THE DETECTION OF WEAK EARTHQUAKES IN THE WESTERN BOHEMIAN SWARM AREA THROUGH THE DEPLOYMENT OF SEISMIC ARRAYS

Jaroslav ŠTRUNC* and Milan BROŽ

Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, v.v.i., V Holešovičkách 41, 182 09 Prague, Czech Republic
**Corresponding author's e-mail* strunc@irsm.cas.cz

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ABSTRACT
The NKCA and KVCA small-aperture (~ 90 m) seismic arrays in western Bohemia represent the second deployment of this type in the Czech Republic. The arrays have a regular triangular geometric configuration with high gain three-component seismographs in each corner of the triangle. This allows very weak local earthquakes to be detected with a high degree of precision and, thereby, substantially enhances the results of the pre-existing local seismic network (WEBNET). This paper reports on the pilot measurement period. It summarises the final configuration of the arrays and compares the derived results. The measured data have been analysed using the DP/EP system developed by NORSAR. This incorporates several array techniques such as beamforming, *f-k analysis*, and the cross-correlation method. It has been shown that during the study period, the levels of seismic activity recorded by the seismic arrays were up to fifteen times greater than the levels recorded by the pre-existing seismic network.

KEYWORDS weak earthquakes, seismic array, small-aperture, beamforming, f-k analysis, cross-correlation

1. INTRODUCTION

A seismic array is a geometric configuration of seismographs within a certain region. The spacing of sensors can range from tens of meters to hundreds of kilometres. The size of an array, its aperture, is defined by the largest horizontal distance between a pair of sensors. We are going to analyse the data from array deployments in the western Bohemia those are the second and third array placements after the first array, OSTC, in the eastern Bohemia (Brož et al., 2006), in the further text.

The first seismic array experiments were performed almost sixty years ago during the 1950s. Numerous geometric configurations have been deployed since that time. These configurations have, in general, developed away from orthogonal oriented lines towards concentric circles or grids. Within any given array, one site acts as the reference point with all other stations situated relative to that reference point. The most famous seismic arrays are ARCES, NORES, and NORSAR in Norway; GERES and Gräfenberg in Germany; Yellowknife and EKA in the United Kingdom; and Warramunga in Australia. The largest seismic array in the world is LASA in the USA. This array has an aperture of up to 200 km and comprises more than 500 seismographs. It has already been operating for more than thirty years (Schweitzer et al., 2002).

A seismic array forms a special type of seismic network that can be constructed from one- or three-component seismographs. However, an array is better able to detect and characterise signals from earthquakes or explosions than a single three-component station. Therefore, seismic arrays are generally deployed for a specific reason such as to monitor a nuclear test area or to monitor an important source of natural earthquakes. The principle differences between a seismic array and a seismic network are to be found during the process of data analysis. From an array, techniques such as *beamforming* enable the signal-to-noise ratio to be increased while *f-k analysis* enables the power distribution to be calculated and the approach direction to be defined. Nonetheless, common methods such as LTA/STA detectors and filtering are also applied (Schweitzer et al., 2002). The most important prerequisite for successful data analysis relates to the accurate timing of an event. Each site must be synchronised precisely so that exact differences in the signal arrival times are recorded.

2. WEBNET: A UNIQUE NATURAL LABORATORY

An earthquake swarm area occurs in the western part of the Czech Republic near its border with Germany. Many events occur beneath the village of Nový Kostel at depths of between 8 to 11 km. Several earthquake swarm episodes have been identified, such as those in, for example, 1903, 1908, 1985/86, and 2000. The most recent, in autumn 2008, was the first

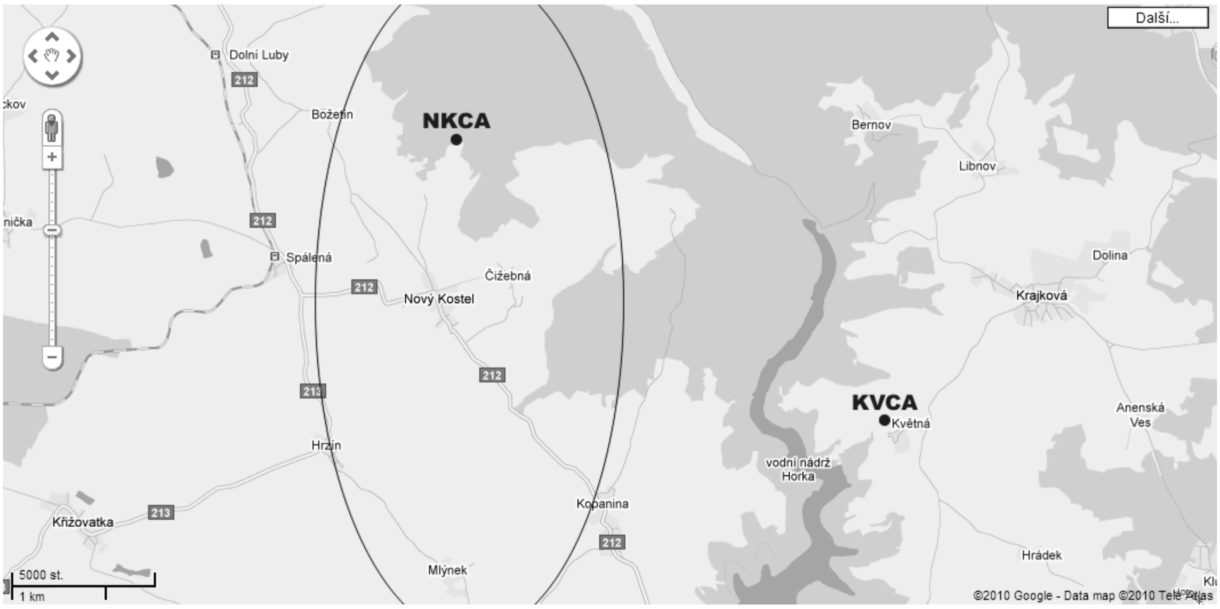

Fig. 1 Location of the seismic arrays, NKCA and KVCA. The ellipse marks the epicentral area.

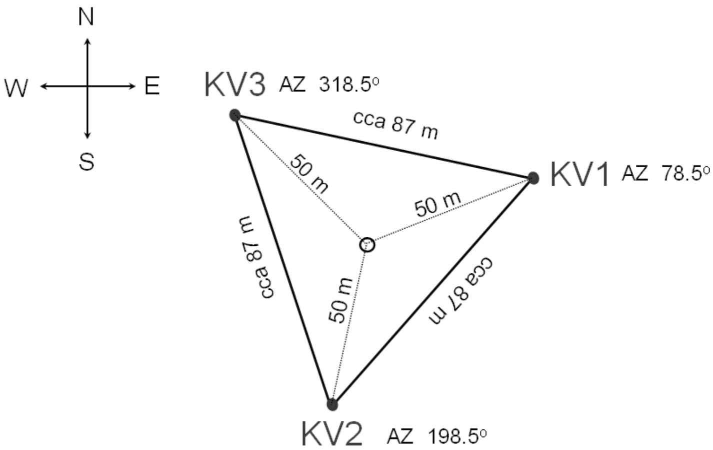

Fig. 2 The layout of the seismic array, KVCA.

to be registered by the local seismic network, WEBNET. The monitoring network currently consists of 13 stations distributed across an area of 50 × 50 km (IG ASCR, 2005). The sites are equipped with sensors with a sensitivity of about 50 V/(m/s), able to reliably record a comparatively wide range of magnitudes from M_L = -1 to M_L = 5.

The main reason for deploying seismic arrays in this area is to increase the ability of the seismic network to detect smaller events without affecting the current automatic data evaluation process. During 2007 and 2008, two experimental seismic arrays were constructed near Nový Kostel (NKCA) and Kvetna (KVCA). These sites are located near the present seismic network stations NKC and KVC. NKCA is situated directly above the main swarm zone, and is suitable for simple event detection. KVCA is situated about 5 km to the southeast, and allows the location of events to be reliably constrained (Fig. 1).

3. CHARACTERISTICS OF THE SEISMIC ARRAYS

The seismic arrays are triangular with an aperture of 87 m. Seismographs are located in each corner of the triangular configuration. KVCA is rotated clockwise with respect to NVCA by around 10° (Fig. 2). The sensors have been labelled KV1 to KV3 and NK1 to NK3, respectively. All of them are three-component sensors with high gain of 2620 V/(m/s) and an eigenfrequency of 4.5 Hz. The

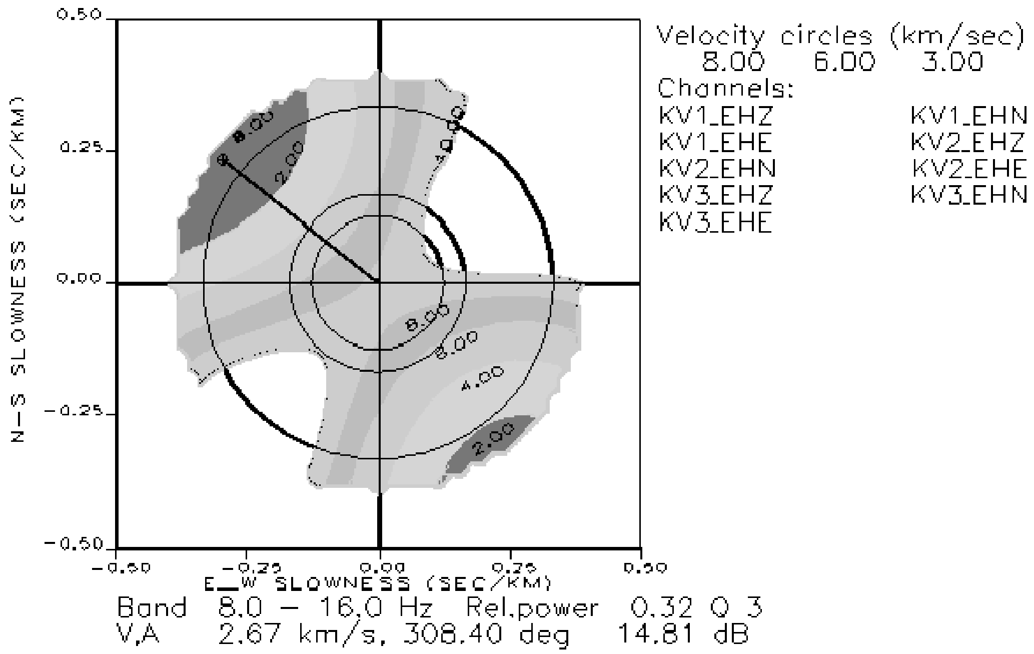

Fig. 3 The KVCA spatial transfer function; the black line that extends from the centre to the northwest reflects the direction of maximum array sensitivity.

sensors incorporate SM6b geophones and low-noise amplifiers. The geophone transfer characteristic is flat within the range 4.5 to 1 kHz. The upper corner frequency of recorded signal is determined by an amplifier that uses analogue anti-alias filter with suppression -20 dB at 50 Hz, and recording data-logger with non-causal digital filter with suppression -60 dB at 50 Hz (Štrunc et al., 2004).

NKCA is located directly above the main hypocentral zone. This means that its ability to locate events within the main swarm area is significantly reduced due to seismic wave coherency. Therefore, the results that form the basis of this paper are derived from KVCA.

The distribution of sensors across an area defines the spatial transfer function of the seismic array. This feature is very important for accurate event location as any false maxima will alter, spuriously, its location. The spatial transfer function is often illustrated the same way as *f-k analysis* (Fig. 3). Unlike other factors such as sensor type, sampling period, or digital filtering, the spatial parameters of the array are often fixed for a protracted period. Therefore, the spatial parameters have to be carefully verified during the preparation phase. As shown in Figure 3, KVCA is orientated towards the area of interest. The dark shading shows the direction of maximum array sensitivity. There are two, the global maximum to the northwest and the local maximum to the southeast. The point at which the axes cross marks the centre of the array. The line coming from the northwest begins above the main earthquake swarm area, under Nový Kostel.

4. DATA ACQUISITION AND ANALYSING SYSTEMS

Seismic signals are continuously registered by the apparatus RUP2004, developed by the Department of Seismology, IRSM ASCR. The system is based on an industrial computer with three USB 21-bit A/D converters (one for each seismometer), a GPS receiver for accurate timing, and LAN/Wi-Fi telemetry. All parts are controlled by a program suite with the same name as the system, RUP2004. The application runs under Windows XP Professional. It can provide both trigger and continuous regimes simultaneously. Data are filtered by a low pass digital filter (40 Hz) and saved onto hard disk which can be downloaded for off-line analysis. A daily message regarding its functional state is sent via GSM. Information regarding events detected by a simplified STA/LTA algorithm is also sent (Štrunc et al., 2004). The signal is stored with sampling of 100 Hz and its real sensitivity is 0.728, expressed in [nm/s per count].

Several systems for the automatic processing of seismic array data have been developed as proprietary software, such as those used in Iceland or Norway. The Norwegian suite DP/EP was developed by NORSAR towards the end of 1980s and remains used today (Fyen, 1989, 2001). It can operate either on-line or off-line and uses CSS data format that can be converted into other formats such as GSE or mSEED. This software runs under the Linux-like operating system. It not only processes data but also evaluates the array design within the framework of the target area, the array transfer function (Schweitzer et al.,

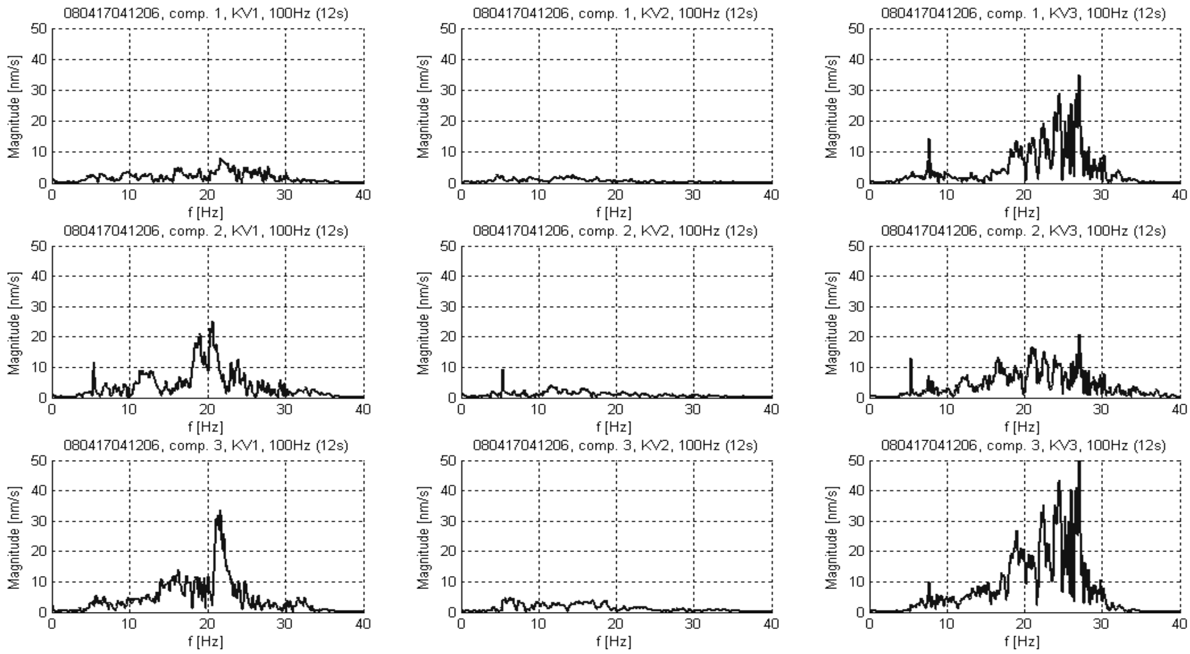

Fig. 4 The frequency spectra of measured signal that contains spurious noise. By rows, components Z, N, E.

2002). The process can be separated into three parts that occur automatically:

- *Detection Phase*. The signal is sampled, filtered, and passed through the STA, STA/LTA, or similar algorithm. Beamforming is used to increases the signal-to-noise ratio. This process requires all coherent signals from each of the seismographs. Different time-corrections are applied to the signal series from each sensor and from this the so-called beams are calculated.
- *Signal Attribute Processing* estimates attributes of the seismic signal including the onset time, period, amplitude, slowness vector (*f-k analysis*).
- *Event Analyzing* investigates the attributes of the seismic signal to define the source of the event. In order to achieve this, the direction of signal approach must be known and the signals have to be identified as either P- or S- waves.

The DP/EP system was given to the IRSM ASCR by NORSAR, and therefore the evaluation of data has been performed using an authorised tool. The support offered by NORSAR has meant that the likelihood of errors caused by our own implementation of the system have been minimised. Consequently, the majority of our analyses focused directly on seismological issues.

The RUP2004 data-logger stores the data in GSE format as one-second blocks within a one-hour file. These have to be converted to a one-hour block GSE file and then to a one-hour CSS file in order to work within the DP/EP system.

5. THE STUDY PERIOD, DATA AND ITS LIMITATIONS

In this study, data from the seismic array pilot project have been examined. The pilot project lasted from 19 April to 8 August 2008, a span of 117 days. During this time, 131 events were detected within the swarm area by the local seismic network WEBNET (Boušková, 2009). The smallest had a magnitude of $M_L = -1$ and the largest of $M_L = 1.7$. Therefore, the pilot project was undertaken during a period of comparative quiescence that was characteristically similar to other quiescent periods in this area.

Basic preliminary signal quality analysis demonstrated some unwanted behaviour in the seismic sensors. A spurious high frequency signal appeared systematically, which become increasingly stronger. Figure 4 provides an example of frequency spectra containing useful signals (an event) and unwanted noise over the same time period. It was necessary to filter the measured signal from each of the sensors to achieve a series with almost the same spectral content. After many tests, it was found that a band pass filter between 8 and 16 Hz provided the most suitable results. This band covers the energy of most events that originate in the main swarm area (Häge and Joswig, 2009). The subsequently undertaken beamforming was still unstable but the cross-correlation method converged in this band.

The origin of this spurious effect is debatable. However, it may be caused by stray earth currents as it often appears progressively and disappears suddenly. It should be noted that all sensors are identical, with the same initial transfer characteristics. Figure 4 and

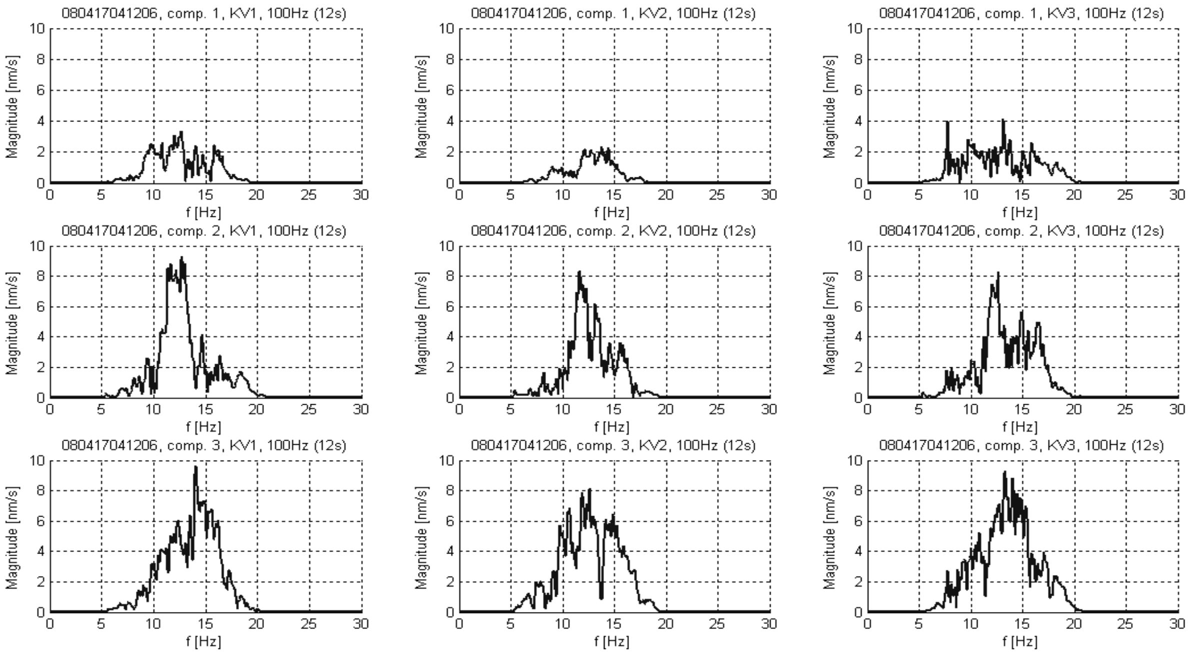

Fig. 5 The signal spectra after 8-16 Hz band pass filtering have been found to produce the maximum achievable similarity between components.

Figure 5 shows example from KVCA but the second site, NKCA, gives almost the same results. During the evaluation process Butterworth filter of the 3rd order, implemented in the DP/EP suite, was used.

The signal quality significantly influences the detection ability of an array. The classic detection process based on beamforming, using beams and an STA/LTA detector, is extremely sensitive to non-compensated changes in the transfer function of sensors. Furthermore, it was impossible to exclude any of the sensors or components as three is the minimum number needed to provide results.

6. DETECTION PROCESS: BEAMFORMING

The DP/EP offers many pre-defined configurations that are able to optimize the detection process. Hundreds of beams are produced that can be combined together. For each single beam, or any unlimited group of beams, its own detection criterion can be defined.

In this task, 227 beams were placed into four frequency bands from 8 to 10, 10 to 12, 12 to 14, and 14 to 16 Hz. These were strictly directed to the fourth quadrant, azimuth 270 ~ 360°, i.e. in the direction of the main swarm area. The detection threshold was altered for each set of beams, from 12.5 to 6.5. This approach generally gives a higher signal-to-noise ratio than is possible from a single sensor. However, our data were found to be unsuitable for this method. The spurious signals proved to be highly significant despite the band pass filtering. These caused many problems such as false event detection and failing to identify events that were obvious just from one sensor; an example of one such effect is shown in Figure 6.

The best results in DP/EP for this classical detection process were achieved with STA/LTA thresholds, e.g. vertical beams $\geq$ 6.5 and horizontal beams $\geq$ 10. As an example, 138 events were automatically detected using beams during 19 April 2008. Of these, 54 were spurious while at least 15 real events were missed. These numbers result from the phase of beam setting, when it is necessary to investigate all the data recorded during the training period (e.g. one day) manually. We checked all automatic triggers with different threshold in the time and frequency domain and compared them with our own manual detections. The training process is time-consuming because of using many different sets of beams and band-pass filters. The visible phases in the training data were also marked. By comparing the manual and automatic results, information regarding the effectiveness of the beams was found.

If we express this result over a longer period such as a year, it is reasonable to suggest that thousands of spurious events would be identified and hundreds of real events missed. These data are not suitable for beamforming. It should be noted that the array data from NKCA are also associated with the same problem.

7. DETECTION PROCESS: CROSS-CORRELATION

Methods based on an *a priori* knowledge the event features have become increasingly popular and more widely utilised. Cross-correlation functions were

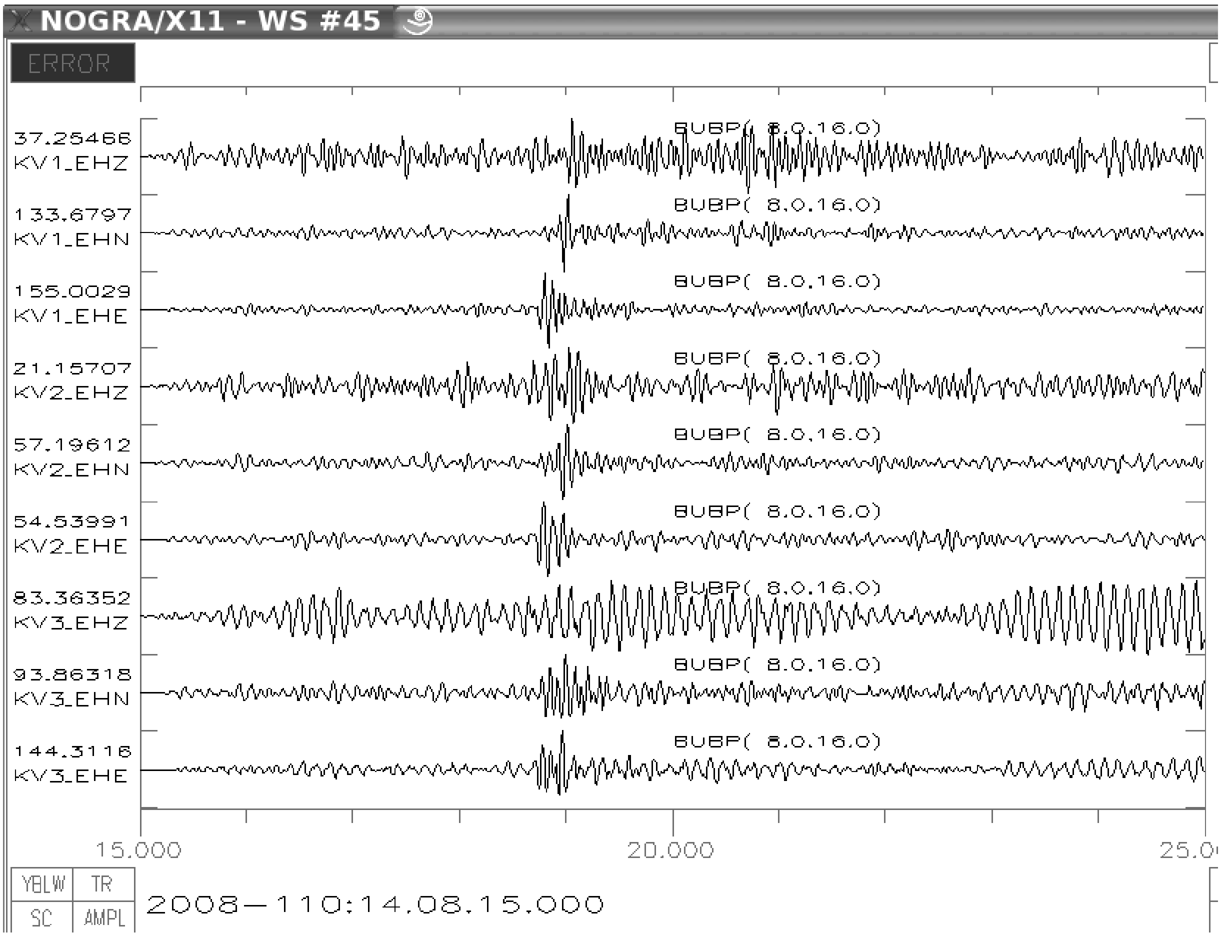

Fig. 6 A detailed example of a seismic event influenced by spurious signals, 8-16 Hz band pass filtered.

recently added to the DP/EP system (Gibbons et al., 2006).

As mentioned above, during the pilot period 131 events were detected by WEBNET. The events originated in 22 nearby locations, with 11 hypocentres located beneath Nový Kostel. These events could be used to provide *a priori* knowledge for other events originating from the same location, so called templates.

We selected 11 suitable events to be used as templates. If more than one event had been detected from the same location by WEBNET, the weakest one was used (generally with $M_L < 1$). These templates were prepared from the seismic array data series. Each template contains samples of each sensor within the array, i.e. 9 traces. There were calculated correlation coefficients between each template and data measured within the 117-day period. As with beamforming, this method defines a threshold of detection. A lower value provides a higher number of detections including false detections, and vice versa. The number of detections depends on the threshold value as shown in Table 1. The quantity "Reduction" in that table means percentage decrease of number of detections between each two steps. The degree of similarity is expressed as an SNR value. This abbreviation can be a little bit confusing but was introduced by DP/EP and we preserve its terminology.

Notice the significant decrease in the first four values, SNR ≥ 6.5 to SNR ≥ 9.5. The next step, to SNR ≥ 10.5, does not fall as steeply. This suggests that somewhere between these two values, there is a compromise between false detections and missing events. A manual comparison between the threshold value SNR ≥ 9.5 and SNR ≥ 10.5 was undertaken for

Table 1 The number of detections and the percentage change between steps.

SNR ≥	Detections	Reduction
6.5	6062	
7.5	2305	62 %
8.5	991	57 %
9.5	540	46 %
10.5	391	28 %
11.5	302	23 %
12.5	251	17 %
13.5	217	14 %
14.5	191	12 %
15.5	167	13 %

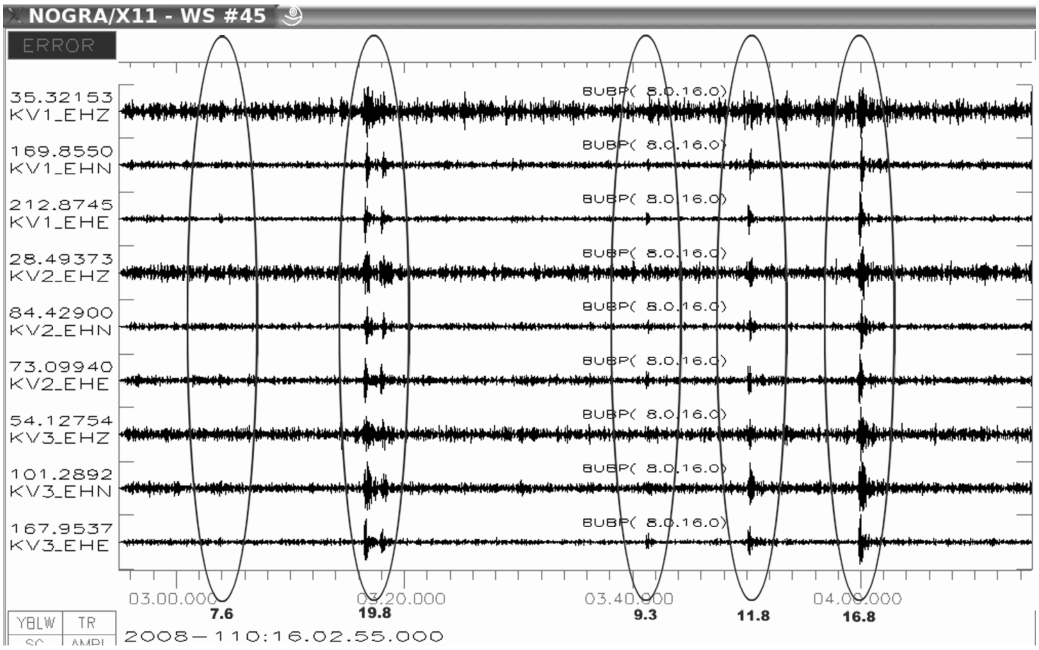

Fig. 7 Cross-correlation values comparison.

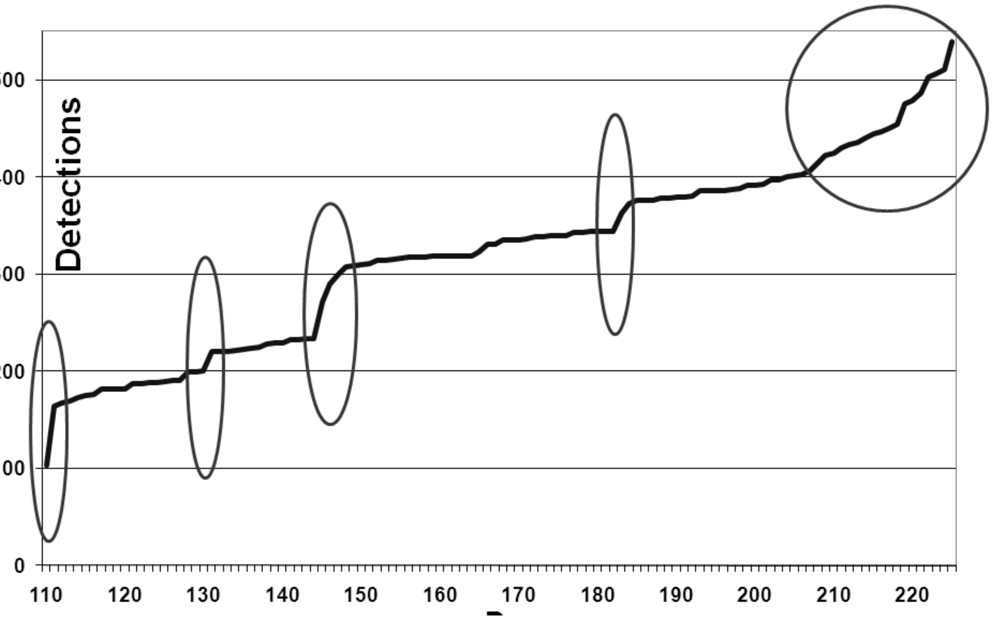

Fig. 8 The accumulative number of detected events between April 19 and August 12 2008.

Table 2 The relationship between the numbers of detections, false detections, and missed events.

SNR ≥	Detections	False	Missed
9.5	103	9	2
10.5	90	3	7

the data recorded on 19th April. The outcome is shown in Table 2. The number of false detections for SNR ≥ 9.5 is lower than 10 %. The final cross-correlation detection procedure for the examined period used this threshold value.

Figure 7 shows a comparison of the cross-correlation values calculated for the most likely template. This confirms the chosen threshold represents a good compromise between true and false detections.

Table 3 Number of detection associated with templates.

Letter	Time	Place	Backazimuth [°]	M_L	WEBNET detections	SNR ≥ 9.5 detections
A	2008-110:11.28.16	Pocatky	340	-0.3	26	162
B	2008-111:18.55.52	Mlynek	250	-0.6	1	12
C	2008-114:19.04.40	Novy Kostel	310	0.1	11	159
G	2008-145:18.54.06	Luby - Zalubi	315	0.7	51	54
H	2008-147:16.32.44	Luby	300	0.5	5	6
L	2008-154:00.27.02	Plesna - Vackov	295	-0.3	1	3
M	2008-156:05.44.33	Lazy	135	0.5	2	4
O	2008-168:23.28.38	Tachov	140	0.3	2	4
S	2008-183:23.17.06	Lesna	270	0.3	13	116
T	2008-192:13.19.08	Kostelni	315	-0.1	1	15
V	2008-220:10.38.01	Milhostov	200	0.3	1	5
		All			114	540

The detection process based on the cross-correlation method led to very interesting results. Figure 8 shows the accumulative number of events. The first two days of the pilot project were characterised by high seismic activity with 103 and 61 events detected, respectively. Although a number of other days were associated with high activity, April 19th was the most seismically active day during the pilot project. Other notable increases in activity are emphasised by ellipses in Figure 8. The final ellipse might represent the onset of the autumn swarm event.

Table 3 shows the results of the cross-correlation method and compares these to the results derived by the seismic network, WEBNET. Each template is marked by a letter and is characterised by its origin time, epicentre, magnitude, and backazimuth relative to KVCA. Notice the amount of detections, the array detected almost five times more events than WEBNET. It is also seen that the array detected around fifteen times more events than WEBNET above the most important epicentral area of Nový Kostel. This demonstrates that events from the main swarm zone are even smaller and more frequent than has been hitherto reported in the annual bulletins. This finding confirms the need for permanent array deployment in this area. It also emphasises the quality of the sensors and validates the techniques used for data analysis.

The cross-correlation method gives more than sufficient results, although it does require a priori information. This pattern cannot be used indefinitely but will have to be updated according to rupture progress. Its main advantage is that detected events do not have to be located because they theoretically originate from the same place as defined in the template. However, this method is not able qualitatively detect new events.

8. DISCUSSION

The current triangular array geometry does not allow any signal redundancy. To improve the results, the number of sensors should be increased or a new array deployed with the same characteristics as KVCA (i.e. not directly above the hypocentral area). Work on both has already begun. During 2010, NKCA was equipped with new sensors (CMG-40T) and the initial results are promising. KVCA was not deemed to be suitable for a similar upgrade because of adverse terrain. During autumn 2010, construction started on a completely new seismic array in Lazy. This locality promises even better noise conditions than KVCA.

The local magnitude of the events has not been calculated due to influence of spurious noise on the measured signal. It is clear, however, that the events detected exclusively by KVCA are much weaker than their templates.

9. CONCLUSIONS

The results presented in this paper show a remarkable amount of seismic activity within the earthquake swarm area of western Bohemia. The pilot project was undertaken during a period of apparent quiescence. It has been shown that during this period, the levels of seismic activity recorded by the seismic arrays were up to fifteen times greater than the levels recorded by the pre-existing seismic network. The study has also shown that the cross-correlation method can increase the ability to detect seismic activity if certain *a priori* information is known. This method is also suitable in situations when the array function has been disabled by some spurious noise or when there has been a sensor malfunction. Taken together, it is concluded that the results of seismic arrays are particularly valuable in earthquake swarm areas during apparently quiescent periods such as that examined here.

ACKNOWLEDGEMENT

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