A multi-master method for detection of weak aftershocks at regional distances using waveform cross correlation

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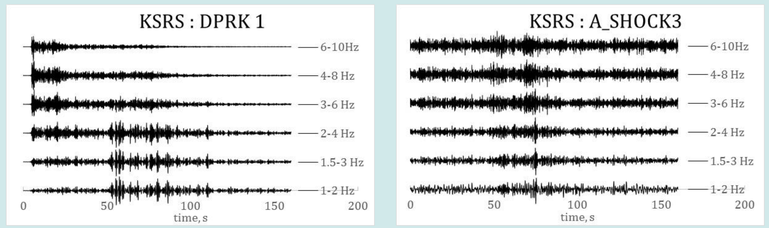
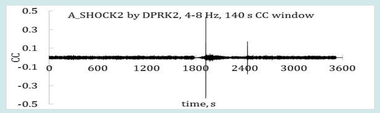
Abstract. Low-magnitude aftershocks of earthquakes and explosions (*e.g.*, the DPRK underground tests) present a challenge to routine seismological methods of signals detection at regional distances and further association into seismic events. Even the method of waveform cross correlation (WCC), which is able to reduce detection threshold by a unit of magnitude, often fails to detect signals at several stations needed for association into reliable event hypotheses because of strong variation in seismic directivity of the earthquake-like sources. We have elaborated upon the WCC method based on a single master and developed a procedure based on the joint use of several adjacent master events with different source mechanisms. The method has been tested at the International Data Centre (IDC) of the Comprehensive Nuclear-Test-Ban Treaty Organization using observations of the aftershock activity induced by the DPRK underground explosions conducted on September 9, 2016 and September 3, 2017 and measured by the seismic network of the International Monitoring System (IMS) as well as by regional non-IMS stations. We used only regional stations in the range from 3.3 to 11 degrees. The set of master events and corresponding waveform templates includes the DPRK explosions and their aftershocks; the latter has been progressively updated with new events found. As a result, the IDC has successfully detected several small (estimated m_b between 2.0 and 3.6) seismic events after two DPRK tests conducted on September 9, 2016 and September 3, 2017. The obtained detections were associated with reliable event hypothesis and then used to locate these events relative to the epicenters of the DPRK explosions. The multi-master WCC method also improves the accuracy of relative location for the DPRK explosions, including the first and the last events.

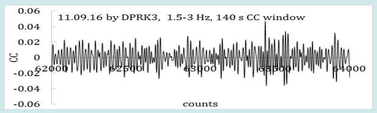
Weak aftershocks and mining blasts

DPRK aftershocks



Waveform cross correlation





Not all aftershocks are easy to find using explosion templates

HIGHEST KSRS SNR_{CC}

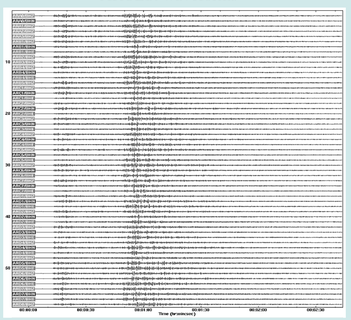
	D1	D2	D3	D4	D5	D6	A1	A2	A3	A4	A5	A6
DPRK1	221	73	45	34	50	66	8.3	37	15	31	23	5.7
DPRK2	88	373	76	246	344	293	8.6	34	18	40	17	7.2
DPRK3	80	534	92	201	468	381	11	47	18	33	14	5.8
DPRK4	39	173	84	303	193	282	9.4	54	12	37	15	6.4
DPRK5	34	135	56	537	120	657	8.7	42	14	35	18	6.5
DPRK6	48	141	70	196	199	597	9.9	51	15	36	15	5.6
A_SHOCK1	5.7	9.1	7.6	7.8	9.4	6.7	107	7.3	8.8	19	12	23
A_SHOCK2	30	53	29	59	72	72	11	112	12	27	14	9.2
A_SHOCK3	19	13	13	15	13	18	9.2	10	87	144	97	8.5
A_SHOCK4	21	65	30	24	81	30	19	21	59	209	79	16
A_SHOCK5	32	20	11	14	23	20	14	12	63	85	151	15
A_SHOCK6	5.2	6.3	5.7	5.5	6.2	5.9	28	5	8.5	13	11	98

HIGHEST USRK SNR_{CC}

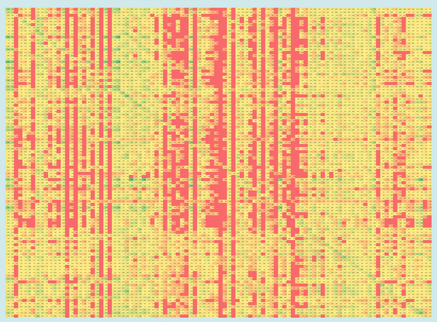
	D2	D3	D4	D5	D6	A1	A2	A3	A4	A5	A6
DPRK2	204	50	273	248	273	14	13	14	42	40	8.2
DPRK3	228	62	182	166	182	16	18	12	34	19	8.6
DPRK4	226	34	539	301	539	23	29	9.7	23	10	11
DPRK5	274	38	291	400	291	26	25	14	16	14	13
DPRK6	252	68	212	356	212	25	27	12	21	14	15
A_SHOCK1	22	13	24	27	24	85	13	6.1	9.5	7.3	17
A_SHOCK2	47	11	71	43	71	15	160	15	51	13	8.9
A_SHOCK3	9.8	11	9.1	12	9.1	7.2	24	67	75	119	6.8
A_SHOCK4	12	11	14	22	14	12	9.2	132	148	83	10
A_SHOCK5	17	8.1	10	15	10	10	22	116	123	100	5
A_SHOCK6	9.3	6.8	11	10	11	17	9.3	7.6	16	5.3	66

AITIK copper mine

ARCES: waveforms

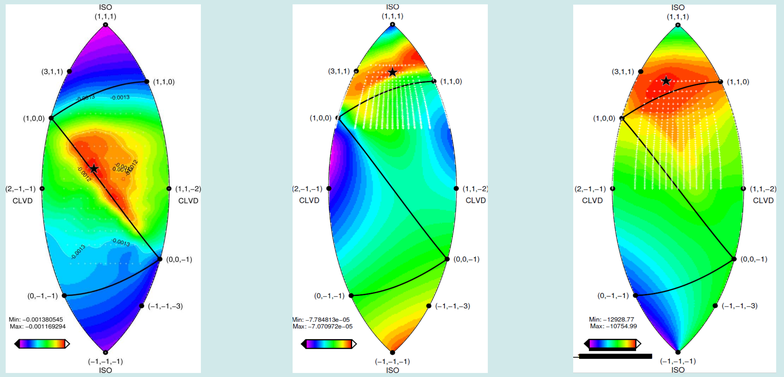


ARCES: SNR on CC-traces

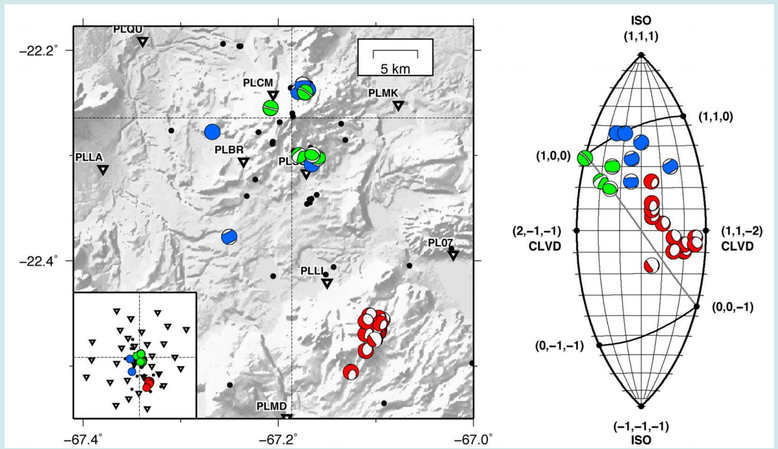


Variation in similarity from blasts at the same mine affects cross correlation results

Multi-master event from the moment tensor estimation perspective



Lune diagram at fixed depth for induced earthquake (left) and two DPRK-2016 explosions. Search region encompasses entire lune, white plus (+) symbols shown grid node locations sampled. Black star shows optimal solution. Color shows joint PDF contoured into 30 equal intervals. Tape and Tape (2015) method is implemented to uniformly discretize the moment tensor space, and then to determine the optimal moment tensor by comparing observed seismograms with synthetic waveforms. Normally double-couple events tend to the center and explosions tend to the upper lune pinnacle.



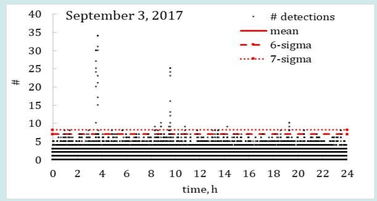
Example from the Uturuncu volcano event processing (Celso Alvizuri and Carl Tape. Full moment tensors for small events (Mw < 3) at Uturuncu volcano, Bolivia. Geophys. J. Int. (2016) 206, 1761–1783 , 2016). Events presented are mostly isotropic, ISO (blue: 6 events), tensional crack, CLVD (green: 5 events), and double couple, DC (red: 14 events). Here, we refer to the analysis of seismic events clustered tightly within small geographical area. The cluster sizes are from 1 to 5 km, which is comparable to the DPRK aftershock zone. With this, while the SW-cluster is populated by only DC events, the near-center cluster and northern cluster are the mixture of CLVD and ISO events. This example demonstrates the necessity of introducing the multi-master approach due to the radiation pattern variability for even compactly populated seismic events considered within identical tectonic and geological settings.

Multi-master approach and select results

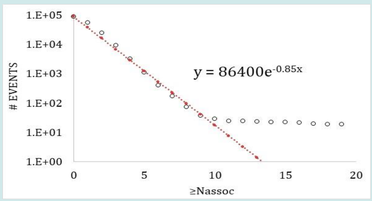
MAJOR MULTI-MASTER REQUIREMENTS:

1. TWO OR MORE EVENTS HAVE TO BE MEASURED AT TWO OR MORE REGIONAL STATIONS
2. EVENTS ARE CLOSE TO EACH OTHER WITH ALMOST EQUAL TRAVEL TIMES TO SEISMIC STATIONS
3. EVENTS ARE CHARACTERIZED BY VARYING RELATIVE AMPLITUDE OF REGIONAL PHASES AT DIFFERENT STATIONS (EFFECT OF DIRECTIVITY OR SOURCE REGION COMPLEXITY)
4. QUALITY OF SIGNALS (e.g. SNR) FOR SELECTED SEISMIC PHASES (e.g. Pn, Pg, Sn, Lg)

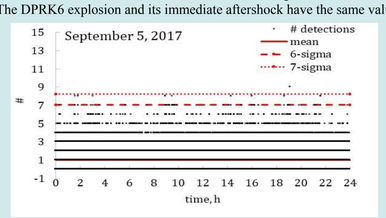
SOME EXAMPLES OF MULTI-MASTER PROCESSING



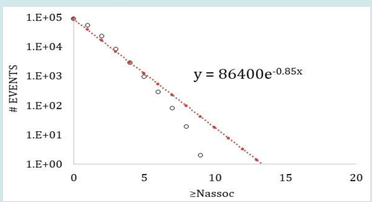
The number of detections from all masters in running 7 s window. The DPRK6 explosion and its immediate aftershock have the same value



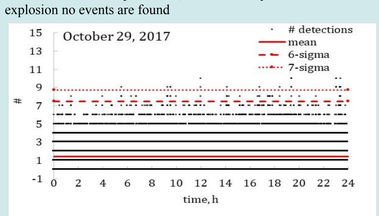
Frequency distribution of the number of detections in 7 s window. The deviation from the exponential (red) distribution is from three real events



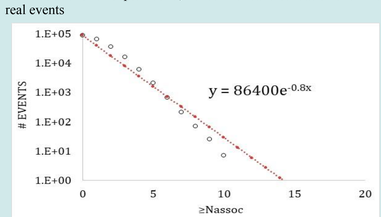
Same as above for September 5, 2017. Two days after the DPRK6 explosion no events are found



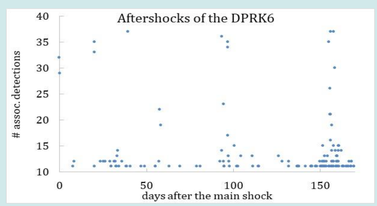
Same as above for September 5, 2017. The real distribution show no real events



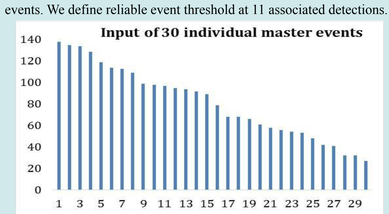
Same as above for October 29, 2017. No events are found.



Same as above for October 29, 2017. The real distribution show no real events. We define reliable event threshold at 11 associated detections.



The evolution of aftershock activity. The strength of event hypotheses is measured by the number of associated detections (>10 from 60)



Input of individual masters (30) to the final set of event hypotheses (161 event in total)

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