The use of waveform cross correlation at a three-component seismic array for detection, location, and magnitude estimation

Kitov Ivan, Sanina Irina

Institute of Geospheres Dynamics, Russian Academy of Sciences

Abstract

Using the waveform cross-correlation technique, we have re-estimated relative locations and magnitudes of 200 events detected by an array consisting of seven 3-C sensors. All these events were quarry blasts conducted at several local/regional mines, which were detected and identified in the course of regional seismotectonic monitoring. From all detected signals we selected those having the highest quality and created a set of three-component templates for further cross correlation study. By changing the length of correlation window and the frequency band of the templates we selected optimal parameters for robust estimates of cross correlation coefficients and relative amplitudes/magnitudes of all signals. The relative locations and magnitude estimates obtained by cross correlation are compared to those in the catalog created in standard interactive analysis.

Conclusion

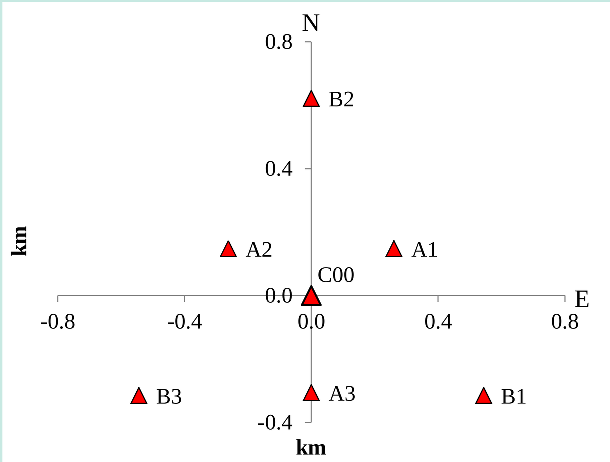
In practice, a sparse network of 3-C stations has a much higher magnitude threshold than a network of seismic arrays. For regional studies, S-wave detection is especially important to recover low-magnitude seismicity when only one small-aperture array is available. We have demonstrated that the use of an array of 3-C sensors allows to substantially reduce detection threshold adding up to 25% percent of correct S-wave signals, which were missed by the sub-group of vertical channels. This finding is in line with a number of similar studies.

We operated a standalone seismic group of 3-C sensors with data processing which included detection and identification of regional seismic events during four months of 2013. Automatic detection of P- and S-waves as well as estimation of their azimuth and slowness provided information necessary for event location and magnitude estimation. All automatically built event hypotheses were interactively reviewed to create a regional event catalogue.

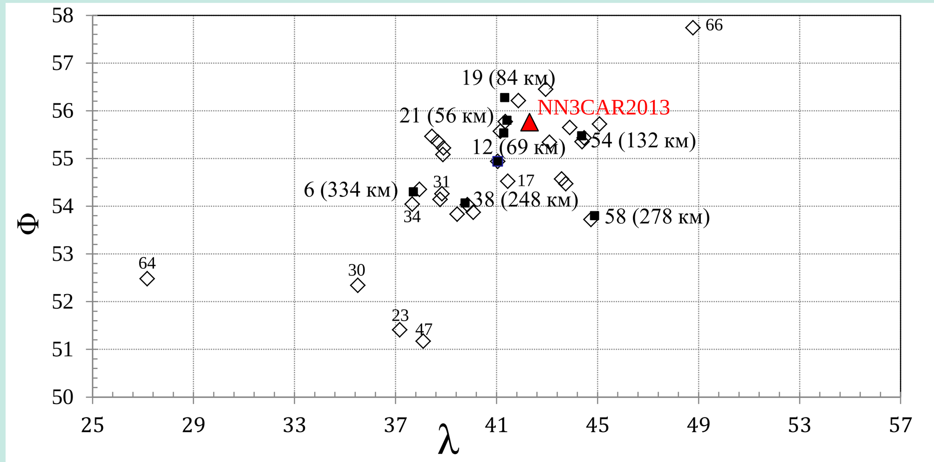
We also studied the performance of this portable seismic array for the purposes of waveform cross correlation with an interactively obtained set of repeating events. Seven quarries with more than dozen recorded blasts were selected in the range 60 to 350 km. After the selection of higher quality 3-C waveform templates for each quarry we calculated multichannel traces of cross correlation coefficients and found that these 3-C templates provide higher signal to noise ratios, SNR_{CC}, than those obtained using vertical channels only. The choice of 3-C sensors also leads to higher specificity of waveform templates and reduces the rate of false alarms. Longer templates with broader frequency content provide an additional improvement in detection capability and signal specificity, but increase calculation time. Overall, the advantage of a 3-C array is based on the full use of signal energy, and is especially important for detection and identification of regional phases of the P- and S- waves.

Using Rg-waves as most sensitive to relative event positions, we have split the set of events associated with quarry 19 into two different set according to cross correlation. In addition, we have found a few events which were not correctly interpreted in the interactive catalogue. For events grouped by cross correlation, we have estimated relative magnitudes. These estimates allow comparison of relative yields of quarry blasts. However, the change in firing scheme can also affect the efficiency of Rg-wave generation.

SMALL APERTURE 3-C ARRAY NN3CAR2013

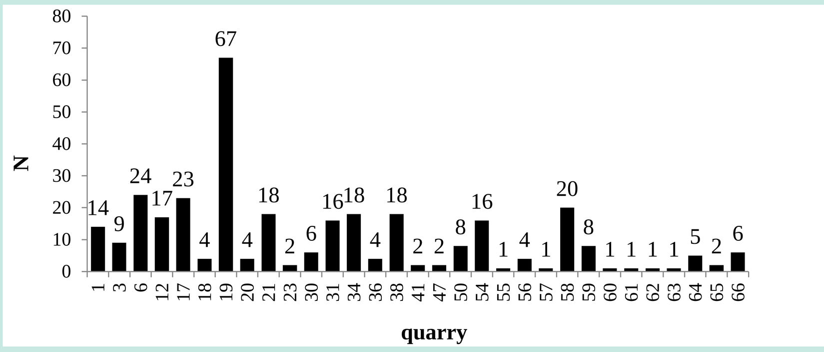


Configuration of NN3CAR2013. There are seven 3-C (H1,H2,Z) sensors. Central sensor (55.76 N 42.31 E) surrounded by two triangles – A and B.

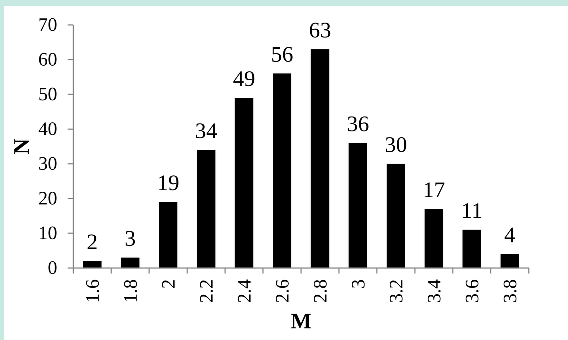


Small aperture seismic array NN3CAR2013 (red triangle) detected signals from 31 quarries. Some of these quarries are characterized by a large number of repeated blasts. We used seven quarries shown by black squares.

The array was operated between May and September 2013. After automatic processing two experienced analysts conducted a thorough interactive analysis and built a catalogue which identified quarry blasts at 31 mines. We selected seven mines (6, 12,19, 21, 38, 54,58) with larger numbers of repeating events. This allow statistical analysis of detection and waveform cross correlation.



Distribution of the number of blasts over quarries. The largest number is for quarry 19.



Distribution of blasts over seismic magnitude estimated by NN3CAR2013. Just a few events were detected by the regional seismological network.

DATA PROCESSING

BEAMFORMING

SENSORS COORDINATES: (x_j, y_j),

WAVEFORMS: v_j

TIME DELAYS: $dt_j = \mathrm{int}[(S_e x_j + S_n y_j)F]$,

BEAM:

$$S(t) = (1/J)\Sigma v_j(t - dt_j)$$

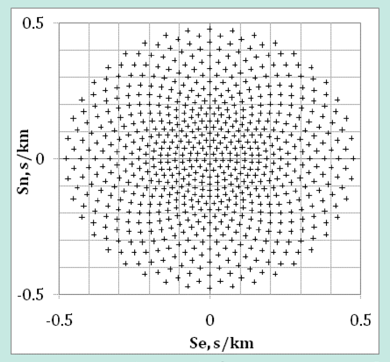
DETECTION THRESHOLD
SNR=STA/LTA>3.5

$$STA(S/2) = \frac{1}{S}\sum_{i=1}^{S}|v(s)| \qquad STA(k) = STA(k-1) + \frac{1}{S}\left[\left|v\left(k+\frac{S}{2}\right)\right| - \left|v\left(k-1-\frac{S}{2}\right)\right|\right]$$

$$LTA(k) = \left(1-\frac{1}{L}\right)LTA(k-1) + \frac{1}{L}STA(k-S)$$

Filters: 2–4 Hz, 3–6 Hz, 4–8 Hz, 6–12 Hz, 8–16 Hz, and 12–24 Hz Butterworth 3-d order

WE CONSIDER THREE SUB-ARRAYS SEPARATELY:
vertical - Z, radial – R, transversal - T



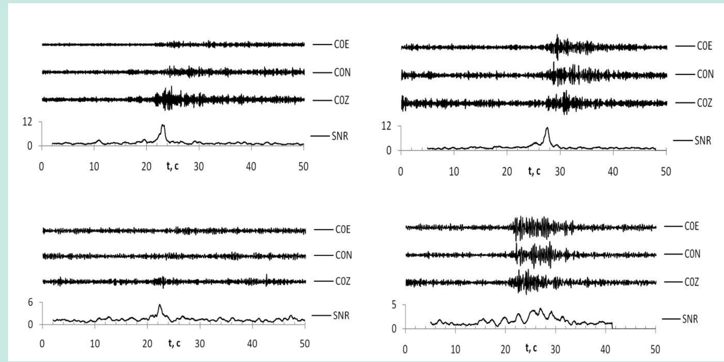
Standard slowness set (S_e, S_n) for automatic beamforming. Sn and Se are in the range -0.5 s/km to +0.5 s/km. Azimuth resolution better than 4.5°.

WAVEFORM CROSS CORRELATION - VERTICAL vs. 3-C ARRAY

Cross correlation coefficient

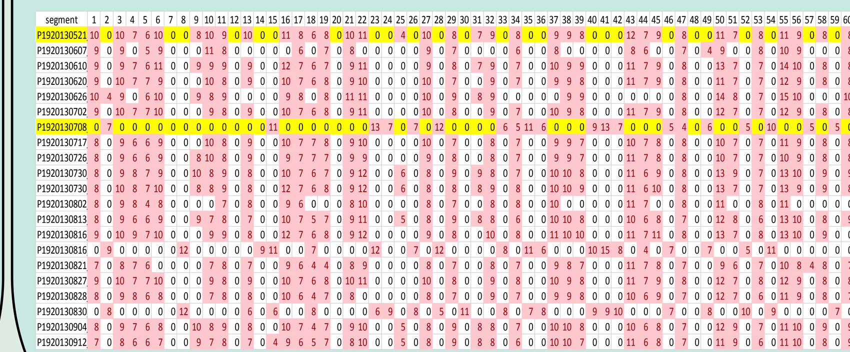
$$CC[\upsilon(t_\upsilon),\omega(t_\omega)] = \frac{\langle \upsilon(t_\upsilon),\omega(t_\omega)\rangle_{N,\Delta t}}{\sqrt{\langle \upsilon(t_\upsilon),\upsilon(t_\upsilon)\rangle_{N,\Delta t}\,\langle \omega(t_\omega),\omega(t_\omega)\rangle_{N,\Delta t}}}$$

CC DETECTION



Several examples of detection with cross correlation: SNR>3.5. Larger signals does not mean better correlation.

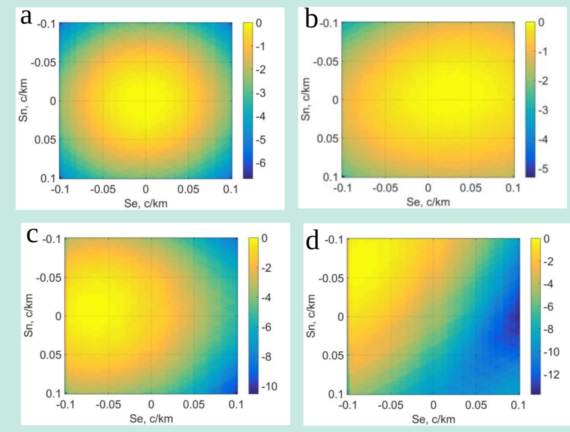
CC DETECTIONS WITH MASTERS 19



Red – detection. Two Rg templates selected for quarry 19.

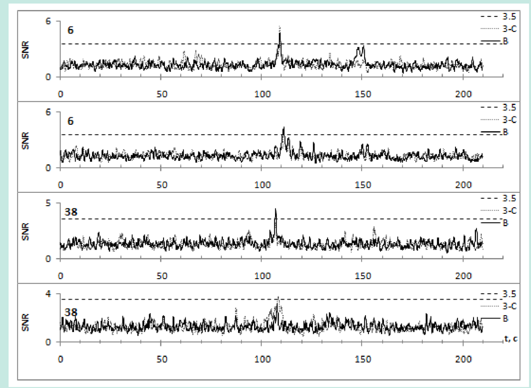
Relative magnitude can be estimated only when signal is detected by cross correlation!

Screening with FK



a – low slowness residual, correct detection
b – slowness residual within the limit of 0.05 s/km
c - slowness residual just beyond the threshold detection rejected
d – slowness residual far beyond the threshold detection rejected

VERTICAL vs. 3-C



RESULTS

Comparison of the number of detections made by 3-C group and by vertical subgroup (V) as well as the difference between averaged SNR_{CC}. We have selected 3 best P-wave and 6 best S-wave templates for each quarry. The negative SNR_{CC} differences are highlighted. The bottom line presents total number of segments (W) for a given quarry less one autocorrelation segment.

	6			12			19			21			38			54			58		
	3-C	V	dSNR	3-C	V	dSNR	3-C	V	dSNR	3-C	V	dSNR	3-C	V	dSNR	3-C	V	dSNR	3-C	V	dSNR
P	16	13	1.9	4	1	0.6	12	16	**-0.8**	11	8	1.8	12	13	0.7	10	10	2.4	13	12	1.1
	15	11	1.6	4	1	0.2	12	6	1.1	11	11	2.6	11	12	1.0	10	9	3.7	13	13	0.3
	15	17	0.2	3	1	0.2	11	10	0.9	11	12	1.1	10	10	**-0.7**	10	9	2.9	13	12	1.0
S	16	14	1.1	9	7	1.3	17	17	2.2	12	12	**-0.4**	12	12	0.4	10	10	3.3	13	11	2.9
	17	15	1.1	8	9	1.0	15	18	**-0.7**	12	12	0.8	12	10	3.5	10	7	3.9	13	11	3.0
	16	14	2.3	8	5	1.2	15	17	1.5	12	12	**-2.1**	12	10	3.0	10	10	4.5	13	11	2.8
	16	13	2.1	8	6	0.9	15	14	0.6	12	12	0.0	12	10	3.4	9	9	3.5	13	2	1.7
	16	9	2.0	5	10	**-1.3**	14	13	1.0	11	12	2.2	11	10	3.1	7	6	2.9	13	11	3.4
	15	13	1.9	2	8	**-0.8**	13	18	**-1.7**	11	11	2.2	11	10	3.5	6	4	2.0	12	11	3.2
W	18			12			19			12			13			10			13		

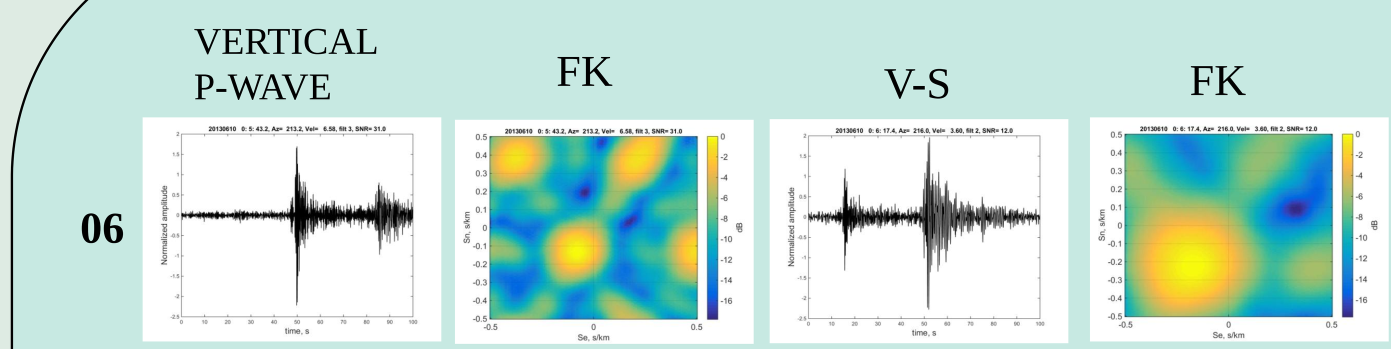
Results of SNR_{CC} calculations for 13 segments from quarry 21 with templates for quarries 12 (21/12), 19 (21/19) и 21 (21/21). Averaged values are listed.

Segment/ template	1	2	3	4	5	6	7	8	9	10	11	12	13
21/12 3-C	4.87	3.95	3.00	2.75	2.97	3.56	3.32	4.82	3.37	2.95	3.90	3.39	2.49
21/12 V	3.51	3.47	4.53	3.24	2.46	2.95	3.56	4.18	4.08	3.17	3.22	2.85	4.20
21/19 3-C	3.82	5.14	7.17	4.87	4.61	4.53	4.09	5.66	5.43	4.96	6.28	4.74	4.78
21/19 V	6.15	8.67	9.92	8.58	6.33	7.00	8.54	8.71	8.95	9.27	8.51	5.65	9.37
21/21 3-C	8.07	9.55	8.32	7.43	5.52	8.23	8.69	10.72	9.16	7.11	5.62	6.88	17.93
21/21 V	6.90	9.19	8.99	7.35	4.46	7.64	7.73	9.83	10.03	8.65	9.84	5.23	11.93

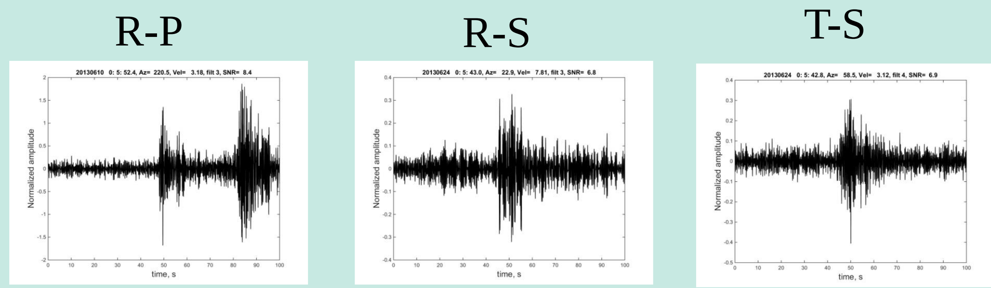
The number of detections by 40 waveform templates after cross correlation with OWN and OTHER segments (total 104 segments) before and after application of slowness threshold of 0.05 s/km.

QUARRY	OWN SEGMENTS						OTHER SEGMENTS					
	Normal length		Longer templates		Wide spectrum		Normal length		Longer templates		Wide spectrum	
	3-C	V	3-C	V	3-C	V	3-C	V	3-C	V	3-C	V
6	109/85	108/81	101/68	90/70	109/85	90/70	50/7	33/3	56/11	28/5	50/5	28/5
12	34/26	30/22	31/22	27/22	27/24	27/22	43/16	58/20	32/15	42/17	24/15	42/17
19	74/50	73/36	69/43	61/34	55/38	73/36	61/23	66/14	35/19	55/12	38/19	65/14
21	61/49	64/51	60/43	62/53	58/56	62/53	38/17	64/16	55/14	57/17	37/15	57/17
38	61/54	59/55	61/50	55/54	58/56	55/49	35/6	39/3	46/14	25/2	27/6	25/2
54	67/53	54/49	51/48	46/42	56/48	46/43	7/2	7/3	13/2	4/1	7/2	4/1
58	82/81	63/62	80/78	64/63	75/75	64/63	10/2	16/4	20/6	11/3	13/7	11/3

BEAMFORMING AND DETECTION

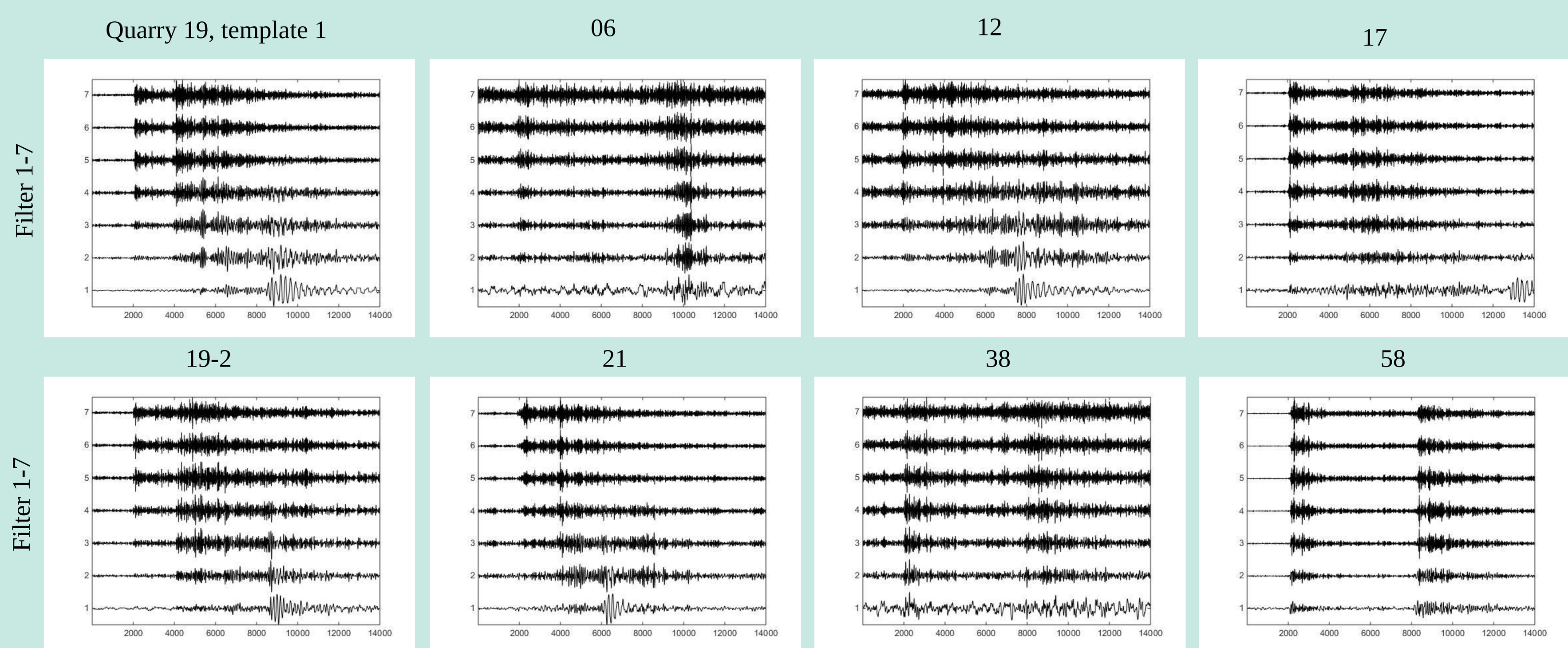


Beams for various components of vertical seismic sub-group steered towards the source of the P- and S- wave from quarry 06.



Beams for two components (R and T) of the 3-C group steered towards the P- and S-wave sources of quarry 06. Peak SNR value for three beams can be observed at transversal (*T*) as well as at radial (*R*) components.. There is a *P*-wave arrival from quarry 6 observed on the beams of vertical channels despite the corresponding traces are steered towards the source of *S*-wave.

WAVEFORM TEMPLATES FOR MASTER EVENTS: CENTRAL VERTICAL CHANNEL



Each detected signal from one of the quarries was used to build a set of waveform templates.

The length of a standard template at one channel was 64 s, including 4 s of noise.

To improve the signal-to-noise ratio, each signal was filtered by 7 filters used for detection.

Total numbers of detections obtained by various sub-arrays for repeating events at seven selected quarries /added S-arrivals (added events)

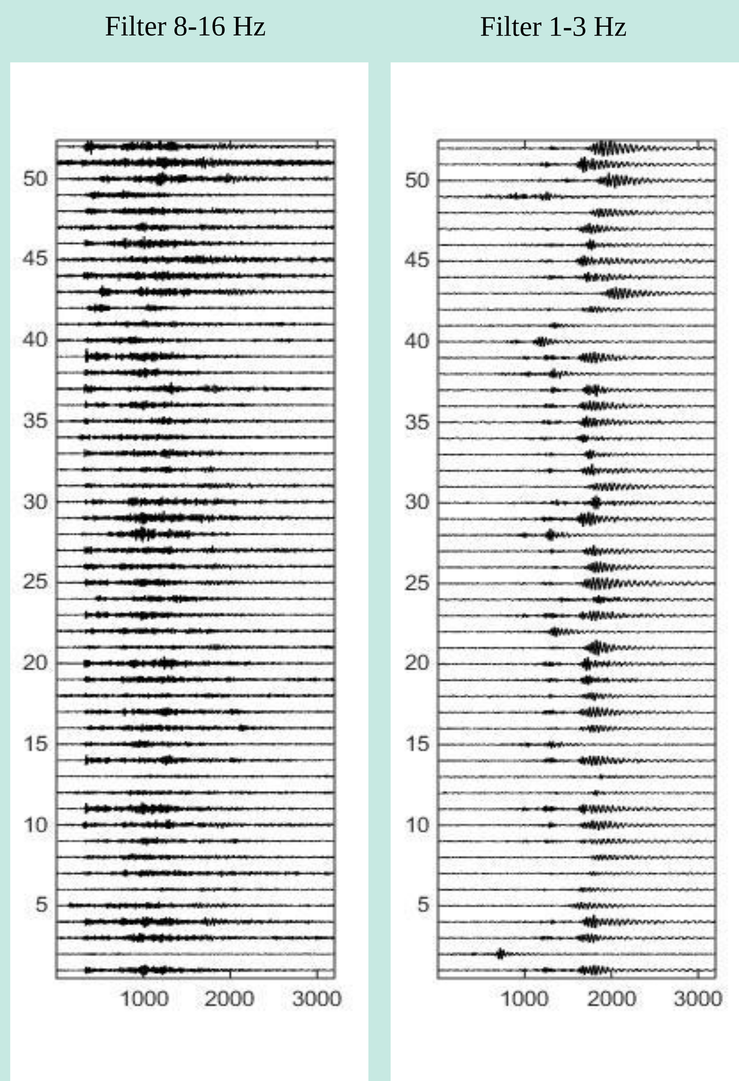
Quarry	Blasts	*A*	*H*1	*H*2	*R*	*T*	*V*
6	19	22/2	18/3	14/3(**1**)	15/2	18/3(**1**)	30(18)
12	12	9/1	9/1	5/2	14/5(**3**)	9/2	12(9)
19	20	18/2	15/3	16/3	28/11(**5**)	21/6(**4**)	23(15)
21	13	14/1	16/1	14/2	15/1(**1**)	16/3(**1**)	22(12)
38	13	17/2	15/2	13/2	12/2	11/1	19(13)
54	11	16/5	13/0	12/1	14/1	13/2	14(11)
58	14	17/1	16/2(**2**)	12/2(**2**)	13/3(**2**)	15/3(**2**)	20(12)

Statistics of detections obtained in various frequency bands

Quarry	Frequency band, Hz						
	1–3	2–4	3–6	4–8	6–12	8–16	12–24
6	0	8	17	4	1	0	0
12	0	0	4	0	1	1	6
19	0	11	0	1	3	2	6
21	0	8	1	0	1	0	12
38	0	5	8	3	1	2	0
54	0	0	0	1	6	6	1
58	0	6	4	7	0	2	1

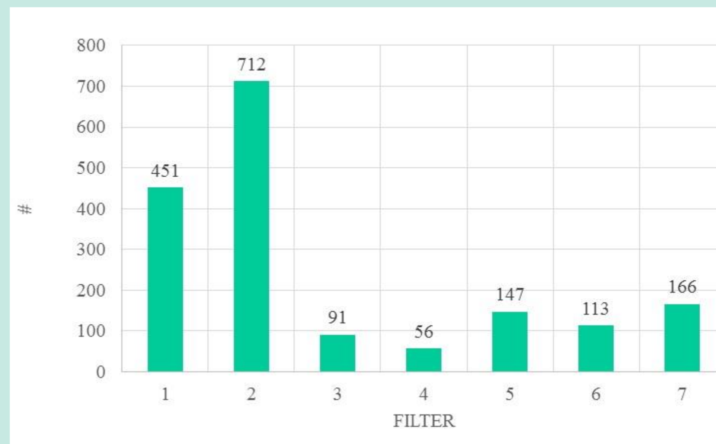
RELATIVE MAGNITUDES AND LOCATIONS

Detected signals from quarry 19

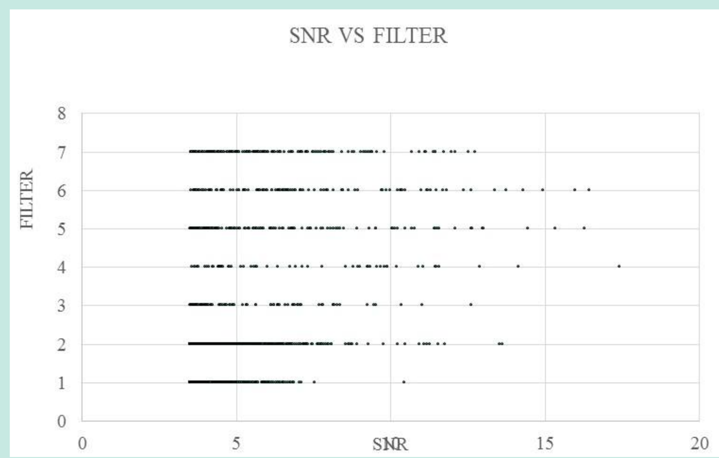


P, S, and Rg waves are different between signals associated with quarry 19 in the original catalogue. Relative positions of sources can be re-estimated by cross correlation.

Statistics of detected signals



The importance of various filters for cross correlation is demonstrated by the frequency distribution of filters actually detected signals from the same source. The best filter depends of the properties of generated signal as well as ambient noise conditions for a given day.



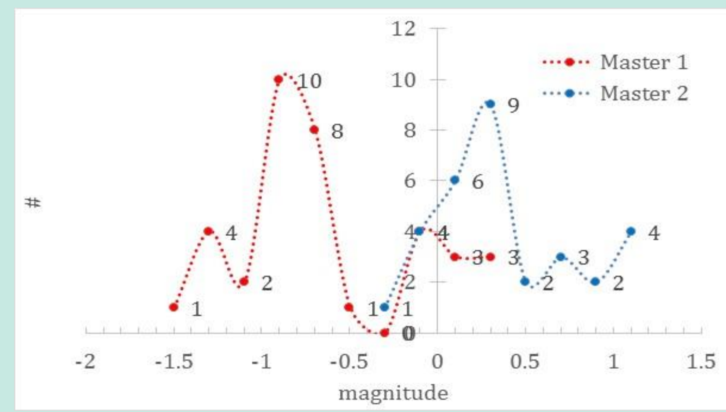
The highest signal-to-noise ratio for cross-correlation traces is obtained for filters 4 to 6. The performance of the low-frequency filter (1-3 Hz) is likely affected by the high-level ambient noise near 1 Hz. However, this filter is important for Rg-wave, which is most sensitive to the position of source within the quarry. This filter was successfully used to distinguish quarry 19 from adjacent quarries.

Events correlating with two selected Rg-templates

Examples of relative location and separation of two quarries. Figure illustrates separation of blasts detected by two different master events (Rg-templates), which both were initially associated with quarry 19. Master 1 and 2 do not cross correlate in any frequency band. The original event locations are scattered and mixed. According to cross correlation, the events correlating with the same master should be close. There are a few examples of wrong identification of quarries 12 and 21 in the interactive bulletin.

Relative magnitudes

$$RM = \log(|x|/|y|) = \log|x| - \log|y|$$



For events with correlating signals, one can define relative magnitude. The distribution of relative magnitudes for two masters demonstrates that master 1 is likely larger than master 2. For master 1, other blasts were generally smaller (negative RM), and master 2 was slightly smaller than other events from the same quarry.

Corresponding author: Ivan Kitov (IDG RAS)
E-mail: Kitov@idg.chph.ras.ru

IDG RAS
http://idg.chph.ras.ru