

Broadband, short-period or geophone nodes? Quality assessment of Passive Seismic signals acquired during the Maupasacq experiment

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Introduction

Passive Seismic is a broad term, incorporating various techniques and methodologies, which all exploit some part of the seismic signal that naturally exists or occurs in the Earth's subsurface. This signal may differ significantly in the form and/or the provenance (e.g. earthquakes, ambient seismic noise, etc.), as well as the frequency content and, subsequently, the part of the subspace on which it may carry useful information.

People involved in Passive Seismic often encounter the question: 'What type of instrument is suitable for a passive seismic survey?'. Passive Seismic instrumentation usually consists of three-component seismic sensors, which mainly differ in the frequency range they are able to record (broad-band, short-period or geophone nodes). Having its roots in seismology, where traditionally broadband stations have been used for decades, but heading towards exploration, where instrumentation has to be cost-efficient and easy to handle in order to permit the adaptation at a reservoir scale, Passive Seismic instrumentation still tries to strike a balance between cost and bandwidth.

Having in mind the variability of Passive Seismic methodologies and instruments, the Maupasacq experiment, a large passive seismic survey, has been launched in the Mauleon basin, SW France. The scope of the experiment was to image the area of interest by jointly applying a number of passive seismic methodologies, each one contributing to the final image with a different piece of useful information. The area of interest was carefully selected as, on one hand, the Mauleon basin consists of a former Cretaceous hyper-extended rift, inverted during pyrenean orogeny and, on the other hand, it provides a means of evaluating the results acquired, as an abundance of geological and geophysical data already exist in the area.

In this context, a dense seismic network of 417 three-component (3C) sensors was deployed in an area of approximately 1500 km². In addition to those, 24 peripheral stations have also been installed in an outer ring, extending the survey area to 3500 km². The network was continuously operating for a recording period of six months (from April to October 2017) and consisted of

three different types of seismic stations: 190 geophone nodes (SG-10 3C SERCEL), 197 3C Seismotech short-period stations and 54 broadband stations (Guralp CMG40, Trillium Compact and Trillium 120). This fact, apart from imposing the difficulty of jointly processing data recorded by different types of instruments, having to deal with different instrument responses and data formats, it also permitted an evaluation of the suitability of each instrument type for each one of the passive seismic methodologies applied.

This evaluation was performed in the course of an initial quality control (QC) procedure of the acquired dataset, permitting the extraction of valuable conclusions on the performance of different types of instruments, operating in the same area, during the same period of time. The main aspects that were evaluated were the acquired signal itself, as well as the frequency content of the recordings, in various circumstances (i.e. the occurrence of a local earthquake or a teleseismic event). Besides, it has been observed that the energy of a passive seismic source seems to play a big role in the definition of the 'real' recording limits of each type of instrument. As a result, the QC procedure, which will be described in the following sections, took into account all types of passive seismic signals that would be exploited in the context of the Maupasacq experiment (seismic noise, local earthquakes, teleseismic events), in order to assess the suitability of each type of instrument.

Data quality control procedure

The Data Quality Control (QC) is a standard procedure that is applied, in order to check the quality of the signal acquired by an installed seismological station, permitting the delineation of possible problems that may be related either to the station's installation, or to local site conditions.

A standard QC procedure of a Passive Seismic dataset usually consists of three distinct steps: a) a noise level evaluation test (NLET), b) the visualization of the frequency content of the recorded seismograms, as a function of time, through spectrograms and c) the examination of the signal of specific recordings. The first two steps are directly related to the frequency content of the acquired dataset and are applied by gathering and analysing

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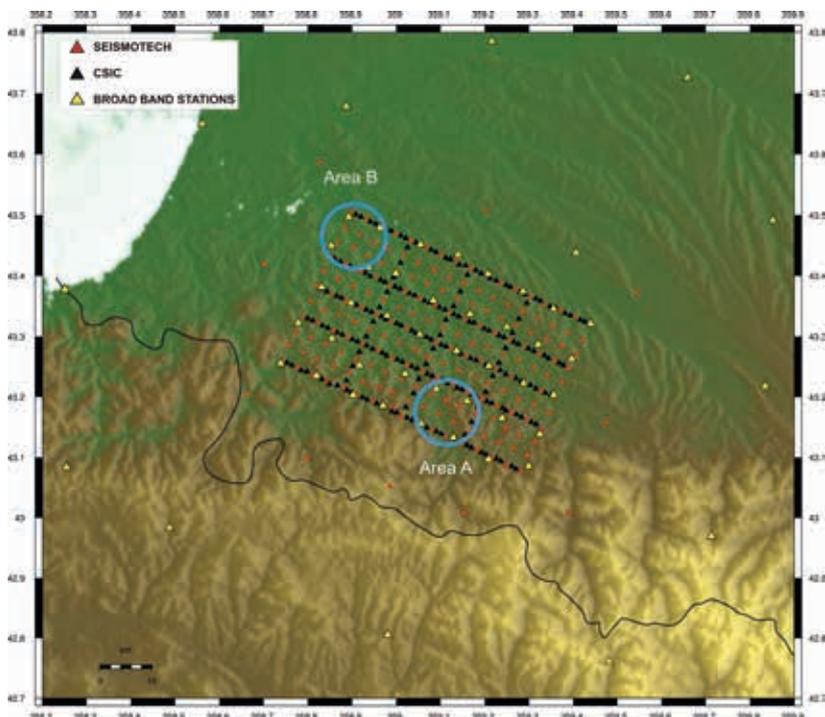


Figure 1 Map of the study area and the installed seismic stations. Red triangles correspond to short-period recorders, black triangles to geophone nodes, while yellow triangles correspond to broadband stations. The areas from which seismic stations of all types were selected, are depicted with cyan circles.

data, corresponding to a specific number of days of the recording period, from each seismic station.

In the context of the Maupasacq passive seismic survey, the QC procedure was adopted for all three different types of instruments that were deployed (geophone nodes, short-period and broadband stations). It is essential to mention that the specific characteristics (i.e. instrument response curve, sampling frequency, etc.) of each one of the three different types of seismic stations had to be taken into consideration, during the application of the QC analysis (e.g. sampling frequency of 100 Hz for the short-period and broad-band stations and 250 Hz for the geophone nodes), as they significantly affect the QC procedure.

The Maupasacq passive seismic network is presented in Figure 1. It consists of 190 geophone nodes (black triangles), deployed along eight profiles, spread along the survey area, with inter-station distances of 1 km, 187 short-period stations (red triangles), deployed at a regular grid of 3x3 km, covering the totality of the survey area and 40 broadband stations (yellow triangles) spread across the survey area. Two outer rings of stations have also been deployed around the survey area (10 short-period and 14 broad-band), in order to better control the local seismicity location. The first one is equipped with short-period stations and installed at about 30-40km from the centre of the network, while the second one is instrumented with broadband stations and located at approximately 25 km farther away.

Even though the QC procedure was applied for the totality of the installed stations, two areas, including seismic stations from each type of instrumentation, were selected to be presented in the context of this work. These areas, located in the north-western and the southern part of the network, respectively, are noted by cyan circles in Figure 1. The selection criterion of these two areas was based on an attempt to identify locations with different site conditions (i.e. noise level, proximity to the mountain), within the same network.

Noise Level Evaluation Test

As the proper operation of a seismic station does not only depend on its installation, but also on local site conditions, the most important being its noise level, a Noise Level Evaluation Test (NLET) is the first step of the QC procedure. Once the Maupasacq data were available, the full dataset recorded by each station was isolated, in order to estimate each site's noise level. In particular, the dataset corresponding to recordings from 1 April until 30 September, 2017, were analysed, using ObsPy, a Python toolbox for seismology (Beyreuther et al., 2010). The analysis followed a standard procedure, commonly applied in seismology, based on the methodology described by McNamara et al. (2004).

According to this, the continuous seismic signals were initially corrected for the instrument response. This was very important since the effect of the three different types of instruments had to

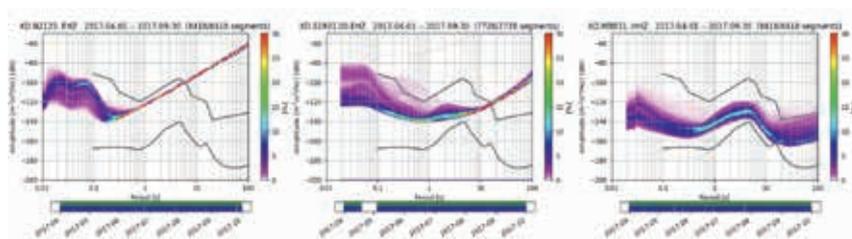


Figure 2 Results obtained by the Noise Level Evaluation Test, applied on three different types of instruments, installed in Area A. The left plot corresponds to the geophone node, the middle plot to the short-period station, while the right plot corresponds to the broadband station.

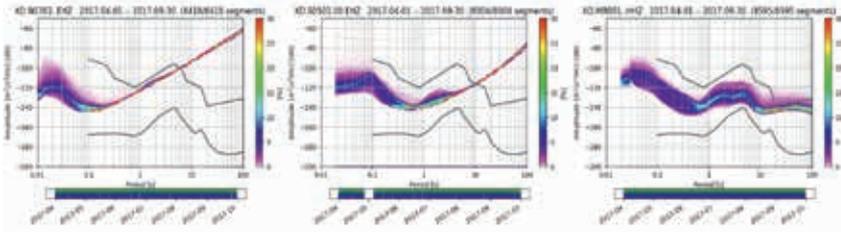


Figure 3 Results obtained by the Noise Level Evaluation Test, applied on three different types of instruments, installed in Area B. The left plot corresponds to the geophone node, the middle plot to the short-period station, while the right plot corresponds to the broadband station.

be removed from the acquired data. The corrected signals were then segmented to 30-minute time series, overlapping by 50%. Overlapping segments were used to reduce variance in the Power Spectral Density (PSD) estimation. The data were pre-processed, since they were subjected to de-mean, de-trend and a cosine tapering procedure. In the specific approach, earthquakes and system transients did not have to be removed because they are generally low-probability occurrences. The next step of the above-mentioned methodology consisted of the estimation of the probability density functions (PDFs), through PSD calculations, in order to evaluate the full range of noise at each given seismic station. For this purpose, the direct Fourier Transform (Cooley and Tukey, 1965) has been applied, permitting the PSD computation, via a finite-range Fast Fourier Transform (FFT) of the original data. The calculated PSDs have then been plotted as a PDF for each component (vertical, North-South, East-West) of a given station (Peterson's curves).

As this methodology is mainly applied in the context of seismological studies, it is designed to allow the estimation of noise levels at a broad range of frequencies, varying from 0.01 Hz (100 s period) up to 100 Hz (0.01 s period). Even though this frequency range is adapted for a broad band of stations and despite the fact that the natural frequency of the short-period sensors was 4.5 Hz ('dragged' down to 1 Hz using the force-balance principle), while that of the geophone nodes was 10 Hz, respectively, the procedure was applied to all three different types of instruments. The limits assumed for assessing the quality of each station are standard noise models (New High Noise Model [NHNM] and New Low Noise Model [NLNM]; Peterson, 1993).

The following figures (Figures 2 and 3) illustrate the NLET outcome for each type of seismic station at the selected areas A and B. The station name, as well as the acquisition time period during which the aforementioned analysis was applied, are noted in the title of each plot; x-axis and y-axis refer to period in logarithmic scale and spectral amplitude, respectively, while the colour-scale corresponds to probability percentage values.

Area A

The first area, which was selected for data QC analysis, lies in the southern part of the Maupasacq network, as shown in Figure 1. This area is located at the foothills of the Pyrenees mountain range, close to seismically active structures. Three different types of stations were selected from Area A, a short-period station (S1931), a geophone node (N2135) and a broad-band station (MBB31). Figure 2 illustrates the results of the above-mentioned analysis (NLET) applied on the totality of the data recorded by each one of the three stations. The left plot corresponds to the geophone node, the middle one to the short-period station, while the right plot corresponds to the broadband station.

Area B

The second area, which was selected for data QC analysis, is located in the north-western part of the Maupasacq network (Figure 1). Similarly to Area A, three stations of different type were selected from Area B, a short-period station (S0501), a geophone node (N0702) and a broadband station (MBB01). The results of the NLET, applied on the totality of the data recorded by the above-mentioned stations, during the whole acquisition period, are depicted in Figure 3. In this case, again, the left plot corresponds to the short-period station, the middle one to the geophone node, while the right plot corresponds to the broadband station.

The results obtained by application of the NLET on data acquired by different stations, installed in both areas, provide us a means of assessing the capability of each instrument to record specific frequency ranges. According to those results, short-period instruments appear to be sensitive to periods up to 7-8 seconds, geophone nodes up to ~3 seconds, while broadband stations are sensitive to periods greater than 20 seconds, as it was expected. This means that instruments of different types have the capacity to record noise down to a certain frequency limit, which is constrained, but not strictly defined by the technical characteristics of each instrument (~0.35 Hz for geophone nodes, ~0.15 Hz for short-period stations and less than 0.05 Hz for broadband stations).

Moreover, it must be mentioned that noise curves corresponding to area A are characterized by greater amplitudes at lower periods (< 0.1 s) than those calculated using data recorded by the stations located in area B. Interpretation of the observed noise energy differences between the two sites is beyond the scope of the present work. However, the existence of higher noise energy in Area A, especially concerning the low frequencies (Figures 2 and 3), provides an indication that the ability of an instrument to record low frequencies does not depend only on its technical characteristics, but also on the amplitude of the passive seismic signal itself. Observing Figures 2 and 3, it becomes obvious that the low-frequency recording limits of each instrument are shifted towards lower frequencies in the case of Area A.

Spectrograms

In general, a spectrogram is a common way to illustrate the frequency content of a seismogram, as it changes with time. More specifically, the frequency spectrum of a seismogram is calculated for a specific frequency range and a predefined time interval. The spectral amplitude values are colour-scaled and, for each frequency, they are displayed as horizontal coloured lines, representing the differences in shaking intensity. By plotting these horizontal lines adjacent to one another, for the desired time period, a time sequence of the frequency spectrum can be formed.

In the case of the Maupasacq experiment, a 30-day sample dataset, from the 1 to 31 July, 2017, was extracted from the com-

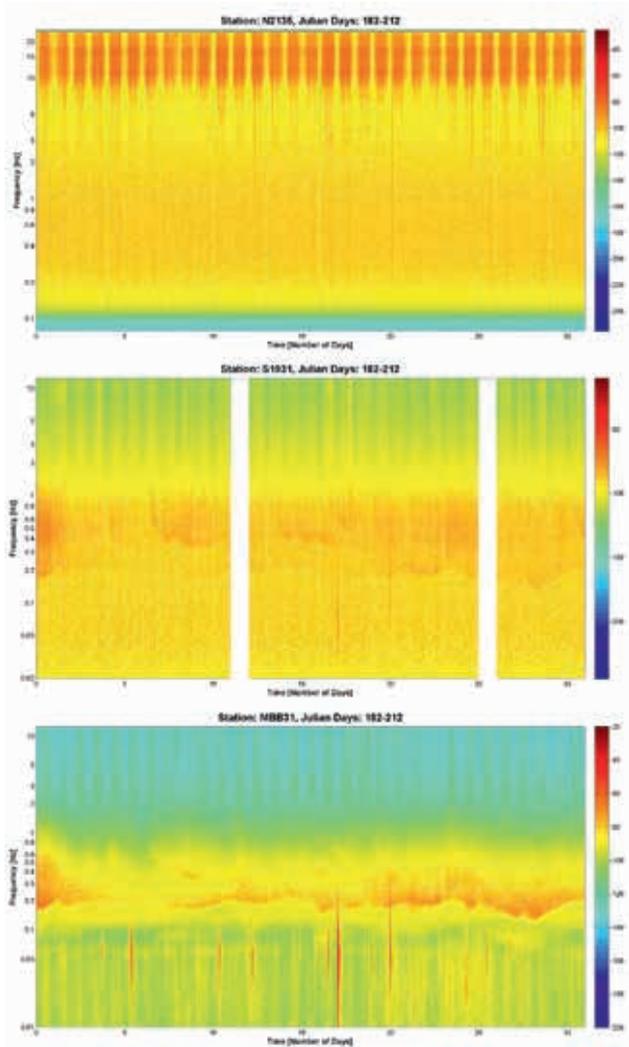


Figure 4 Spectrograms calculated using data acquired by stations located in Area A. The upper plot corresponds to the geophone node, the middle plot to the short-period station, while the lower plot corresponds to the broadband station.

plete dataset for each selected station (the same three different types of stations for areas A and B). These individual datasets were corrected for the instrument response and decimated to 25 Hz, in the cases of short period and broadband stations, and to 50 Hz in the case of the geophone nodes, in order to increase the computational speed, preserving the useful frequency content of data at the same time. The difference in decimation for the different types of instruments was owing to the fact that the sampling frequency of geophone nodes was 250 Hz, while short-period and broadband stations were recording at 100 Hz.

For the estimation of the FFT, a sliding window of 2048 samples was applied, while the time interval used by the algorithm in order to section the initial data was of 15 minutes, with an overlap of 50%. The results obtained by the above-mentioned analysis, regarding stations located in areas A and B are presented in Figures 4 and 5, respectively.

Observing Figures 4 and 5, it becomes obvious that the results obtained by the spectrogram calculations are in accordance with the respective outcome of the Noise Level Evaluation Test. Changes in cultural activity for higher frequencies between day and night, as well as the differences in energy at frequencies greater than 5 Hz,

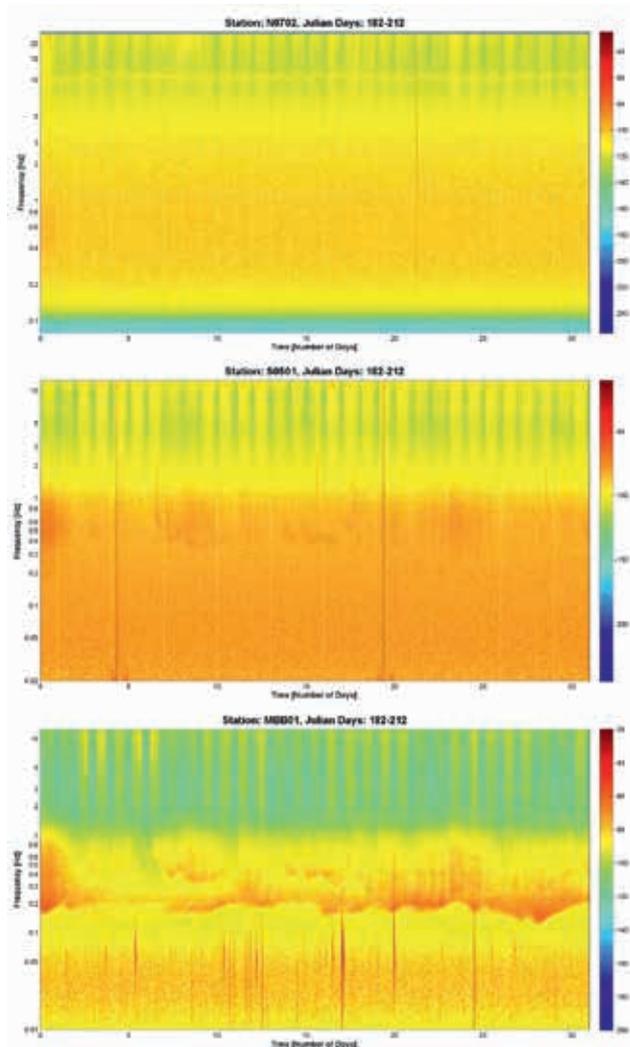


Figure 5 Spectrograms calculated using data acquired by stations located in Area B. The upper plot corresponds to the geophone node, the middle plot to the short-period station, while the lower plot corresponds to the broad-band station.

between working and non-working days, are clearly visible in the spectrograms of all types of instruments. Moreover, low-frequency ambient noise energy in the frequency band around the secondary microseism peak (~7 s), mostly generated in the ocean by the interaction of the oceanic gravity waves (e.g. Longuet-Higgins, 1950), can be clearly identified in the spectrograms of the broadband stations and is still visible, at a more limited extent, in the spectrograms of the short period stations, while in the case of the geophone nodes, the above-mentioned energy is totally absent.

Additionally, it has been mentioned in the previous section that the Peterson curves corresponding to area A appeared to have greater amplitudes at higher frequencies (>10 Hz) than the ones calculated for the stations located in area B. This phenomenon can only be observed in the spectrograms calculated by data obtained by geophone nodes (upper plots), not being present in either the short period (middle plots) or the broadband (bottom plots) recordings. This is owing to the downsampling procedure (25 Hz for short-period and broadband stations and 50 Hz for geophone nodes) that took place prior to the spectrogram calculation, limiting the short-period and broadband stations' visualization to frequencies up to 12.5 Hz.

Event recordings

During the Maupasacq experiment, a total number of 1624 local events were recorded by the installed seismic network. These events were located within or at a very close distance from the Maupasacq network, serving as ‘sources’ for Local Earthquake Tomography. An example of such a local event that was automatically detected the 4 August, 2017, 17:25 GMT is illustrated in Figure 6. The lower part of the plot (stations 1 to 197) depicts signals recorded by the short-period recorders, while the upper part (stations 301 to 490) shows the respective signals recorded by geophone nodes.

Figure 7 illustrates the raw signals of the above-mentioned local event, as it has been recorded by the short-period station and the geophone nodes that were used as example for Area A (S1931 and N2132). No instrument response correction has been applied on the signals. It is noteworthy that local events were adequately recorded by all types of stations (Figures 6 and 7), thus, in the case of Local Earthquake Tomography applications, any type of passive seismic instrument could be deployed.

Another issue that has to be discussed is how the different types of instruments are affected by the existence of high-energy, low-frequency signals (i.e. teleseismic events). A characteristic example is the Mw6.4, Kos island (Greece) earthquake, which occurred on 20 July, 2017, and was recorded by the Maupasacq network. This teleseismic event had an epicentral distance of 2500 km (calculated from the centre of the network) and a frequency content ranging from 2 up to 40 seconds (0.025 up to 0.5 Hz). In order to evaluate the capability of the different types

of instruments to record low-frequency, high-energy signals, three examples of the earthquake’s signal, as it was recorded by the installed stations, are illustrated in Figure 8. In order to proceed to a fair comparison of each station’s performance, each instrument’s response was removed, using corner frequencies at 0.1 Hz (Figure 8A), 0.05 Hz (Figure 8B) and 0.033 Hz (Figure 8C). A broadband station was considered as the reference instrument that was used for assessing the performance of the short-period stations and the geophone nodes.

Figure 8A depicts the Kos island earthquake, as this was recorded by a geophone node (upper plot), a short-period station (middle plot) and a broadband station (bottom plot). The recorded signals have endured instrument correction with a corner frequency at 0.1 Hz (10 s) and it is evident that both instruments manage to highlight the useful information. In the cases of instrument correction, using corner frequencies at 0.05 and 0.033 Hz, the geophone node fails to designate the propagating low-frequency energy, in opposition to the short-period station, which still performs adequately well, as it is illustrated in Figures 8B and 8C, respectively. Taking into account the aforementioned observations, one can easily understand that in the case of the existence of a low-frequency signal, characterized by a significant amount of energy (e.g. teleseismic event), it can be sufficiently recorded by both short-period instruments and geophone nodes, even though frequency analysis (e.g. spectrograms) insinuate that these types of instruments do not have the ability to record frequencies below 0.15 and 0.35 Hz, respectively.

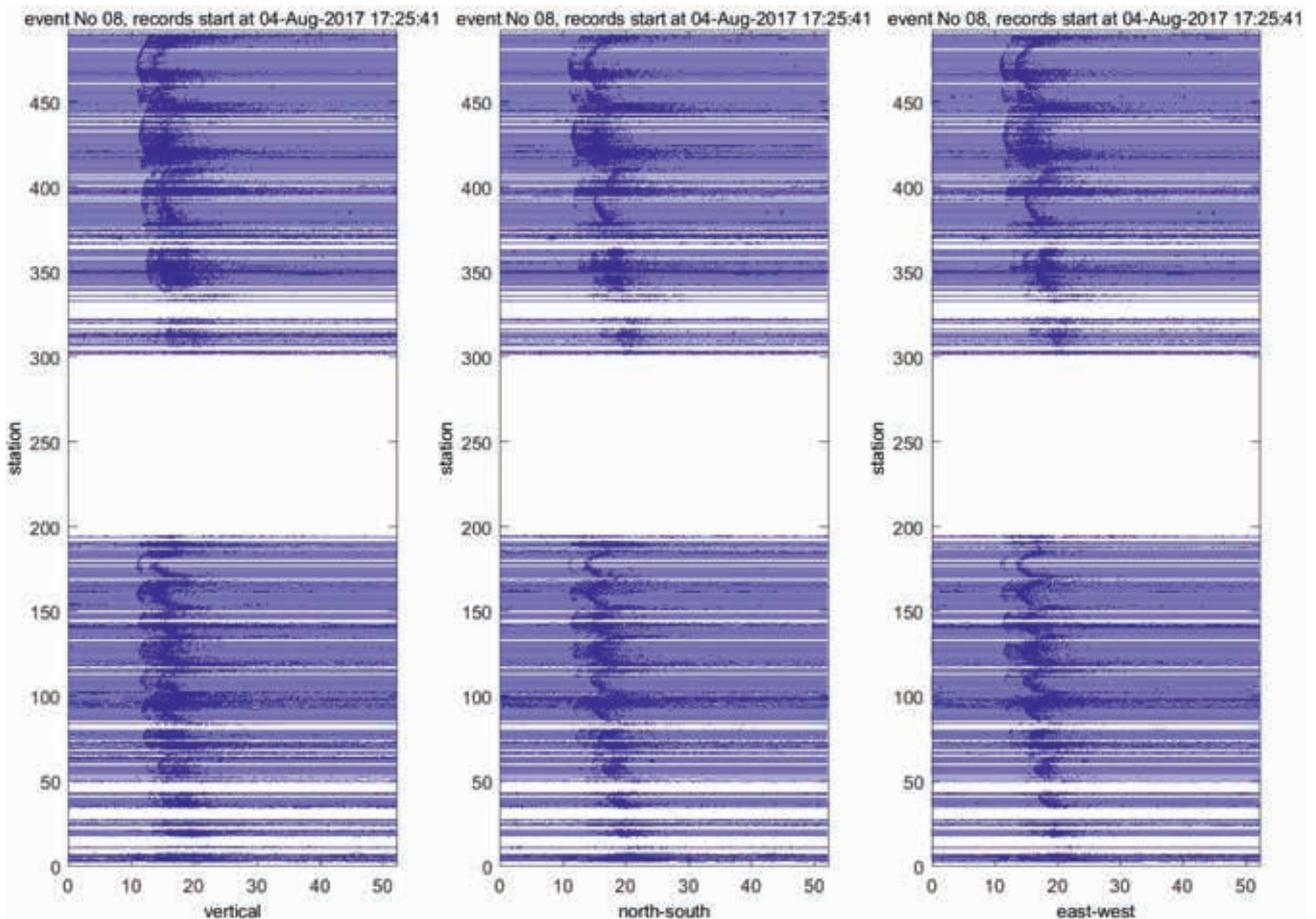


Figure 6 Example of a local event, as it was recorded by short-period stations (lower part, stations 1-197) and geophone nodes (upper part, stations 301-490).

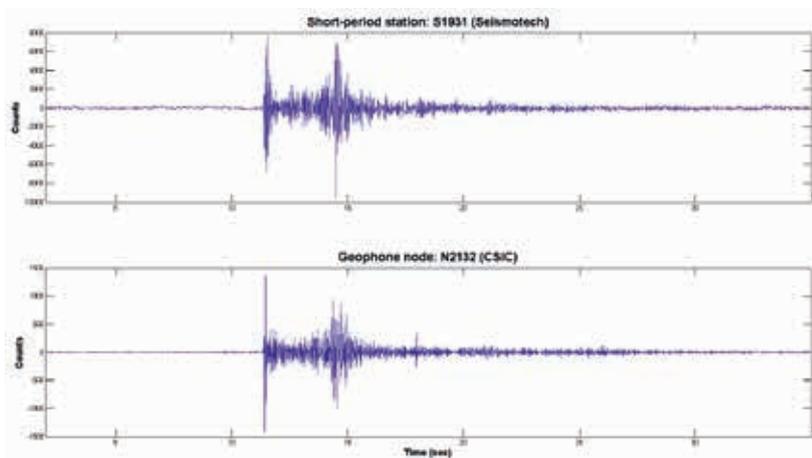


Figure 7 Example of the recordings of a short-period station (upper plot) and a geophone node (bottom plot) of the local event that was automatically detected in August, 2017.

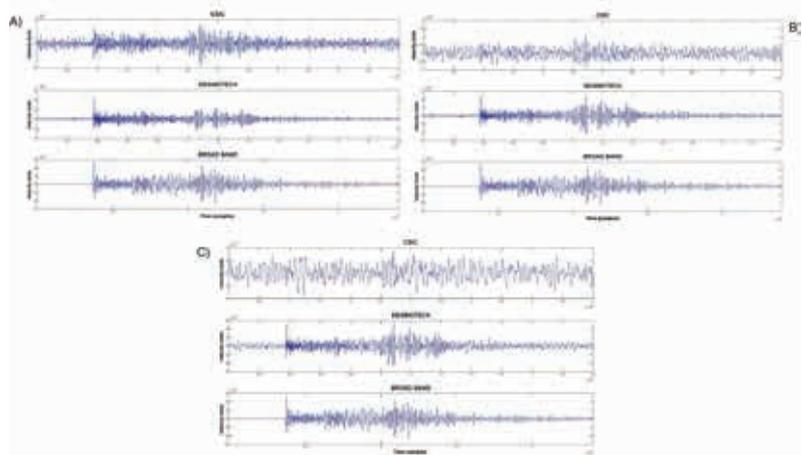


Figure 8 Examples of the Kos island earthquake, as this latter was recorded by the different types of instrumentation. Plot A illustrates the signal of the teleseismic event, after instrument correction with a corner frequency at 0.1 Hz (10 s), plot B illustrates the same signal, after instrument correction with a corner frequency at 0.05 Hz (20 s), while in plot C the signal had endured instrument correction with a corner frequency at 0.033 Hz (30 s).

Conclusions

The Maupasacq experiment provided a great opportunity to test Passive Seismic methodologies and instrumentation, at all levels. Having a large Passive Seismic dataset (six months of continuous recordings), acquired using three different types of instruments, permitted the assessment of the advantages and limitations of each one, both in terms of operational facility and in terms of quality of the acquired seismic signals.

For anyone involved in passive seismic acquisition, it is obvious that operationally geophone nodes, followed by short-period stations, are much simpler to handle and deploy than the traditional seismological broadband instruments. Moreover, these two types of instruments are significantly cheaper than broadband sensors since an instrument's cost largely depends on the natural frequency of the sensor. On the other hand, the performance of a broadband sensor is undoubtedly not comparable to any other type of passive seismic instrument.

Taking all these facts into account, an effort has been made to assess the adequacy of the quality of the acquired signal for each type of instrument in the context of each passive seismic methodology that was planned to be applied. This was performed by applying a quality control procedure on the acquired data.

According to the results of this quality assessment, any type of instrument would be suitable for launching a local earthquake tomography study. However, in the case of an ambient noise tomography study, targeting areas at a deep level and having to exploit low frequencies, or a methodology involving full-wave-

form inversion, geophone nodes seem to have a limitation on the lowest frequencies that can be correctly recorded, even in cases where the low-frequency signals are characterized by significant energy, while short-period sensors seem to manage to adequately record exploitable signals. This has been confirmed both by using frequency analysis techniques, such as the NLET or the spectrograms, and by comparison of the recorded signals.

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