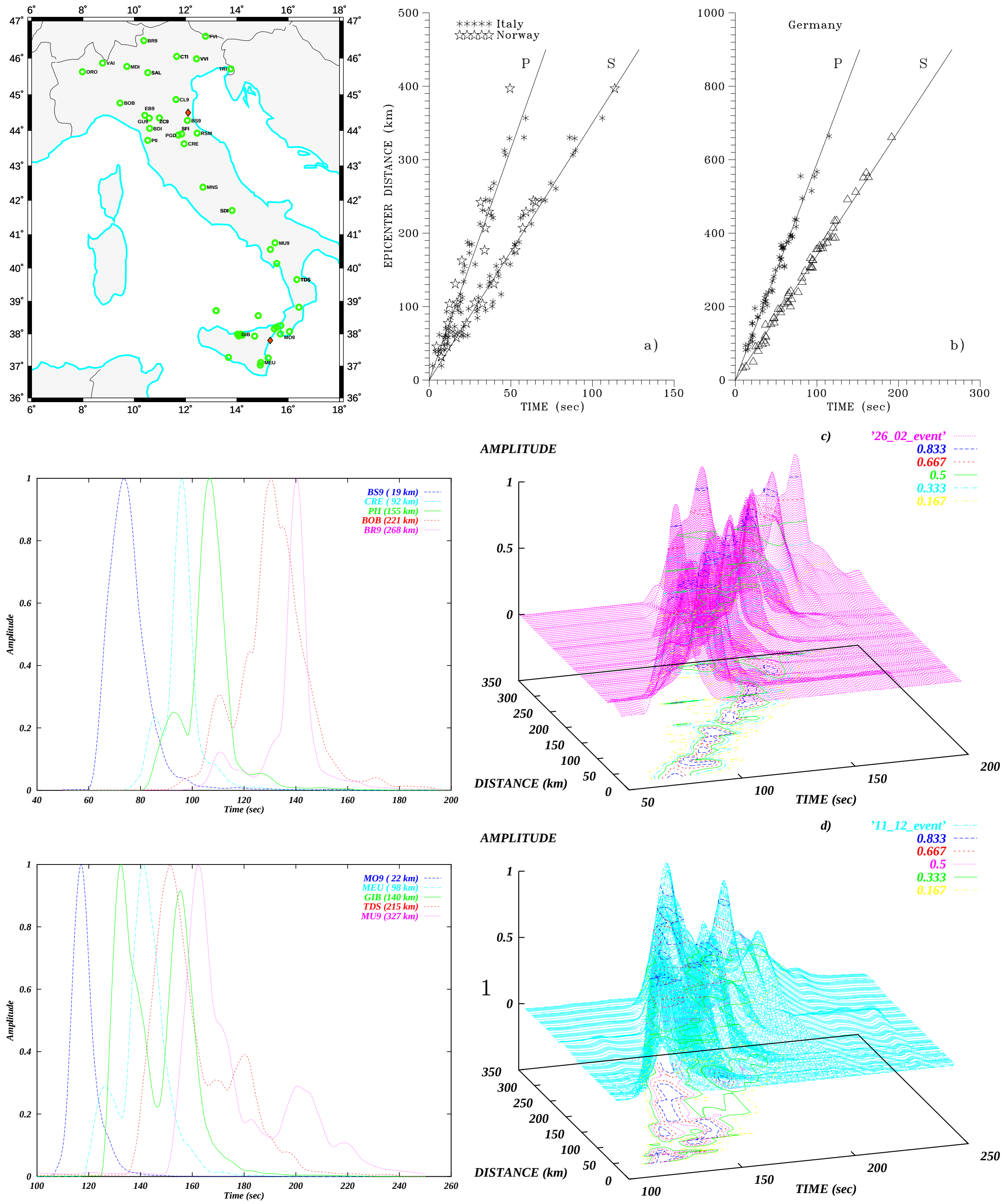

Figure 2: **Energetic Wavelets.** Examples of EE-transformed **real** data are given with Italian network station records. `Top, left:` • Epicenters of events 26.02.1995 (12.08 E, 44.49 N) and 11.02.1995 (15.61 E, 37.81 N) are marked by the *rhombus*, N.Italy stations are marked by *rings*. `Below, left:` • a set of EE-transformed records from 26.02.1995- event; `right:` the same records unrolled with respect the epicenter distance; `Bottom:`• records of the 11.02.1995- event. Note the *linear spreading* of EW (**c**) being typical of *diffusion processes*. `Top, right:` • preliminary estimates of P- and S-EW *travel times curves* on the base of Italian, Norwegian and German networks' data. The corresponding EW-velocities are 6.3 km/s and 3.5 km/s for Italy/Norway (`left`) and 5.9 km/s and 3.4 km/s for Germany (`right`).