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JOINT ACCURATE TIME-FREQUENCY AND HIGH-RESOLUTION ARRAY ANALYSIS, A TOOL FOR SITE EFFECTS ESTIMATION?

Sylvette BONNEFOY-CLAUDET¹, Miriam KRISTEKOVA², Jozef KRISTEK^{1,2}, Peter MOCZO^{1,2}, Giuseppe DI GIULIO³, Antonio ROVELLI³
*1 FMFI, Comenius University, Bratislava, Slovak Republic
2 Geophysical Institute, Slovak Academy of Sciences, Bratislava, Slovak Republic
3 INGV, Roma, Italy*

ABSTRACT - The goal of this study is to explain the peculiarities of earthquake motion in the Colfiorito basin, central Italy, during the Umbria-Marche seismic sequence. We mainly focus on the ~2 min long duration of the horizontal coda waves observed in aftershocks. To estimate the wave-propagation properties (apparent velocity and back azimuth) of the motion, we first determine the time-dependent spectral structure using accurate time-frequency (TFA) analysis, and then we apply high-resolution array analysis to the selected most energetic parts of the motion. Within the frequency range 0.5 to 3 Hz, we point out that the first part of motion is mainly due to the body-wave resonance (both P- and S-wave). Though the TFA indicates at later times energy concentrations around 1 and 2 Hz, the limited frequency range of the array analysis enables to demonstrate only persistent horizontal coda wave around 1 Hz. The array analysis gives surface-wave apparent velocities of the coda. The back azimuths of these waves are systematically different from those of epicenters. The long duration of the horizontal ground motion in the Colfiorito basin is mainly due to diffracted surface waves along the entire border of the basin, that is, not only due to single reflector.

1. Introduction

On September 26, 1997, two moderate earthquakes (ML 5.6 and 5.8) occurred a few kilometers from the Colfiorito village (Figure 1). These events started the Umbria-Marche seismic sequence that lasted until middle of 1998. The 1 Hz wave trains in the horizontal components of strong motion accelerograms have been demonstrated, and interpreted as edge-diffracted horizontally propagating surface waves, by Rovelli et al. (2001).

In order to achieve further information about the basin response to local earthquakes, Di Giulio et al. (2003) installed a second four-station small-aperture array (~140m) in the central part of the Colfiorito plain. Using the Frankel et al. (1991) technique to estimate backazimuth and apparent velocity of wave trains crossing the array, they observed that the synchronism between the array stations breaks down because of diffraction from the NW edge of the basin. Apparent velocities decrease quickly to an asymptotic value around 300 m/s. Moreover, particle motion in the horizontal plane is transversal to the direction of arrival to the array, suggesting a propagation of Love waves (Di Giulio et al., 2003).

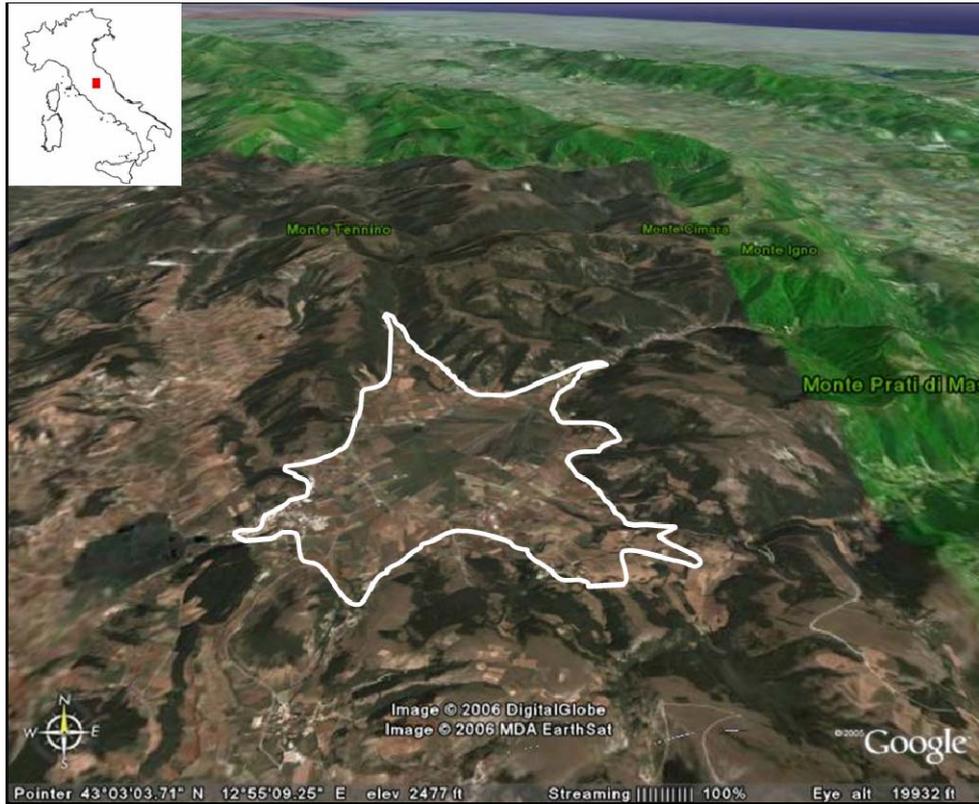


Figure 1. Localisation of the Colfiorito plain (white line), central Italy. Modified from ©Google Earth.

As shown by Di Giulio et al. (2003), to interpret other possible strong diffractors from the remaining parts of seismograms, we have to face the problem of separating multiple phases interfering simultaneously in time (Cornou et al., 2003a, 2003b; Schissole, 2002). To achieve this, we propose to apply a joint accurate time-frequency (TFA) and high-resolution array analysis to array seismograms recorded during the Di Giulio et al. (2003) experiment. First, using the TFA analysis code developed by Kristekova (2006) we estimate the most energetic parts of the asynchronous horizontal motion due to edge-diffracted wave at 1 s. In the second step, we apply the high-resolution array analysis method (Capon, 1969) to array seismograms corresponding to time windows selected by TFA.

2. Earthquakes dataset and characteristics of motion

Table 1. Parameters of the earthquakes used in this study

Event	Date	Epicentral distance (km)	Source depth (km)	Source backazimuth (°)	Magnitude
1	24.02.98	15	2	181	3.6
4	06.03.98	2	8	193	2.1
5	07.03.98	8	10	274	2.7

Strong ground motions due to local earthquakes were recorded by the array stations deployed in the central part of the Colfiorito basin. The array is composed of three stations (triaxial Guralp CMG40T) installed at the vertices of a triangle whose sides were 121, 126 and 141 m long. One more station was installed at the south-east of the basin, on a rock

site (Figure 2). In this study, only 3 earthquakes with reasonable signal-to-noise ratio were considered (Table 1). Seismograms show large amplifications of the ground motion and the long duration of the coda in the array stations compared to the bedrock station. Moreover, filtered time sequences indicate that, at 1 Hz, a synchronous motion dominates the first 5 seconds of the record (Figure 3). Later parts of the motions at stations are asynchronous. The largest amplitudes occur during the asynchronous motion in the early coda.

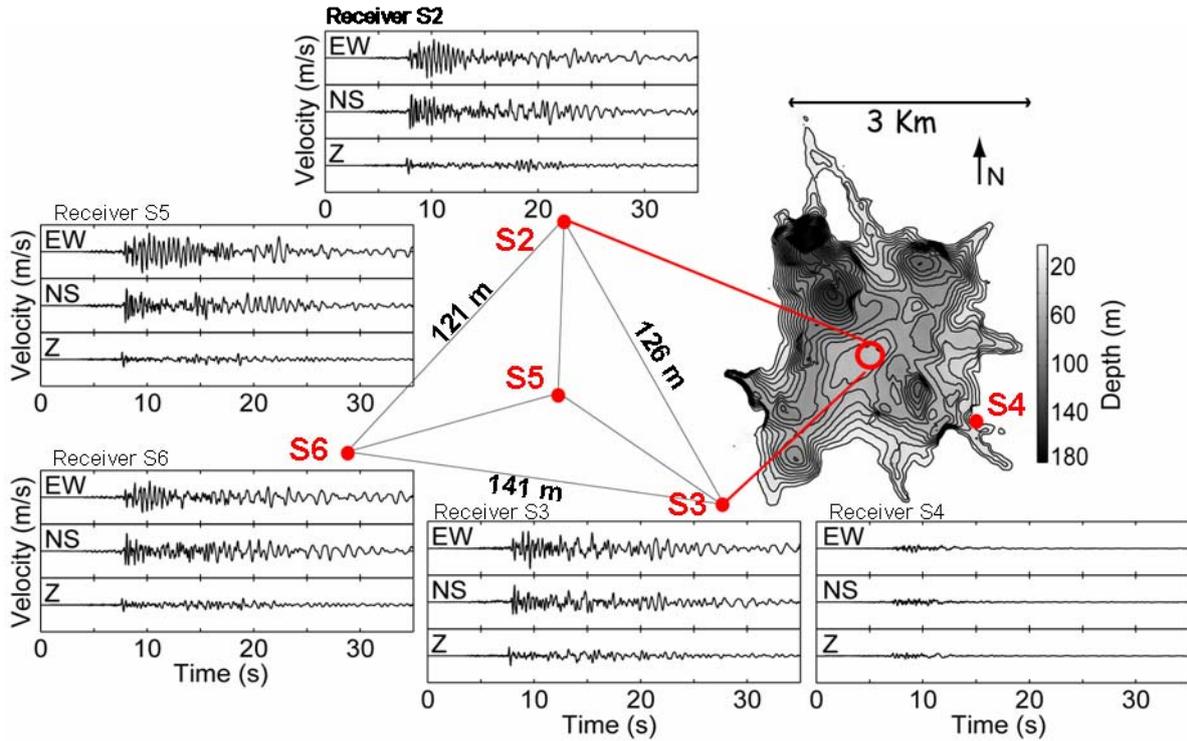


Figure 2. Position of the receivers (S2, S3, S5 and S6 are located within the sediments, while S4 is located on the rock site). 3-component records of event 1 are also displayed; the amplitude scale is the same for each plot and ranges from -0.2 to 0.2 cm/s.

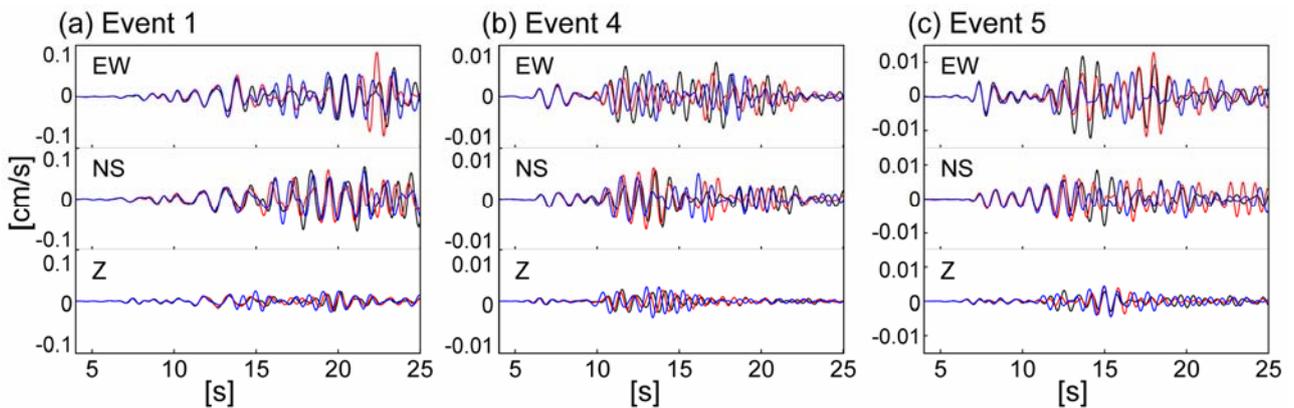


Figure 3. Band-pass filtered seismograms (0.5–1.5 Hz) of events 1, 4 and 5 (see Table 1). Only seismograms of the array receivers on the sediments are shown here (receivers S2, S3, S5 and S6).

3. Time-Frequency Analysis (TFA)

Accurate TFA (Kristekova, 2006) has been applied to raw seismograms. Figure 4 displays results for the frequency range from 0.5 to 50 Hz. The TFA of all events shows that the most energetic part of the motion corresponds to the first seconds of seismograms. For events 1 and 5, whose epicentral distances are larger than 3 km, the coda has lower frequency content.

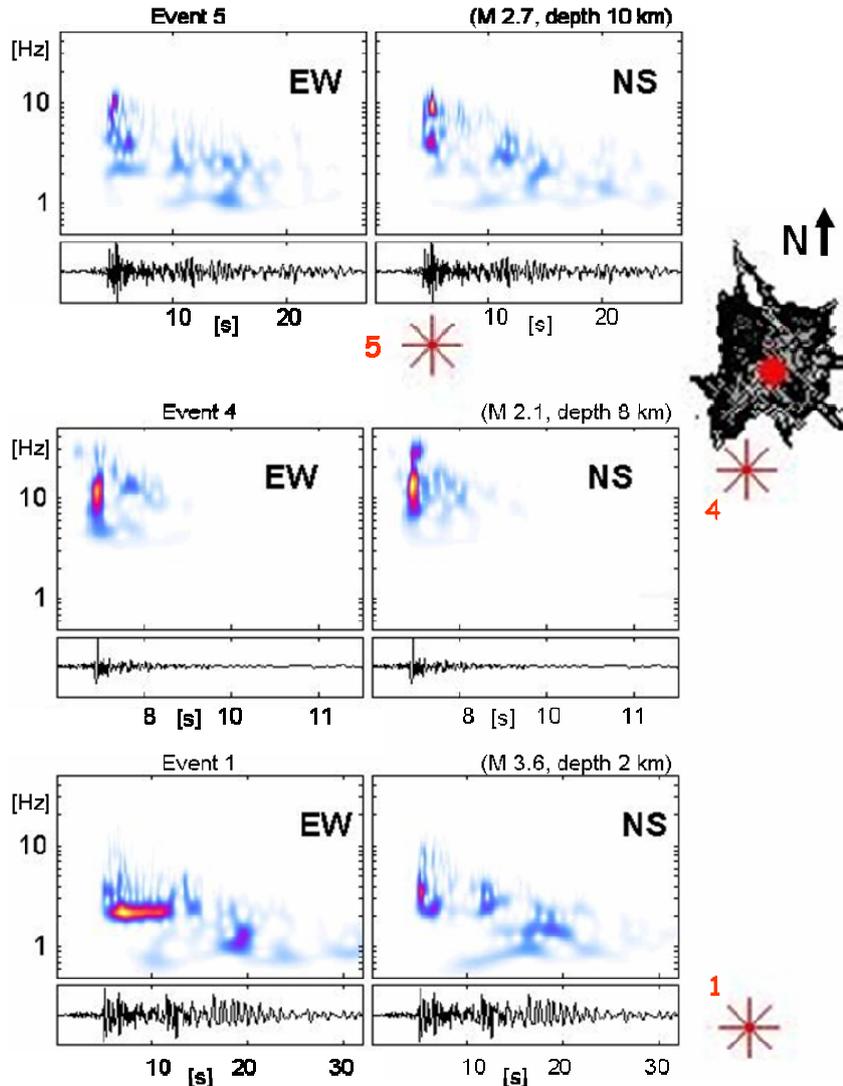


Figure 4. TFA for 0.5 - 50 Hz of the horizontal components for each event (see Table for more details about the event parameters). The color scale (light blue to yellow color) is normalized according to the maximum energy amplitude individually for each event. Red stars show the epicentral positions.

The time-frequency envelope misfits between the reference rock-site seismogram S4 and sediment-site seismograms S2, S3, S5 and S6 reveal the spectral amplification of motion at low frequencies at sediment sites (Figure 5). The main energy is concentrated around 0.8-1.2 Hz and 2 Hz. The relative proportion of energy between these two groups may depend on the source parameters (magnitude, epicentral distance, depth and backazimuth).

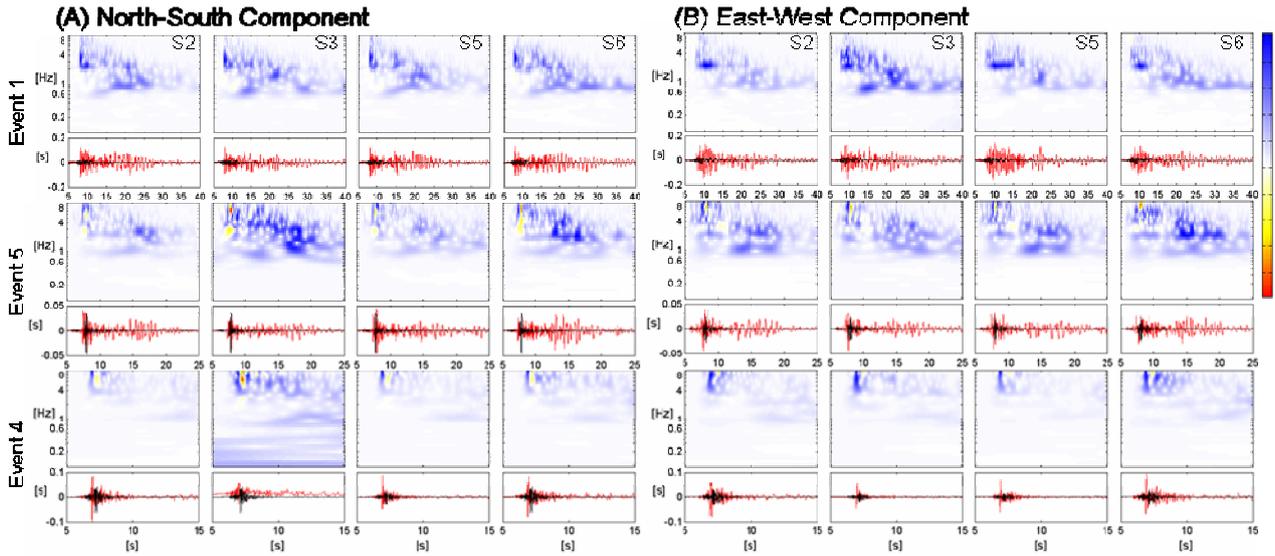


Figure 5. (A) Time-frequency envelope misfit between the reference seismogram (rock site) and sediment site for the North-South component. The analysis is performed for each event (top: event 1, middle: event 5, bottom: event 4), for each array receiver (from left to right: S2, S3, S5, S6). (B) The same for the East-West component. The time-frequency misfits are computed according Kristekova et al. (2006).

As Rovelli et al. (2001) and Di Giulio et al. (2003) have demonstrated the 1 Hz edge-diffracted surface waves, we will focus the next analysis at motion around 1 Hz. Moreover, the array aperture (~ 140 m) can yield sufficient resolution only in the frequency range from 0.8 to 1.2 Hz. Zooming in the 0.8 - 1.2 Hz frequency range we can recognize the most energetic part of the horizontal motion within this frequency range.

Figure 6 shows the results of the TFA applied to array-station seismograms for each event. The time windows corresponding to the most energetic part of horizontal motion have been selected taking into account

- 1) the strong variability of the motion (in time and spectral domains) within the array,
- 2) the sufficient time duration needed for the array analysis to estimate the wave propagation parameter, i.e., approximately 4-5 times the target period (i.e., 4-5 seconds).

4. Array analysis

We apply the CAPON high-resolution frequency-wavenumber method (Capon, 1969), implemented in the CAP software (Ohrnberger, 2004) to the selected time windows defined by TFA. Operating with sliding time windows and narrow frequency bands, this method provides the wave propagation parameters (azimuth and slowness as functions of frequency) of the most coherent plane wave arrivals. Here we use a wavenumber grid layout sampled equidistantly in slowness and azimuth (azimuth and slowness sampling set to 5 degrees and 0.0035 s/km, respectively). The frequency band is centered at 1 Hz ([0.95 - 1.05] Hz). An example of visualization is shown in Figure 7.

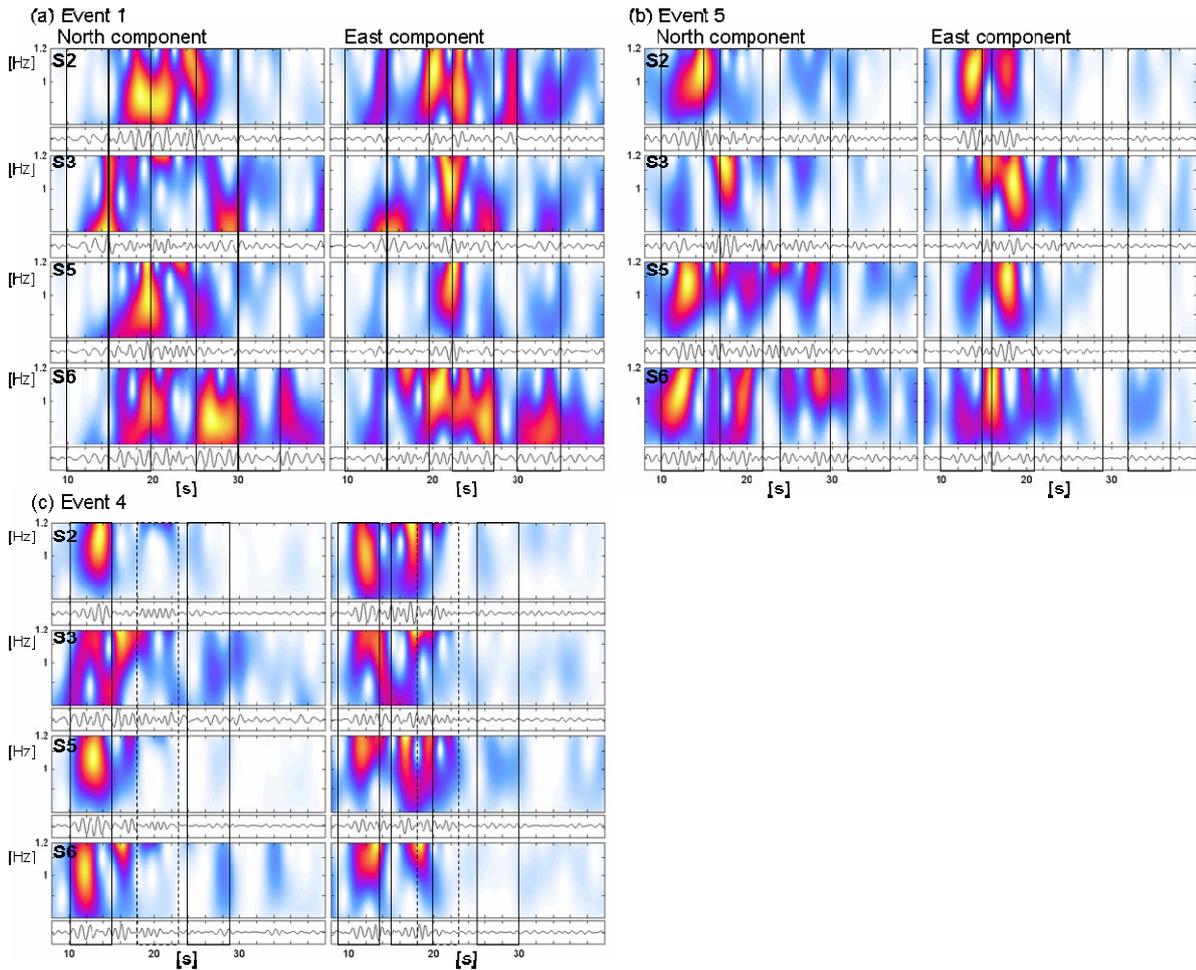


Figure 6: (a) TFA applied to the 0.8 - 1.2 Hz frequency range of the North (left panel) and East (right panel) components of the array-station seismograms for event 1. See Figure 5 for the color scale. Seismograms displayed at the bottom of each TFA picture are band-pass filtered in the 0.5 - 1.5 Hz range and normalized to the local maximum amplitude. (b) and (c) show the same for events 5 and 4, respectively. The selection of the most energetic time windows for each event is indicated in each TFA plot (black rectangles).

Figure 8 shows, for event 4, a large difference in estimates of the wave propagation parameters for the NS and EW components (particularly at later time). This can be due to the almost vertical earthquake motion incidence. In this case we do not expect too much generation of the edge diffracted surface waves. CAPON analysis performed for the time windows 15 - 20 s for event 1 (East component) also illustrates the difficulty to estimate the wave propagation parameters, when two waves are propagating exactly in the same time. However, we can make the following comments:

- 1) the estimated phase velocities, from 200 to 400 m/s, are close to the surface-wave velocity,
- 2) we confirm the existence of the NW reflector during the first 5 s of the asynchronous motion, as already shown by Di Giulio et al. (2003),
- 3) a second diffractor is located at the SE edge of the basin, at the opposite side of the basin margin with respect to the first one,
- 4) a third diffractor can be identified in the NE edge of the basin.

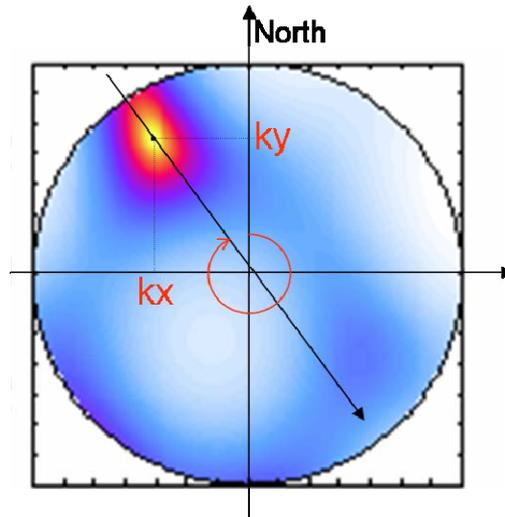


Figure 7: Example of visualization of CAPON analysis. The normalized power estimate of the CAPON estimator is displayed in the wavenumber plane. The maxima give the estimate of the most coherent plane waves propagating through the array. The apparent phase velocity is given by $2\pi/k$, where $k = \sqrt{k_x^2 + k_y^2}$; the source backazimuth is given by $\arctan(k_x/k_y)$.

5. Conclusions

The joint accurate TFA and high-resolution array analysis applied to earthquake records allow to investigate the structure and the behavior of the motion in the Colfiorito basin. The TFA highlights the 1-2 Hz dominant part of the motion in the coda at sediment sites. This part of the motion is mainly dominated by the edge waves diffracted at the edges of the basin. These waves propagate with the surface-wave velocities. We identify three diffractors located at the NW, SE and NE edges of the Colfiorito basin.

The joint TFA and array analysis applied here show the limits of the approach. When the earthquake motion is impinging almost vertically, CAPON analysis is not able to give a correct estimate of the wave-propagation parameters (the assumption of a horizontal plane wave crossing the array may be not applicable here). Moreover, if it is not possible to separate in time two (or more) waves recorded at the same time at one receiver and traveling with the same frequency, CAPON analysis cannot give accurate results.

This study will be followed by investigation of the effect of source (backazimuth, depth, magnitude, source parameters) on the generation of the 1 Hz edge-diffracted surface waves. For this purpose we have constructed a 3D numerical model of the basin, and we will simulate ground motion in the basin using a 3D finite-difference scheme.

6. Acknowledgement

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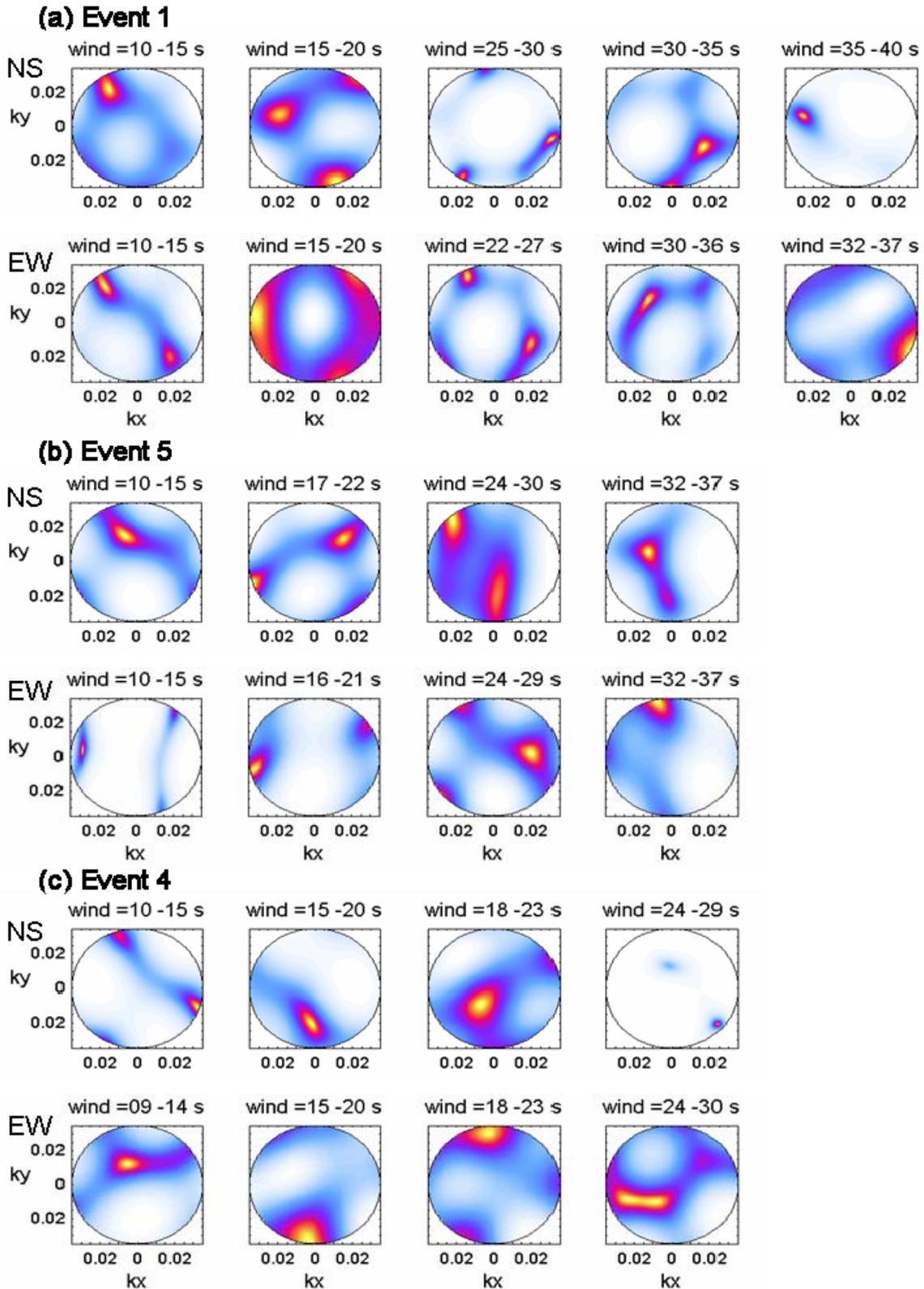


Figure 8: (a) Results of CAPON analysis for the North (top) and East (bottom) components applied to the array-station seismograms. The array analysis is applied to the selected time windows (wind) defined by the TFA (see Figure 6). The color scale is normalized according to the maximum energy amplitude (yellow color) individually for each plot. (b) and (c) show the same for events 5 and 4, respectively.

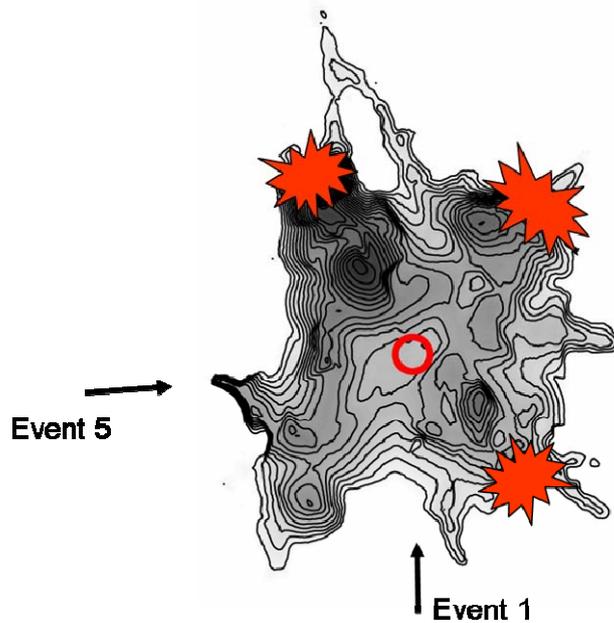


Figure 9: Localization of the edge diffractors in the Colfiorito basin (red). For comparison, the backazimuths of the events 1 and 5 are also indicated (black arrows). The red circle indicates the position of the array.

7. References

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