A novel approach to automatic monitoring of regional seismic events

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Summary

Improved event detection and location capability of regional networks can be achieved by developing and incorporating new concepts for seismic data analysis. Our strategy for automatic event location is tied to transforming high-frequency data to **energetic wavelet** envelopes (**EW**-transform) and is anchored in the theory of pulse propagation in a randomly stratified medium with waveguides. Testing the new method on mining events from southern Norway, our epicenter determinations were far better than those derived by the analyst (bulletins). In Germany our scheme could handle very weak events for which interactive analysis failed. With the method it is possible to reduce the data volume for on-line transmission - by *in situ* (i.e. at the recording site) resampling of records from digitizing frequency 40 - 80 Hz to 2 Hz. Our automatic location scheme is 'robust' in the sense that no crustal information is needed for its realization, once the network has been trained through the development of proper EW travel time curves.

Event location/detection

The conventional approach to the problem of seismic event detection and subsequent localization is a four-step process:

(1) signal detection,
(2) phase identification (P, S, etc),
(3) phase association (matching phases from many stations), and
(4) event location using 'phase association' parameters.

This approach is not attractive for automated location analysis; a four-step process is rather clumsy and for poor to moderate signal-to-noise ratio the first 3 tasks are error-prone. We find that by using the energetic wavelet envelope transform (EW-transform) of records, we can merge the above 4 tasks into one; that is reformulate the problem as a joint *event* location/detection problem.

The steps involved are: EW-association$\Rightarrow$ event pre-location$\Rightarrow$ EW-identification$\Rightarrow$ event detection.

These steps in our **real-time event localization algorithm** are described below.

In-situ seismic record analysis.

The 'raw' vertical-component high-frequency records are pre-filtered in the band 2-4 Hz and/or 5-10 Hz, where the signal-to-noise ratio is optimum for local/regional events, and then subjected to the *EW*-transform as illustrated in Figure 1 and 2.

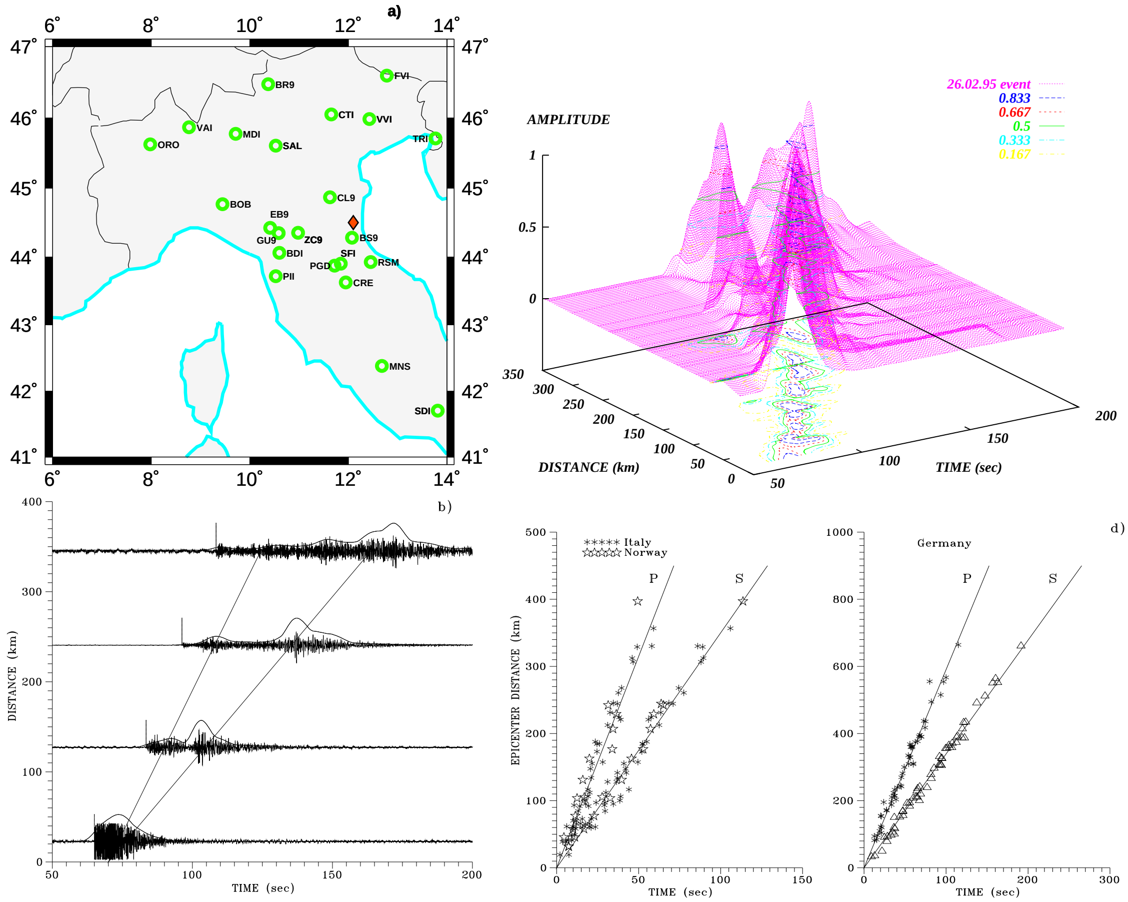

Figure 1: Example of energetic wavelet processing from stations *green circles* of the Italian network for an event 26.02.1995 *red rhombus*. b). Original waveform records and EW-envelopes. First arrivals are marked with *flags* **c)** The entire set of relevant dimensionless envelopes, ordered with respect to epicenter distances. Amplitude isolines are drawn below. Note the *linear spreading* of EW (**c**) which is typical of *diffusion processes.* **d)** P- and S-energetic wavelet travel times curves for Italian, Norwegian and German networks. The P- and S-EW maxima are automatically identified and picked at the event *post-localization stage.* The dispersion of maxima for the German network was essentially reduced after a brief period of 'network training'. The corresponding EW-velocities are 6.3 km/s and 3.5 km/s for Italy/Norway and 5.9 km/s and 3.4 km/s for Germany.

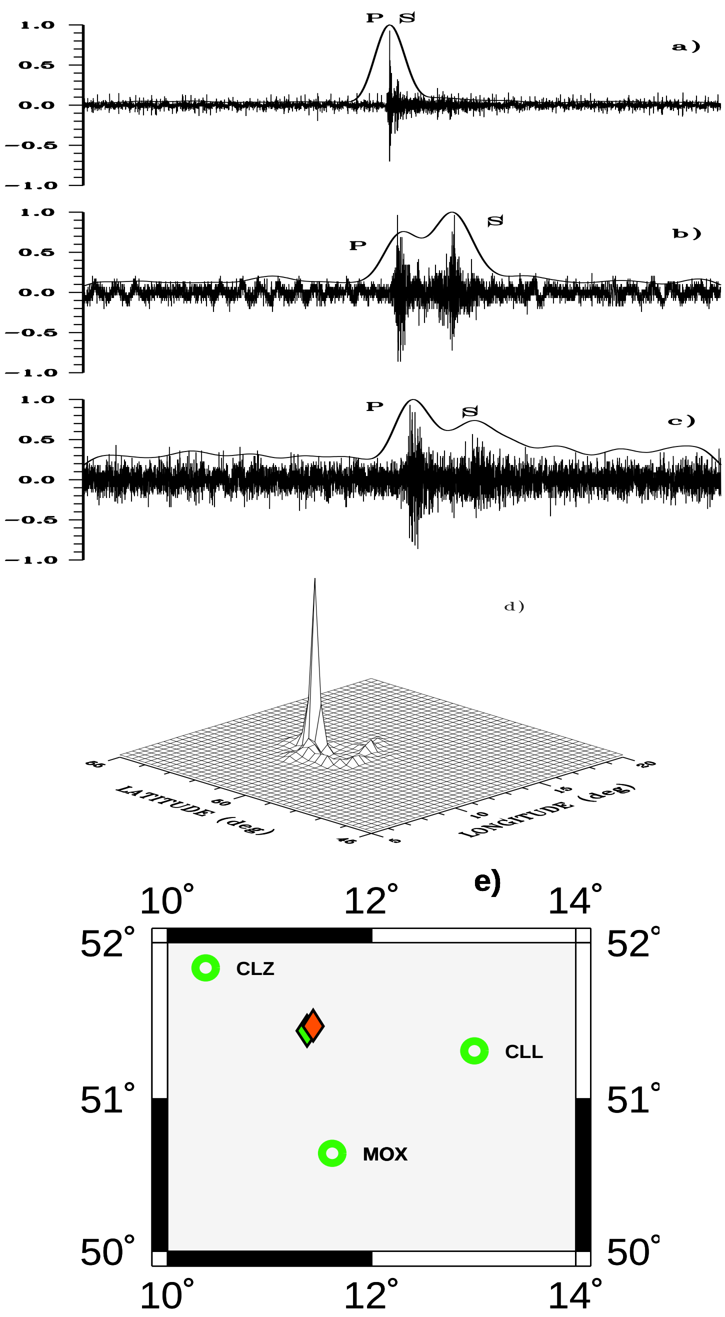

Figure 2: Location of a weak ($M_L \sim 1.2$) mining event from Harz area, Germany. The 'raw' records, prefiltered in the band 5-10 Hz, and the corresponding envelopes [**a)-c)**] clearly indicate the better signal-to-noise ratio for EWs, than for P_g - and S_n/L_g - phases. The best source image 'snapshot', extracted automatically with time-scanning of EnIC is shown in **d).** The three stations used from the German network CLZ (87 km), MOX (94 km) and CLL (116 km), are shown in **e)** with bulletin and our location marked by *green* and *red rhombuses* respectively. Differential epicenter parameters are 0.01 N (latitude) and 0.02 E (longitude).

The theoretical basis of EW-transform is that pulse propagation in a randomly stratified medium should create an energy wave train with diffusion in space and time, and therefore the energy distribution recorded by a station can be interpreted as a random realization of a diffusion process in time domain. Two main wavefield intensity components occur in the vicinity of the free surface, namely *primary energetic wavelets*, or **P- EW**, and *secondary-*, or **S-EW**, which exhibit distinct group velocities which are quite different from P_n, S_n or L_g phase velocities. It is important to note that these velocities are nearly independent of local crustal structure, focal depths and source mechanisms (Figure 1), as expected from theory.

The validity of this EW-transform was tested on real data from Germany, Italy and Norway and the results are presented in Figure 1d. Similar phenomena would exist in a deterministic isotropic stratified medium with waveguides. [Kennett, 1983]. It is sufficient to transmit just EW-transformed traces to the network HUB for subsequent event location and detection analysis.

Event location.

We pose the problem as a linear **inversion of EW- forms** with respect to an artificial *energetic source image*: i.e. an arbitrary space/time distribution of point-like incoherent sources. An infinite set of distributions exists that can fit the observed data quite well, but there should be just one that approximates an impulse emitted at a proper time/space location.

Note, that a *network area* is defined by a minimum of 4-5 network stations - which are located at distances from the source of less than 1000 km - in our tests we used grid size 10 x 10 deg^2 in latitude/longitude and gridding units 20 km and 1 sec in space/time. An essential step in **network training** is estimation of P- and S- EW velocities, or a part of *self-learning* of networks. This involves joint inversion of EW-forms from N events with respect to 3 x N parameters (epicenter coordinates, origin times) plus proper P- and S- EW velocities, from which travel time curves are constructed.

The steps involved in the location procedure are:

Normalized migration: each network station is considered to be a source which in reversed time 'emits' all samples of the corresponding EW-record into the network area with appropriate P- and S-EW velocities. [Note, to avoid errors during estimation of a 'true' amplitude, all EW-records are normalized with respect to the corresponding maxima]. This procedure provides us with a *source image* in the network monitoring area at each 0.5 - 1.0 sec (depends on a digitizing frequency of EW-records). The normalized migration applied here is similar to that described by Biryulina and Ryzhikov [Ryzhikov and Biryulina, 1995]

Source image dimensionless measure: We extract *the best* source image 'snapshot', namely the one most focused in space. This requires the introduction of the Entropy of source Image Contrast (*EnIC*) [Biryulina and Ryzhikov,1995] The corresponding time is associated with the event origin time, while the spatial coordinate of the source image maximum indicates the event location.

Proper detection involves estimations of a few parmeters such as 'sharpness' of a source image, self-consistency of P- and S-EWs identification, signal-to-noise ratios for both P- and S-EWs, and magnitude. In a post-event location/detection stage we may introduce finer gridding for more refined epicenter localtion. Moreover, the EW-transforms also provide us with estimates of

peak P- and S- signal amplitudes within the 'raw' trace filtered passband(s) and hence a mean for event magnitude estimation (Mendi and Husebye, 1994). These parameters are also widely used in seismic event classification studies.
The above type of automatically extracted seismic record parameters are well-suited for advanced network training. This can address problems such as more refined EW-velocity estimates. event magnitudes, event classification parameters and relative contributions of individual stations in a network. Since our automatic event location scheme 'works' with P- and S-wavelet maxima, the detectability of weak events is excellent as demonstrated in Figure **??**. Despite the low-frequency nature of the EW-wavelets the event location accuracy is also very good as shown in Figure 3.

Concluding remarks

Here we have used the expression " location in real time", since the time involved in processing is small compared to the travel time from source to receiver. In our case it takes about 4 minutes for signal to reach the most remote station, while the location/detection algorithm takes only a few seconds of computer time to analyze 5-minute record segments from 10 stations. Our processing scheme has been tested on weak events (Germany and Norway - e.g. with Figure 2 and 3), interfering events (Germany), but not on a continuous data stream from a network. The reason for this is that for the networks we have used only segments with known/presumed signal presence are retained in permanent storage, therefore it was rather difficult to simulate continuous data stream. Nevertheless we are confident that our scheme will analyze continuous data stream in the same efficient manner as for segmented data. In this contribution we have also described and demonstrated a strategy for the training of regional seismic networks. The approach appears to be flexible and nearly invariant with respect to a crustal structure and thus should be easy transportable to any network even in adverse tectonic regions.

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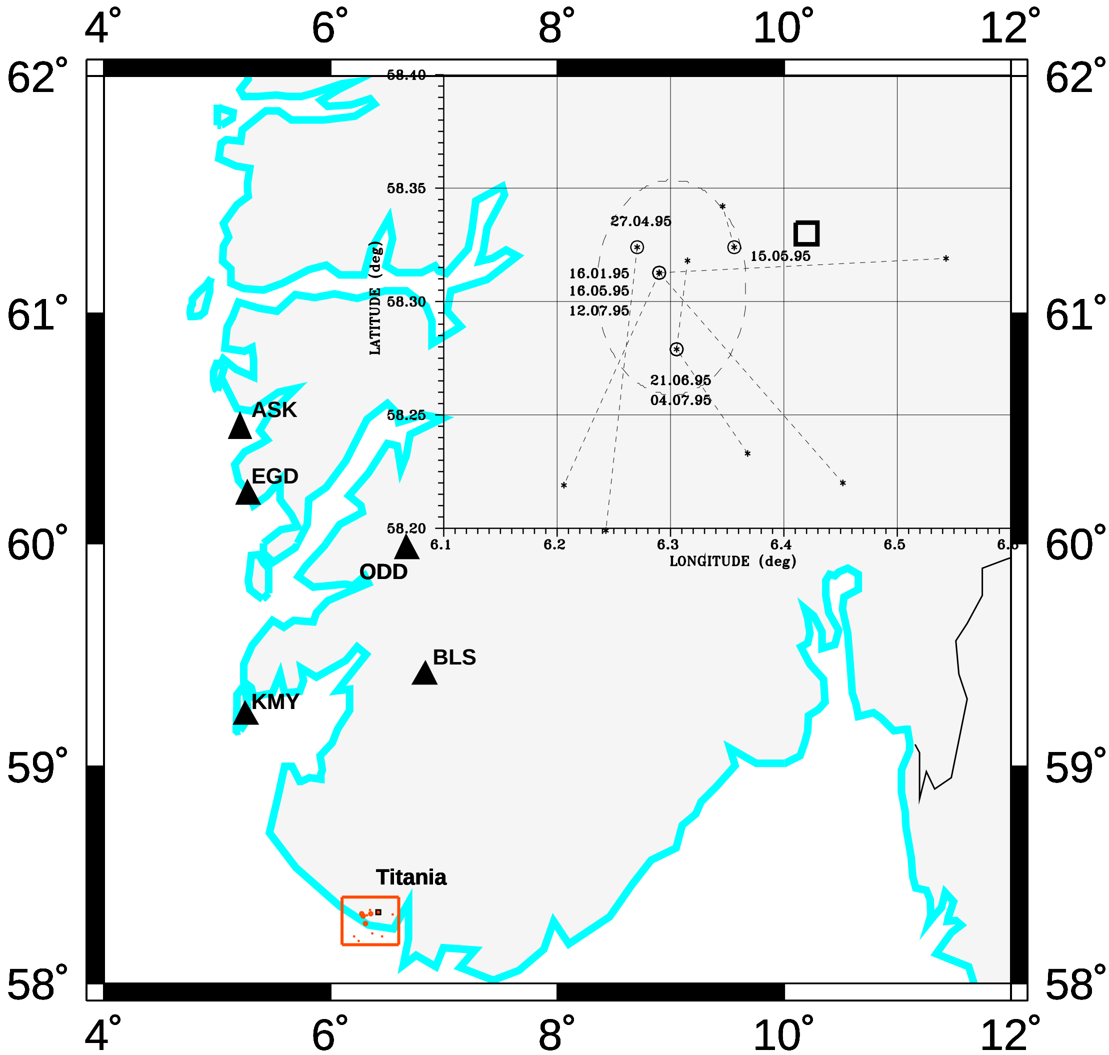

Figure 3: Automatic location of 7 seismic events in the Titania mine on the south coast of Norway (*red box* below). The stations used, part of the Norwegian Seismograph Network, are marked by *triangles*. The upper right corner shows a zoom display of the mining area (grid unit here is approximately 5 km). Our solutions are shown by *'ringed' asterisks* while the corresponding bulletin solutions are marked by *asterisks* only. The location of the mine itself by a *box*. The axizes of confidence ellipses are $\sim$ 3 times shorter for the automatic scheme than for analyst solutions. No a priori crustal information is used in our analysis.