SEISMIC INTERFEROMETRY BY CROSS-CORRELATION WITH AND WITHOUT ARRAY-FORMING. APPLICATION ON AMBIENT-NOISE RECORDINGS FROM THE MIZIL AREA (ROMANIA)

IONELIA PANEA[1], DEYAN DRAGANOV[2], VICTOR MOCANU[1], MIRELA SPITA[1]

[1] *University of Bucharest, Faculty of Geology and Geophysics, Department of Geophysics, 6 Traian Vuia St., 020956, Bucharest, Romania, ipanea2@yahoo.com*
[2] *Delft University of Technology, Department of Geotechnology, P.O.Box 5048, 2600 GA Delft, The Netherlands*

Seismic Interferometry (SI) is a method used to retrieve surface and body waves from ambient-noise recordings. The results of this method, represented by virtual-source gathers, are considered equivalent to the source gathers from the active seismic reflection surveys. We apply SI by cross-correlation on two different ambient-noise dataset recorded in 2009 and 2011 in the Mizil area (Romania) with the purpose to retrieve the body-wave reflected waves from the recorded noise. The input data to SI is represented by ambient-noise panels without dominant surface waves. The separation of the panels with and without dominant surface waves was done after the visual evaluation of surface waves in the time domain. Array-forming is used to attenuate the remaining surface waves before SI. Passive seismic sections were obtained after the processing of the SI results and compared with the active seismic section from a seismic reflection survey performed in the vicinity of the passive array. Most of the reflections seen on the passive seismic sections correlate well with those seen on the active seismic section. The remaining surface waves on the panels without dominant surface waves affect the continuity of the shallow reflections retrieved from the noise recorded in 2011.

Key words: seismic interferometry, passive seismic, ambient noise, body-wave reflections, surface waves, Mizil, Romania.

1. INTRODUCTION

Seismic Interferometry (SI) retrieves reflected and surface waves from ambient-noise recordings using various algorithms (cross-correlation, deconvolution and multi-dimensional deconvolution). The SI method is based on the acoustic daylight-imaging principle proposed by Claerbout (1968) for a one-dimensional medium. According to this principle, the reflection response can be obtained by auto-correlating the transmission response of a deep noise source. Later, Wapenaar *et al.* (2002) extended the one-dimensional method to a general 3D medium (acoustic and elastic) using the reciprocity theorems of the correlation and convolution type (Wapenaar *et al.*, 2002; van Manen *et al.*, 2005; Wapenaar and Fokkema, 2006) and using stationary-phase analysis (Snieder, 2004). The theory is applied for a lossless medium surrounded by a boundary of sources. Snieder (2007) showed that the seismic arrivals can be retrieved if the receivers, from which we get the ambient-noise recordings, are surrounded by a complete volume of sources and the sources density is proportional to the intrinsic losses. In all these methods, the SI responses are obtained by cross-correlating pairs of receivers. The SI method is known as SI by cross-correlation and it is known as a very stable method.

Both type of waves, body and surface, can be successfully retrieved using SI by cross-correlation. Surface waves were retrieved from ambient noise generated by sources located near and at the Earth's surface (*e.g.* Shapiro and Campillo, 2004; Sabra *et al.*, 2005; Panea *et al.*, 2012). The S-wave velocities can be obtained after the processing of the retrieved surface waves, via analysis of the dispersion curves (Panea *et al.*, 2012). Information about the S-wave velocities can also be extracted from the surface waves present on raw passive seismic data or vertically stacked passive data (Panea *et al.*, 2010; Panea *et al.*, 2012). Grecu *et al.* (2010) extracted the Rayleigh waves from seismological recordings using SI by cross-correlation. Then, the S-wave velocities were obtained after the analysis of the dispersion images.

SI by cross-correlation can also be used to retrieve body-wave reflections from ambient-noise recordings (Draganov *et al.*, 2007; Draganov *et al.*, 2009; Zhan *et al.*, 2010; Ruigrok *et al.*, 2011; Draganov and Panea, 2011).

The retrieval of the body-wave reflections is affected by the presence of the surface waves, which are waves characterized by low frequencies and large amplitudes. To bring forward retrieved body-wave reflections, the surface waves have to be suppressed before the use of SI. This suppression can be done by choosing a specific frequency interval for the filtering of ambient-noise recordings, in which the reflections are dominant, by using arrays of receivers or, simply, by removing the recordings dominated by surface waves; the last option reduce the amount of passive data for SI and is considered to be not a very good choice because we may lose interesting data.

In this paper, we use SI by cross-correlation to retrieve body-wave reflections from ambient-noise recordings obtained in two passive seismic surveys performed at the same location but in different period of times. We compute the SI responses using as input data the noise panels without dominant surface waves. The remaining surface waves seen on the panels from 2011 were attenuated using array-forming with 12 elements. Then, the SI responses are processed to obtain migrated time sections for the subsurface.

2. DATA DESCRIPTION

The passive data analyzed in this paper were recorded in the Mizil area (Romania) in 2009 and 2011. The location of the passive survey is close to that of an active seismic reflection survey performed in the past for hydrocarbon exploration. In this way, we can compare the results of active and passive seismic surveys represented by migrated time seismic sections.

The Mizil area is close to the seismically active Câmpulung–Făgăraş–Sinaia and Vrancea areas. The continuous seismic activity represented by shallow and intermediate earthquakes provides significant amount of data which contain information about the seismic reflectivity of the subsurface. An earthquake with magnitude of 2.6 took place in the Vrancea zone during the passive measurements performed in August 2011, according to the database provided by the National Institute for Earth Physics, Măgurele, Romania; unfortunately, the waves generated by this earthquake could not be observed on the passive data. The teleseismic events observed at the seismological stations during the passive measurements from 2009 and 2011 had low magnitude and they could not be observed on our data.

Mizil is a small town with a population of about 16000 inhabitants with agriculture as main activity and very little industrial activity. The traffic to and from it, even during the day hours, was relative low.

2.1. DESCRIPTION OF THE PASSIVE SEISMIC SURVEY PERFORMED IN 2009

The ambient-noise acquisition was done over a period of six hours using two Geodes (Geometrics) with 24 vertical-component geophones each; the natural frequency of the geophones is 4.5 Hz. The geophones were planted along two orthogonal lines, one parallel to the active seismic reflection line and the other one perpendicular to it (Fig. 1). The geophone spacing was 2.5 m; the geophones were labeled with G1, G2, … G24 on both lines starting from the east-most and the north-most directions (Fig. 1). The time sampling interval was 0.001 s and the auto-saving of data was done after each second. The maximum frequency contained by the recorded arrivals is 500 Hz, as a result of the chosen time sampling interval.

The analyzed seismic energy has two types of sources, natural (micro-earthquakes and shallow earthquakes) and anthropogenic sources (*e.g.* passing cars, trains, etc.). The source of the strong coherent noise (surface waves) seen on the noise panels is represented by the passing trains on the railway line located at about 2 km away from the passive survey (Fig. 1); this type of source is named *distant source* (Panea *et al.*, 2010). Surface waves weaker in amplitude were generated by the passing cars on the secondary roads from the vicinity of the passive survey (Fig. 1); this type of source is named *closer source* (Panea *et al.*, 2010). The quality control of the recorded noise panels was performed in the field to verify that the measurements were taken properly.

We display in Fig. 2 examples of ambient-noise panels recorded along the NE and NW lines. Dominant surface waves generated by distant and closer sources can be easily identified (Fig. 2a-d). These panels are useful for SI by cross-correlation if the purpose is to retrieve surface waves and useless for the retrieval of the body-wave reflections. One way to use these panels in the retrieval of reflected waves is to attenuate the dominant surface waves via frequency filtering or array-forming. In case of this dataset, the band-pass frequency filtering partially attenuated the reflected arrivals because their frequency content is overlapped with that of the surface waves. Array-forming was used to attenuate these noisy waves but the remaining noise is still strong on array responses and its presence can degrade the quality of SI results. The panels displayed in Fig. 2e-f are useful for the retrieval of accurate body-wave reflections.

The frequency spectra up to 60 Hz of the recorded noise panels on both directions are displayed in Fig. 3; for comparison, we display the spectrum of a source gather recorded in an active seismic reflection survey. The frequency spectra for passive data were computed by applying the one-dimensional Fourier transform to the results of the summation of all the traces from all panels recorded, separate, on the NE and NW lines. The main effect of this summation is on dominant surface waves, some of them will be attenuated but it is useful for our study in which we want to retrieve and analyze the body-wave reflections. According to the displayed spectra, the surface waves characterized by frequencies 4–12 Hz are strong on the panels recorded on the NE line (Fig. 3a). The active source gather contains reflected waves characterized by frequencies of 12 – 40 Hz, with a dominant frequency of 20 Hz. As expected, the reflected waves contained by the passive records are weak in amplitude and difficult to be seen at this stage of analysis.

Fig. 1 – Map of the Mizil area showing the position of the passive experiment from 2009 (the white rectangle). AS – active seismic reflection line, NR – national road, SR – secondary road, RW – railway line, white star – active shot record. The inset shows the geometry of the passive array, consisting of two orthogonal lines of 24 vertical geophones (G1 to G24) spaced at 2.5 m. Source of the map: http://maps.google.com.

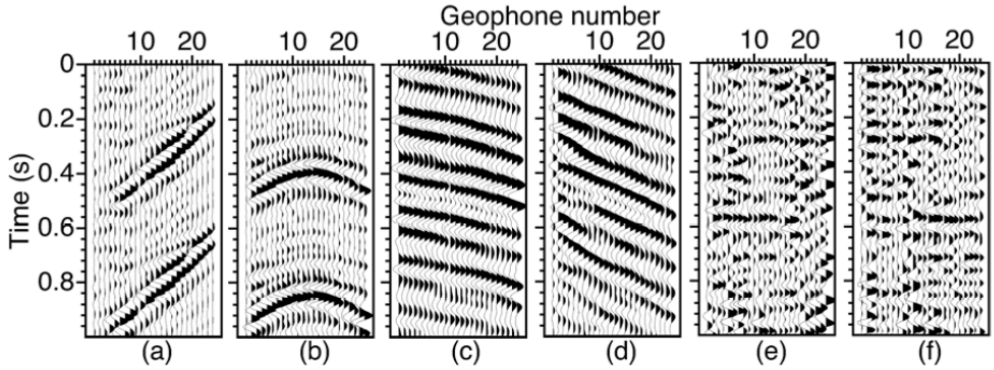

Fig. 2 – Examples of ambient-noise panels (a–d) with and (e, f) without dominant surface waves; the geophones were planted along the NE (a, c, e) and NW line (b, d, f), see the inset in Fig. 1.

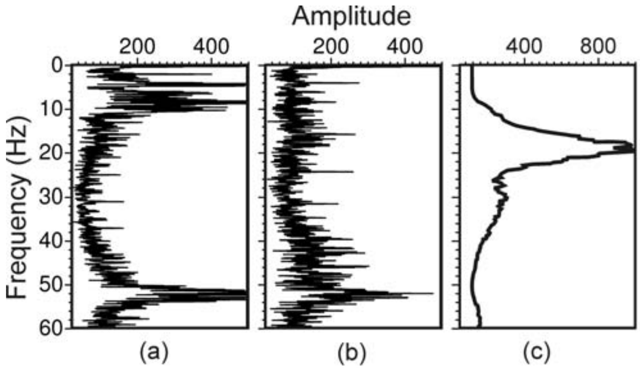

Fig. 3 – Frequency spectrum of ambient-noise panels recorded on the NE (a), NW passive lines (b) and of active shot-gather with the position along the active seismic line given the white star in Fig. 1(c).

2.2. DESCRIPTION OF THE PASSIVE SEISMIC SURVEY PERFORMED IN 2011

A new passive seismic survey was performed in 2011 at the same location with that one from 2009. The ambient-noise data acquisition was done over a period of about 5 hours using three Geodes (Geometrics) with 24 vertical-component geophones each; the natural frequency of the geophones is 4.5 Hz. A number of 48 geophones were planted on the NE line and 24 geophones were planted on the NW line (Fig. 4). The geophone spacing was 2.5 m. In case of the NE line, the geophones were labeled with G1, G2…G48 starting from east-most direction, while for the NW line, the geophones were labeled with G1, G2, … G24 starting from north-most direction. The time sampling interval was 0.001 s and the auto-saving of data was done after every 10 s. The maximum frequency contained by the recorded arrivals is 500 Hz. The same type of seismic sources, natural and anthropogenic, described in the previous section acted during the passive measurements.

We display in Fig. 5 examples of panels with and without dominant surface waves generated by distant sources (*e.g.* passing trains coming, sometimes, from both directions at the same time, to and from the Mizil town); such surface waves can be seen in Fig. 5a. The panels which contain this type of waves have to be removed from the input data to SI if the purpose is to extract the body-wave reflections. Fortunately, the surface waves recorded during this passive survey are weaker in amplitude comparing with those recorded in 2009. We display in Fig. 6 the frequency spectra of the noise panels recorded in 2009 and 2011 using the geophones planted along the NE line. The presence of the surface waves is clear on the spectrum obtained for the data recorded in 2009, they are characterized by frequencies of 4 – 12 Hz. The possible body-wave reflections contained by the noise panels recorded in 2011 are greater in amplitude than those present on the panels from 2009 (Fig. 6). Therefore, we expect to retrieve better body-wave reflections using the seismic interferometry.

The amplitude of the recorded non-coherent noise varies from one trace to another or from one group of traces to another (Fig. 5). Strong non-coherent noise can be seen on different geophone locations from one panel to another, which means that we have to normalize the amplitude of all recorded noise panels before the use of SI. A number of six geophones located in the central part of the NE line, G20 – G25, had very bad geophone-soil coupling, therefore they do not contain valuable information (Fig. 5).

Fig. 4 – Map of the Mizil area showing the position of the passive experiment from 2011 (the white rectangle). AS – active seismic reflection line, NR – national road, SR – secondary road, RW – railway line. The inset shows the geometry of the passive array, consisting of two orthogonal lines of vertical geophones spaced at 2.5 m (G1 to G24 on the NW line and G1 to G48 on the NE line). Source of the map: http://maps.google.com

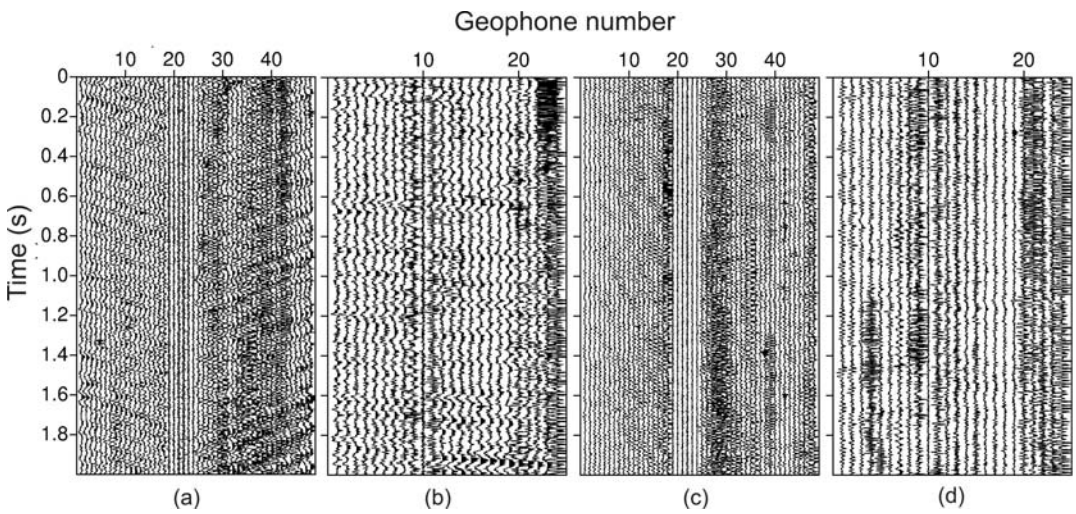

Fig. 5 – Examples of ambient-noise panels (a, b) with and (c, d) without dominant surface waves; the geophones were planted along the NE (a, c) and NW line (b, d), see the inset in Fig. 4.

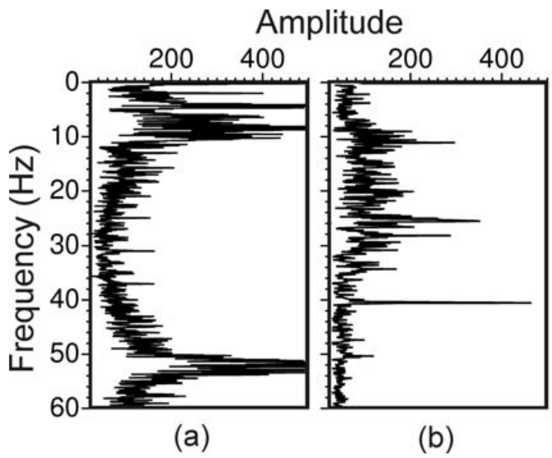

Fig. 6 – Frequency spectrum of ambient-noise panels recorded on the NE line in 2009 (a) and 2011 (b).

3. SEISMIC INTERFEROMETRY WITHOUT ARRAY-FORMING

In this section, we present the results of SI by cross-correlation on pre-processed ambient-noise panels; the pre-processing means amplitude normalization applied to all noise panels remained after the visual evaluation of the surface waves. The visual evaluation is done in the time domain; all panels with visible surface waves generated by distant and closer sources are removed from the input dataset to SI.

The SI by cross-correlation is applied with the purpose to retrieve the body-wave reflections from the recorded ambient noise. The relation we use in the computation of the SI responses is:

$$\left\{G^{v,\tau}_{z,z}\left(x_A,x_B,t\right)+G^{v,\tau}_{z,z}\left(x_A,x_B,-t\right)\right\}*s(t)\approx \approx\sum_{i=1}^{N}V^{obs,i}_{z}(x_A,t)*V^{obs,i}_{z}(x_B,-t) \quad (1)$$

where $G^{v,\tau}_{z,z}(x_A,x_B,\pm t)$ denote the Green's function and its time-reversed version between positions x_A and x_B, t denotes time, $v^{obs,i}_{z}$ represents the component of the particle velocity recorded in the vertical direction in the ith noise panel, *s(t)* stands for the auto-correlation of the source time function of the noise sources, *N* is the number of used noise panels and * denotes convolution. Eq. (1) is taken from Wapenaar and Fokkema (2006) with one modification, the ensemble average is replaced with a summation over the available noise panels.

The SI results are represented by a collection of virtual-source gathers similar with those from the active seismic surveys; the number of virtual-source gathers is equal with the number of geophones used in a passive line (or number of traces from one noise panel).

The SI results are obtained in two steps. First, we correlate the master trace with itself, defining an auto-correlation response, and with all other traces from one ambient-noise panel, defining the cross-correlation response. A master trace is a trace selected from the analyzed noise panel at which we will obtain the position of the virtual source, which ideally correspond with the position of the source from an active seismic survey. In our study, the master trace will be chosen at the location of geophones G1, G2 until the last one from the NE and NW line. At the end, the correlation responses for one noise panel are represented by a number of correlation panels equal with the number of traces from the analyzed noise panel. Next, the correlation is repeated for the second noise panel and the obtained correlation panels will be summed with those obtained for the first noise panel. The procedure is repeated until we sum the correlation panels obtained for all noise panels used in SI. The final correlation responses are represented by a number of summed correlation panels which contain positive (causal) and negative (a-causal) times.

The second step in the computation of the SI results is to create the virtual-source gathers. These gathers are obtained by summing the causal and a-causal times of the summed correlation panels. According to the theory, the causal and a-causal times are the same if the illumination of the passive line is homogeneous, meaning that the sources are regular distributed into the subsurface and illuminate the passive line from all directions. In this case, the SI response can be obtained by taking either of the two parts. If the illumination of the passive line is not homogeneous, some parts of the Green's function are retrieved at causal times and some parts of the Green's function are retrieved at a-causal times.

In our experiment, the illumination of the passive line is not homogeneous and the SI results will be computed following the approach presented in Ruigrok *et al.* (2011): for geophones with a field number higher than the number of the master trace we use the retrieved time-reversed a-causal times, while for geophones with a lower field number we use the causal times.

3.1. SI BY CROSS-CORRELATION ON THE PASSIVE DATA RECORDED IN 2009

In this section we present the SI results computed for the noise panels recorded on the NE line of the passive array used in the survey performed in 2009. We use the SI by cross-correlation to retrieve the body-wave reflections from the recorded ambient noise. Examples of ambient-noise panels are displayed in Fig. 2. Only the panels without dominant surface waves were used for SI by cross-correlation, like those displayed in Fig. 2e, f. The separation of the noise panels without dominant surface waves from those with dominant surface waves was done after the visual evaluation of the surface waves in the time domain.

A number of 900 noise panels were selected from the total of 1183 noise panels; the trace length is 16 s. The correlation was done as described above and we obtained 24 summed correlation panels; the master trace was chosen at the position of each geophone from the passive line. Examples of such panels are displayed in Fig. 7. Continuous events assumed to be body-wave reflections can be seen on the correlation responses.

The virtual-source gathers are obtained after the summation of the causal and a-causal times following the approach presented in Ruigrok *et al.* (2011). We display examples of virtual-source gathers in Fig. 8. We can see clear reflected waves characterized by high amplitudes and good continuity at 0.04 s, 0.4 – 0.6 s, 1.24 s and 1.6 – 2.0 s.

In order to verify if the retrieved reflected waves are real or not, we process the virtual source gathers with the purpose to obtain a time seismic section, which will be compared with the time seismic section obtained after the processing of active seismic data. The processing of the virtual-source gathers was done using the same frequency filter (11–36 Hz) and velocity model used in the processing of the active data. The passive and active seismic sections are displayed in Fig. 9, the passive seismic section in blue-red and the active seismic section in black-white with red corresponding to black. The spatial distance covered by the passive seismic section is about 50 m. By comparing the reflections seen on the passive and active seismic sections we notice a good correspondence in case of those which appear at 0.1 – 0.4 s, 1.05 – 1.15 s, 1.25 – 1.5 s, 1.6 – 2.0 s.

3.2. SI BY CROSS-CORRELATION ON THE PASSIVE DATA RECORDED IN 2011

In this section we present the SI results computed for the noise panels recorded on the NE line of the passive array used in the survey performed in 2011. The SI method is applied with the purpose to retrieve the body-wave reflections from the ambient noise. The input data to SI is represented by noise panels without dominant surface waves, like those displayed in Fig. 5c,d. The separation of the noise panels without surface waves from those with surface waves was done after the visual evaluation of the surface waves performed in the time domain.

As written above, the SI results were obtained in two steps, correlation and summation. The correlation was done for master trace at each geophone position along the NE line, from G1 to G48. The correlation panels obtained for master traces at G20-G25 contain zero traces, because the traces from these geophones are zero. Again, because the illumination of the passive array is not homogeneous, the summation of the causal and a-causal times was done following the approach presented in Ruigrok *et al.* (2011). We display in Fig. 10 examples of virtual-source gathers obtained for master trace at geophones G1, G10, G36 and G48. The remaining surface waves on the noise panels were retrieved after SI (Fig. 10c, d); the displayed virtual-source gathers show clear surface waves characterized by velocities ranging from 250 m/s to 400 m/s. The head waves were also retrieved after the SI by cross-correlation. They can be seen on the displayed gathers as linear events characterized by velocity of about 2350 m/s. The arrival time at maximum offset is about 0.05 s. These type of waves occur due to the action of distant sources. The body-wave reflections were also retrieved using SI. Unfortunately, their continuity on large offsets was interrupted by the remaining surface waves on the analized noise panels. In addition, the presence of six zero traces decreased the amplitude of the retrieved reflected waves.

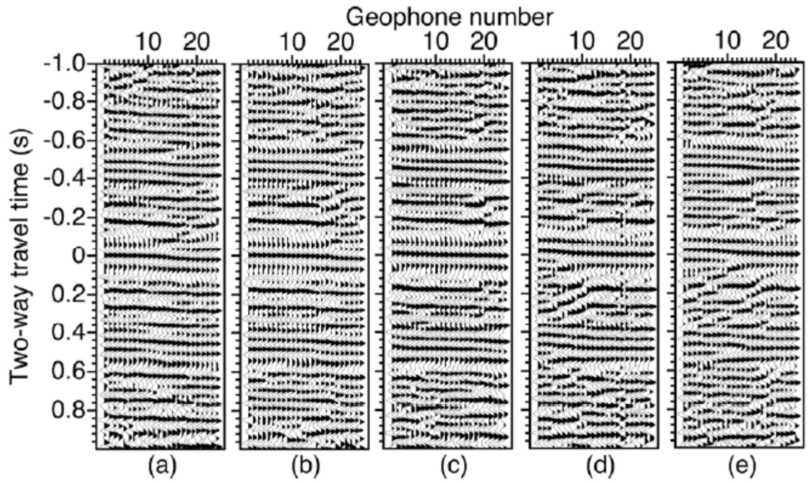

Fig. 7 – Summed correlation panels obtained for master trace at geophones (a) G1, (b) G6, (c) G12, (d) G18 and (e) G24; the noise panels were recorded on the NE line.

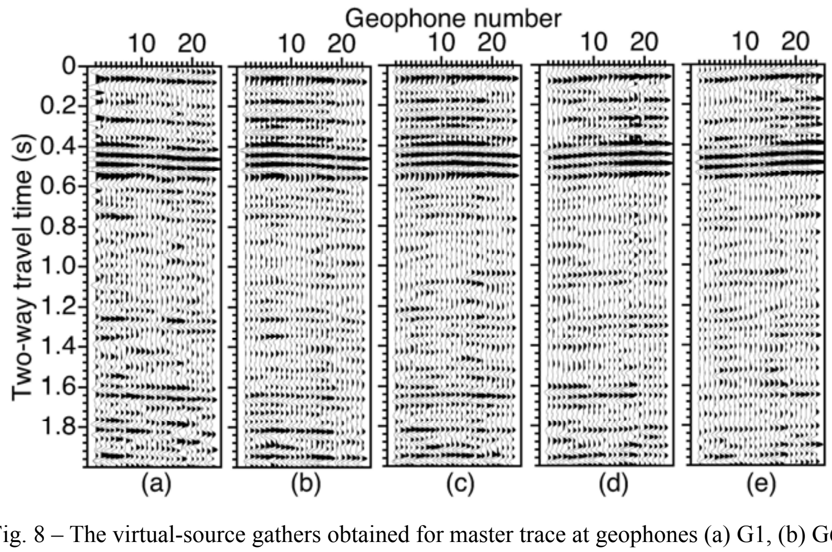

Fig. 8 – The virtual-source gathers obtained for master trace at geophones (a) G1, (b) G6, (c) G12, (d) G18 and (e) G24; the noise panels were recorded on the NE line.

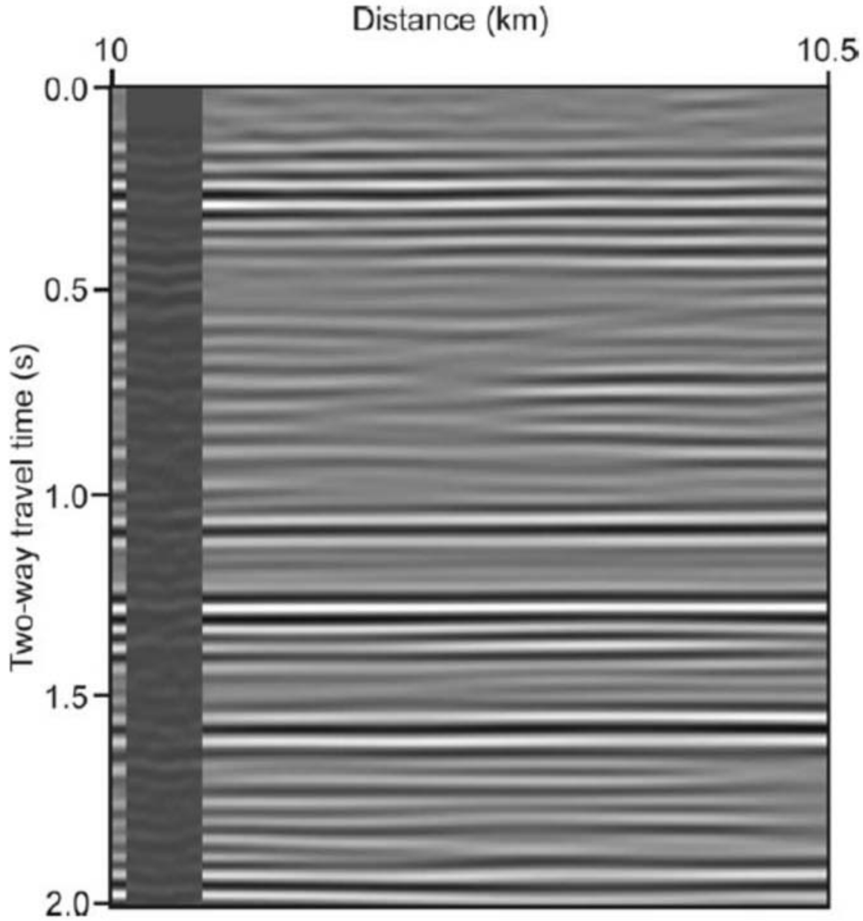

Fig. 9 – Passive seismic section (blue-red) overlaid on the active seismic section (black-white); red corresponds to black.

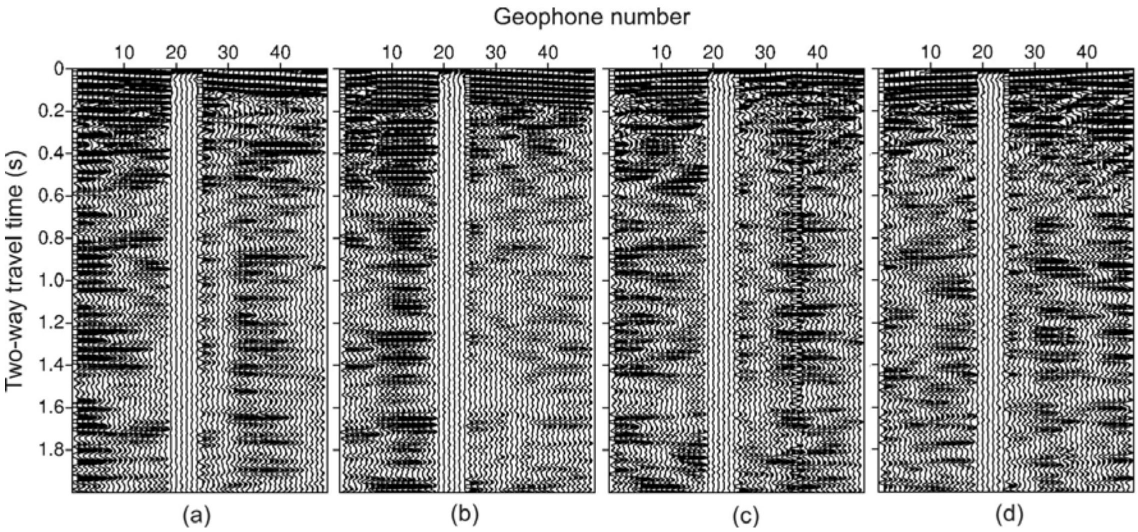

Fig. 10 – The virtual-source gathers obtained for master trace at geophones (a) G1, (b) G10, (c) G36 and (d) G48; the noise panels were recorded on the NE line.

In order to verify if the retrieved reflected waves are real or not, we processed the virtual-source gathers using the same flow/parameters like in case of data from 2009. The passive seismic section is displayed in Fig. 11b; the passive section (blue-red) is overlaid on the active section (black-white), red corresponds to black. For comparison, we display in Fig. 11a the passive section obtained after the processing of data recorded in 2009.

Looking at the passive and active seismic sections displayed in Fig. 11b, we notice a good correspondence between the retrieved reflections and those seen on the active seismic section on the time interval of 1.0–2.0 s. The remaining surface waves on the input passive data to SI affect the retrieval of the reflected waves; their continuity is interrupted by the presence of these noisy waves (Fig. 11b). In addition, the reflections retrieved from the noise recorded in 2011 are stronger in amplitude than those retrieved from the noise recorded in 2009. We expected this result after the analysis and comparison of the frequency spectra displayed in Fig. 6.

One way to retrieve clear reflections is to use array-forming in order to fill in the empty traces from the geophones G20-G25 and, at the same time, to attenuate the remaining surface waves on the analyzed panels.

4. SEISMIC INTERFEROMETRY WITH ARRAY-FORMING

Array-forming is a method used to attenuate the coherent noise seen on land seismic data. The array responses can be obtained in two ways, directly in the field or before the data processing using single-sensor recordings (Panea, 2007); the latter way gives better array responses because it allows a pre-processing of the single-sensor data, such as the application of static corrections to remove the effect of rough topography and near-surface velocity variations. Two parameters are important in array-forming, the spacing between the array elements (Δx_g) and the group interval, which is the spacing between the centers of two adjacent arrays (Δx_G). The size of Δx_g is chosen such that the remaining surface waves will not be spatially aliased, while the size of Δx_G is chosen such that the recorded reflected waves will not be affected by spatially aliasing. The formulas (2) and (3) are used to compute the optimum size of Δx_g and Δx_G.

$$k_{N,zg} = k_{\max,zg} = \frac{1}{\lambda_{\min,zg}} = \frac{1}{V_{\min,zg} T_{\min,zg}} = \frac{f_{\max,zg}}{V_{\min,zg}} = \frac{1}{2\Delta x_g} \quad (2)$$

where, $k_{N,zg}$ is the Nyquist wavenumber which allows the recording of surface waves without being spatially aliased, $\lambda_{min,zg}$ is the wavelength corresponding to the Nyquist wavenumber, $V_{min,zg}$, $T_{min,zg}$, $f_{max,zg}$ are the minimum apparent velocity, minimum period and maximum frequency which characterize the surface waves.

$$k_{N,s} = k_{\max,s} = \frac{1}{\lambda_{\min,s}} = \frac{1}{V_{\min,s} T_{\min,s}} = \frac{f_{\max,s}}{V_{\min,s}} = \frac{1}{2\Delta x_G} \quad (3)$$

where, $k_{N,s}$ is the Nyquist wavenumber which allows the recording of reflected waves without being spatially aliased, $\lambda_{min,s}$ is the wavelength corresponding to the Nyquist wavenumber, $V_{min,s}$, $T_{min,s}$, $f_{max,s}$ are the minimum apparent velocity, minimum period and maximum frequency which characterize the reflected waves.

In this section we use array-forming on noise panels without dominant surface waves selected after the visual evaluation of the coherent noise performed in the time domain. These panels were recorded on the NE line in the passive survey done in 2011. The array responses are computed in two steps: first, we sum a number of traces equal to the desired number of arrays elements, then, we resample the output of summing at the group interval (Panea, 2007). In case of our data, the spacing between array elements and group interval is the same (2.5 m) in order to preserve traces for SI method.

We display in Fig. 12a, b the responses of array-forming with 5 elements for one noise panel recorded on the NE and NW lines. The remaining surface waves are still clear and characterized by relative high amplitude. Also, the remaining non-coherent noise characterized by high amplitude is also present on the array responses. On the NW line, the remaining surface waves are not visible but they were not well attenuated after array-forming because of their hyperbolic shape, being waves generated by sources located outside the passive line.

The traces from G20-G25 contain seismic information after array-forming with 5 elements; this is an advantage of using array-forming on this dataset. Looking at the array responses displayed in the (f, k)-domain, we notice that the energy of the remaining surface waves is clear up to about 16 Hz (Fig. 13). The vertical white stripes seen on the (f, k)-amplitude spectrum indicate the position of the rejection notches from the array response (the rejection notches indicate the wavenumbers at which the amplitude spectrum of array response is zero).

Better surface waves attenuation is done for array-forming with 12 elements. We display in Fig. 12c, d the array responses for the same noise panel used in array-forming for 5 elements. By comparing the array responses for 5 and 12 elements displayed in the (t, x)-domain we notice that the remaining surface waves are weaker after array-forming with 12 elements. Unfortunately, the non-coherent noises appear, sometimes, as short horizontal events characterized by high amplitude and these events will be treated as reflected waves during SI. The amplitude corrections applied before SI will attenuate the high amplitude of this type of noise. The effect of array-forming with 12 elements on the surface waves is clear in the (f, k)-domain; the energy of the remaining surface waves on the frequency interval 0 – 16 Hz is much smaller after array-forming with 12 elements than after array-forming with 5 elements (Fig. 13).

Having the responses of array-forming with 12 elements as input data to SI, we compute the virtual-source gathers for master traces at the location of geophones G1 to G40. We display in Fig. 14 the virtual-source gathers for master trace at geophones G1 and G40 on the NE line. The effect of array-forming is clear on the SI results, the surface waves are not visible on the displayed virtual-source gathers. The head and reflected waves are retrieved using SI by cross-correlation. We do not compute the virtual-source gathers for the NW line because the retrieved reflected waves can be altered by the presence of the remaining surface waves after array-forming.

Looking at the SI results we can say that the retrieved reflected waves are more visible after array-forming and show better continuity comparing with that one of the reflected waves seen on the SI results obtained before array-forming (compare Figs. 10 and 14). There is a small time shift observed in the time of the retrieved reflected waves after array-forming between the geophones G18 and G19 and this is thought to be due to the presence of zero traces (Fig. 14).

The virtual-source gathers were processed using the same flow/parameters to obtain a passive seismic section. In Fig. 15b we display the passive seismic section (in blue-red) overlaid with the active seismic section (in black-white). By comparing the passive and active seismic sections, good correspondence is seen between the active reflected waves and the reflected waves retrieved from the ambient noise recorded in 2009 and 2011 which appear at 0.1–0.4 s, 1.25–1.4 s and 1.6–2.0 s (Fig. 15a,b). Clear reflections with high amplitude can be seen between 0.4–0.7 s on the passive seismic section displayed in Fig. 15b.

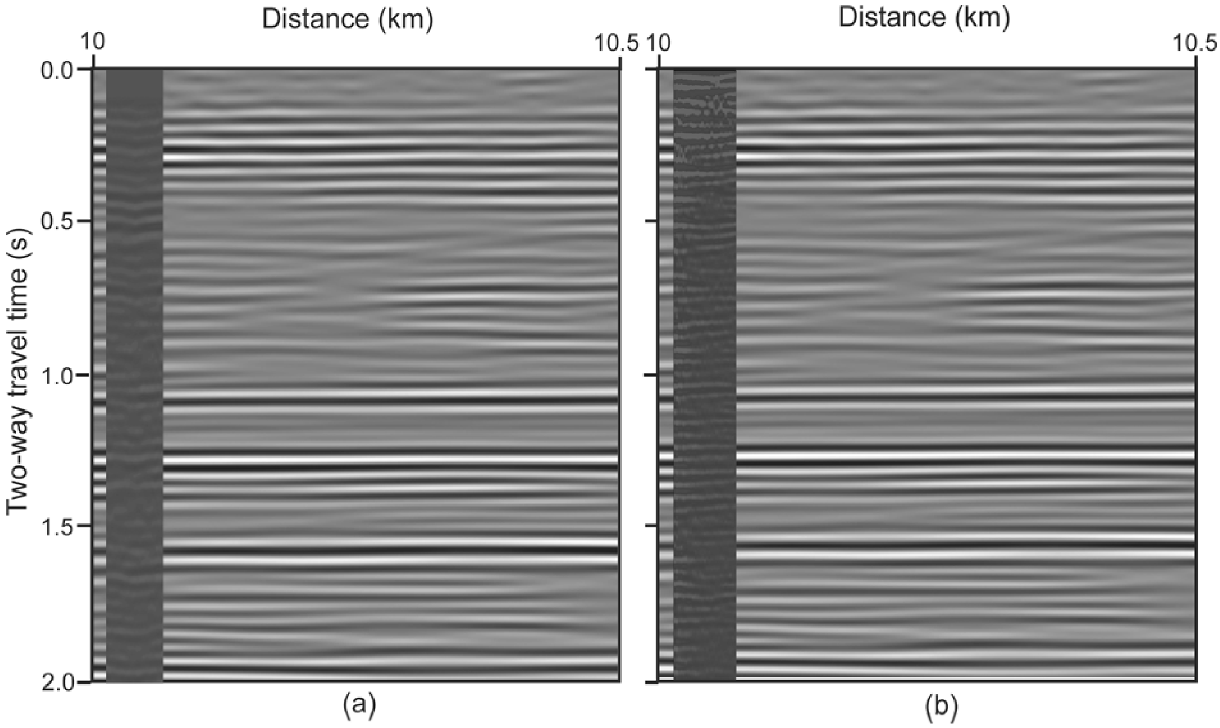

Fig. 11 – Passive seismic section (blue-red) overlaid on the active seismic section (black-white); red corresponds to black.

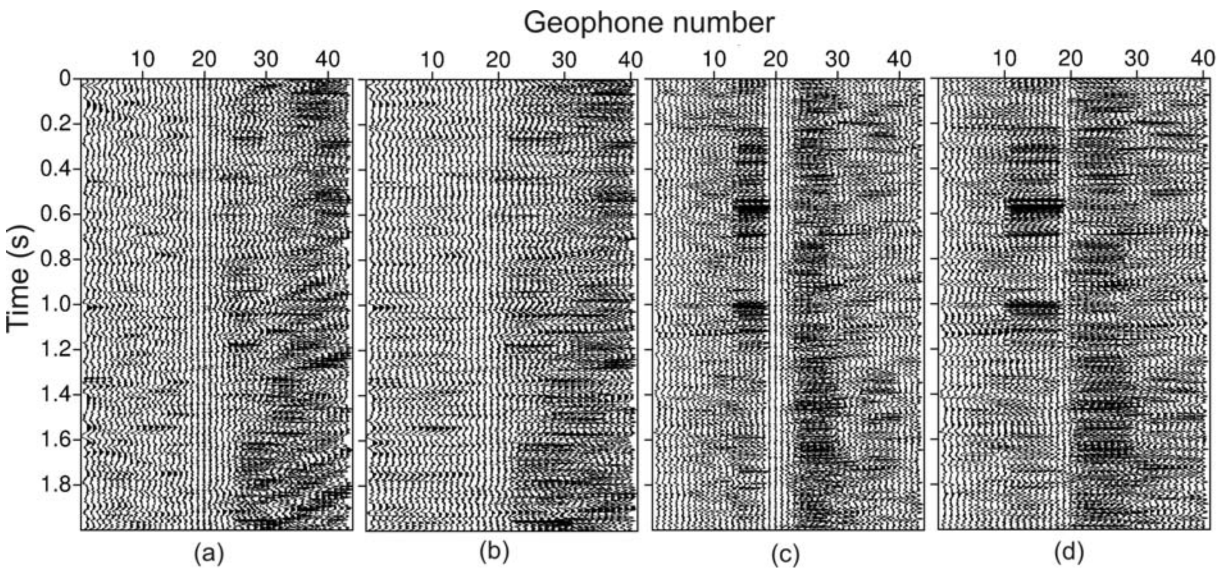

Fig. 12 – Ambient-noise panels displayed in the (t, x)-domain after array-forming with 5 elements on the NE line (a) and NW line (b) and with 12 elements on the NE line (c) and NW line (d).

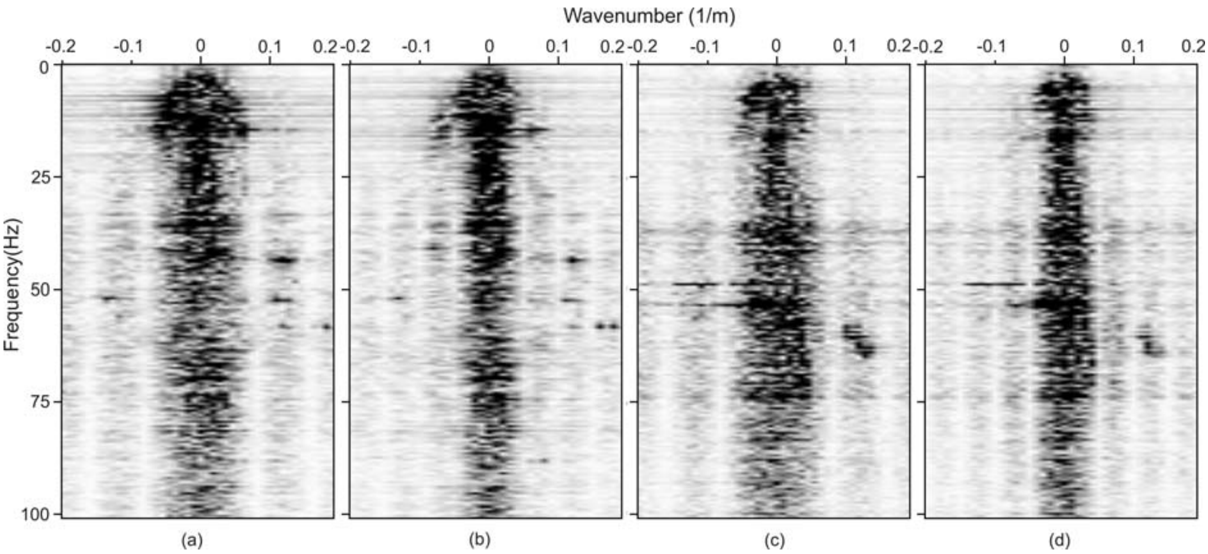

Fig. 13 – Ambient-noise panels displayed in the (f, k)-domain after array-forming with 5 elements on the NE line (a) and NW line (b) and with 12 elements on the NE line (c) and NW line (d).

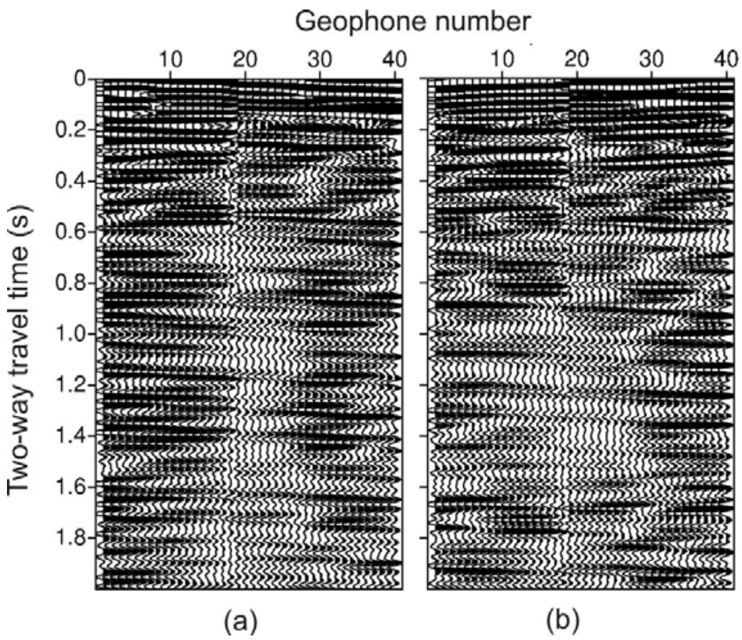

Fig. 14 – The virtual-source gathers obtained after array-forming for master traces at geophones (a) G1 and (b) G40; the noise panels were recorded on the NE line.

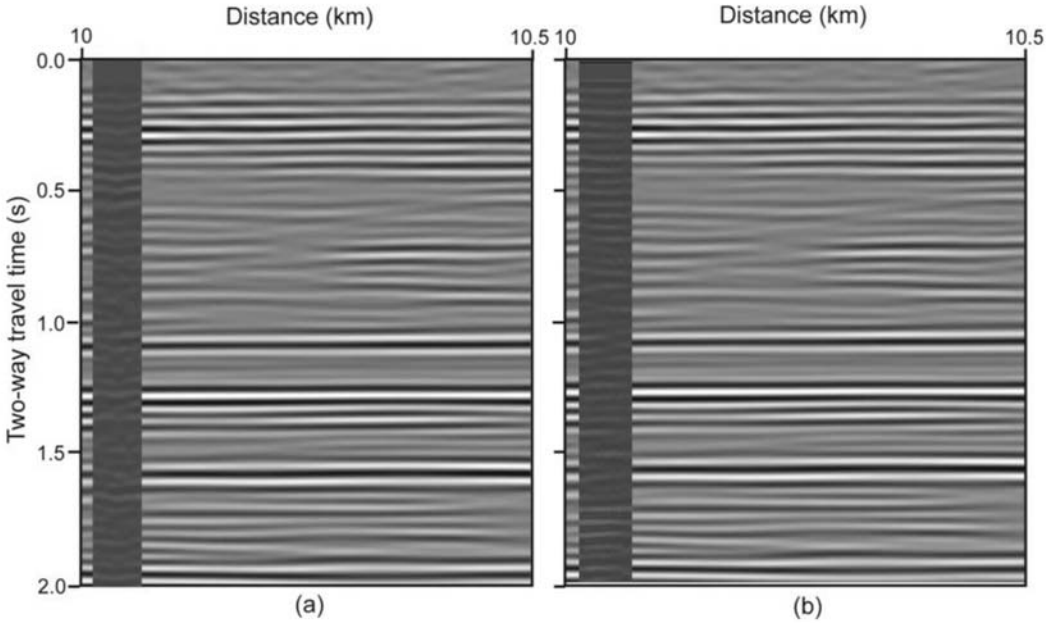

Fig. 15 – Passive seismic sections obtained for the passive survey performed in (a) 2009 and (b) 2011 after array-forming applied on the ambient-noise panels recorded on the NE line; the active seismic section is displayed in black-white, red corresponds to black.

5. CONCLUSIONS

We applied Seismic Interferometry (SI) by cross-correlation on two different ambient-noise dataset recorded in 2009 and 2011 in the Mizil area, Romania. The spectral analysis of the recorded ambient noise showed that the surface waves are dominant on the passive data recorded in 2009, while the body-wave reflected waves present on the noise recorded in 2011 are characterized by larger amplitude than those present on the data from 2009. Therefore, we expected to retrieve clearer reflections from the noise recorded in 2011.

In case of dataset from 2009, the SI was applied only on ambient-noise panels without dominant surface waves. The separation of panels with and without dominant surface waves was done after the visual evaluation of these noisy waves in the time domain. The retrieved reflections correlate well with those seen on the active seismic survey performed in the vicinity of the passive seismic survey. Clearer reflections characterized by higher amplitude were obtained after the processing of the SI results based on the noise panels without dominant surface waves recorded in 2011. In addition, array-forming was used to attenuate the remaining surface waves from the selected noise panels helping, in this way, for a better retrieval of the reflected waves from the analyzed noise.

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