SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

CTBTO
PREPARATORY COMMISSION

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

Poster No. P2.3-356

CTBTO

POSTER

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

Waveform cross-correlation is a natural method to detect repeating signals. Mine blasts are an example of repeating seismic/infrasound events with very close epicenters. In some areas, hundreds of mining blasts per year are measured by the IMS and built by the IDC

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

The IDC has been testing a prototype WCC-based pipeline to find repeating mining events matching the event definition criteria (EDC) for the Reviewed Event Bulletin (REB). The REB is used as a source of master events with seismic and infrasound waveform templates. Several open-pit mines create intensive acoustic waves detected by the IMS infrasound network and these detections are used to build seismic-infrasound events matching the EDC. The prototype pipeline is processing seismic and infrasound data continuously and we systematically compare the cross-correlation bulletin (XSEL) with the automatic bulletin (SEL3) and the REB. This comparison is used to tune the defining parameters of data processing.

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

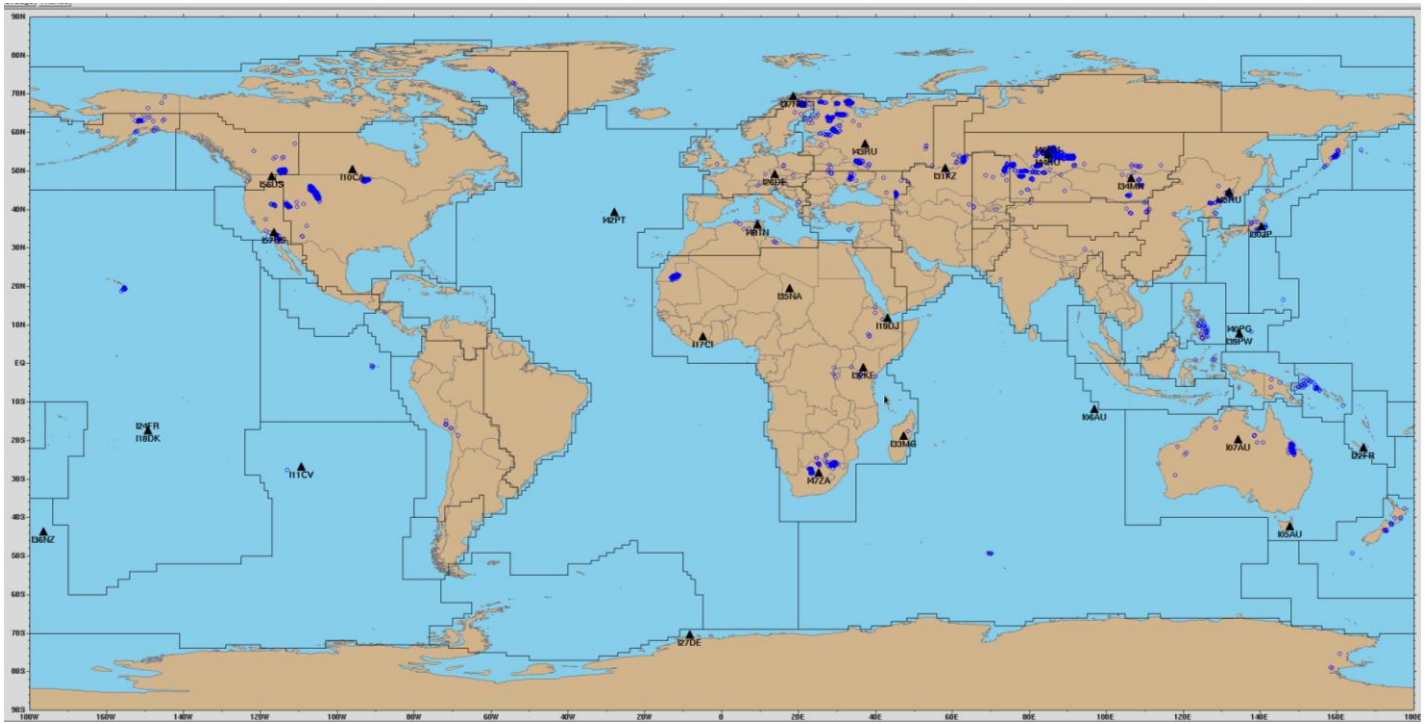
- Events to find: pure seismic, seismic/infrasound, and pure infrasound
- Historical events within the studied area
- Waveform cross correlation as a tool to find similar events
- Selection of master events
- Creation of XSEL with seismic and infrasound stations
- Results
- Discussion

SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION



There are mining areas with events having just 1 infrasound arrival, but two and three also possible. In Africa, there is an open pit with blasts recorder by two infrasound stations I35NA and I47ZA and one 3-C seismic station BOSA. Such events are also found in XSEL processing. Master events are collected to process pure infrasound mining events.

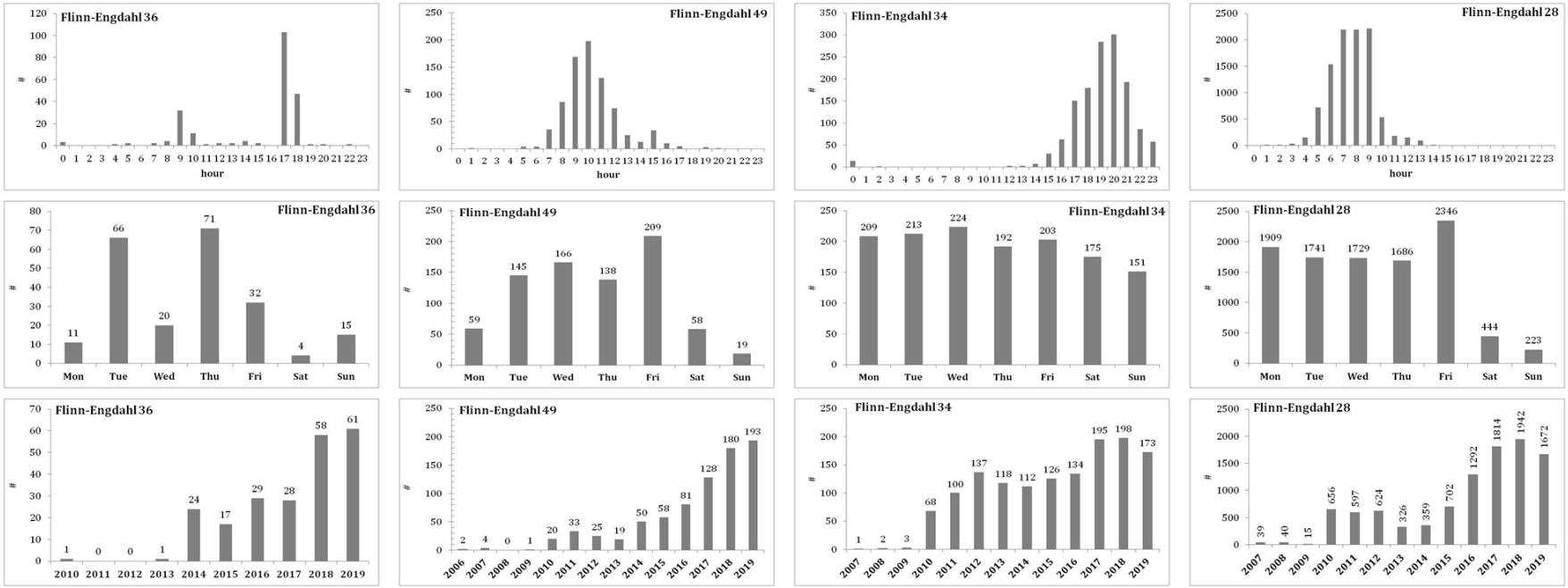
SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION

REB MINING EVENTS **WITH** INFRASOUND



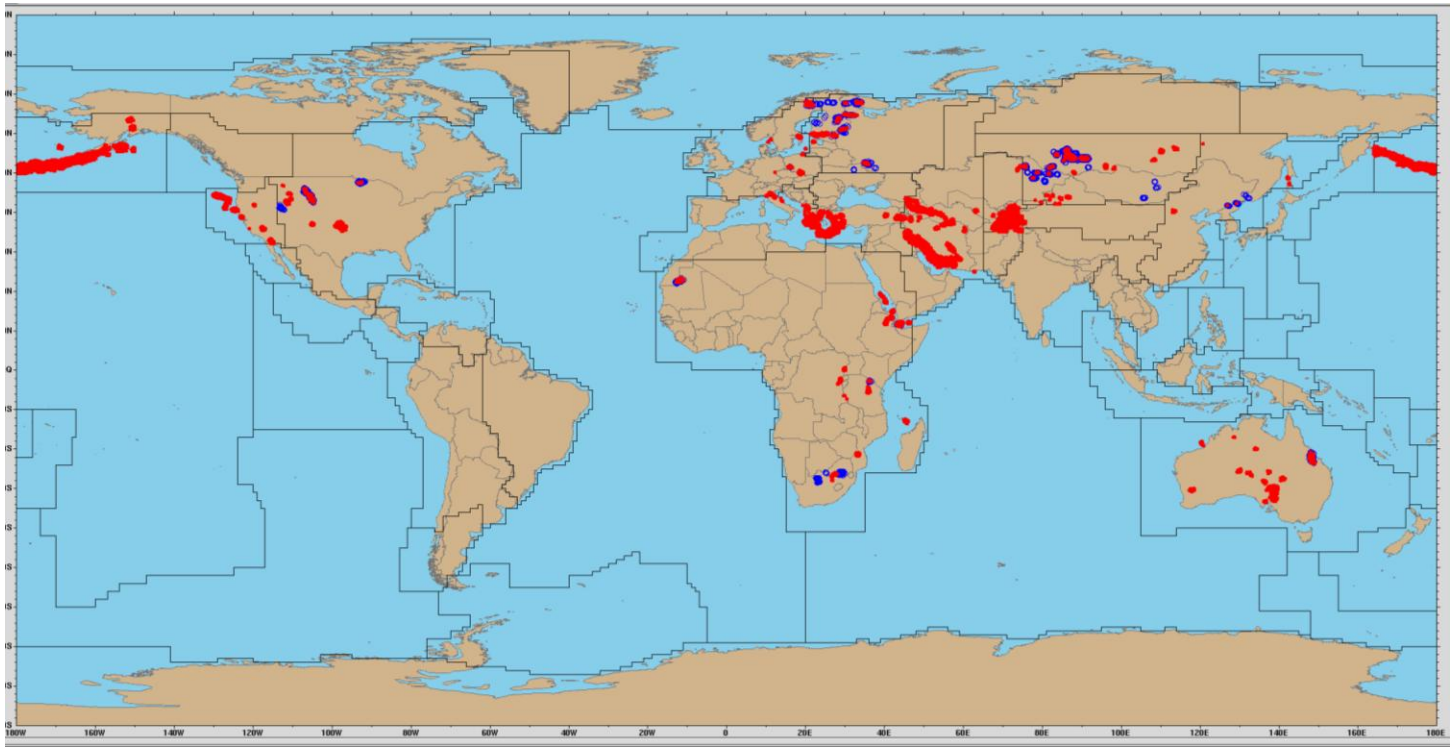
The number of REB mining events with infrasound has been increasing since 2014. These events can hardly be confused with non-mining events: narrow time slots and rare on weekends (except Eastern North America - Flinn-Engdahl region 34). The most active region 28 – Lake Issyk-Kul to Lake Baykal – with total number of events ~2000 per year.

SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION

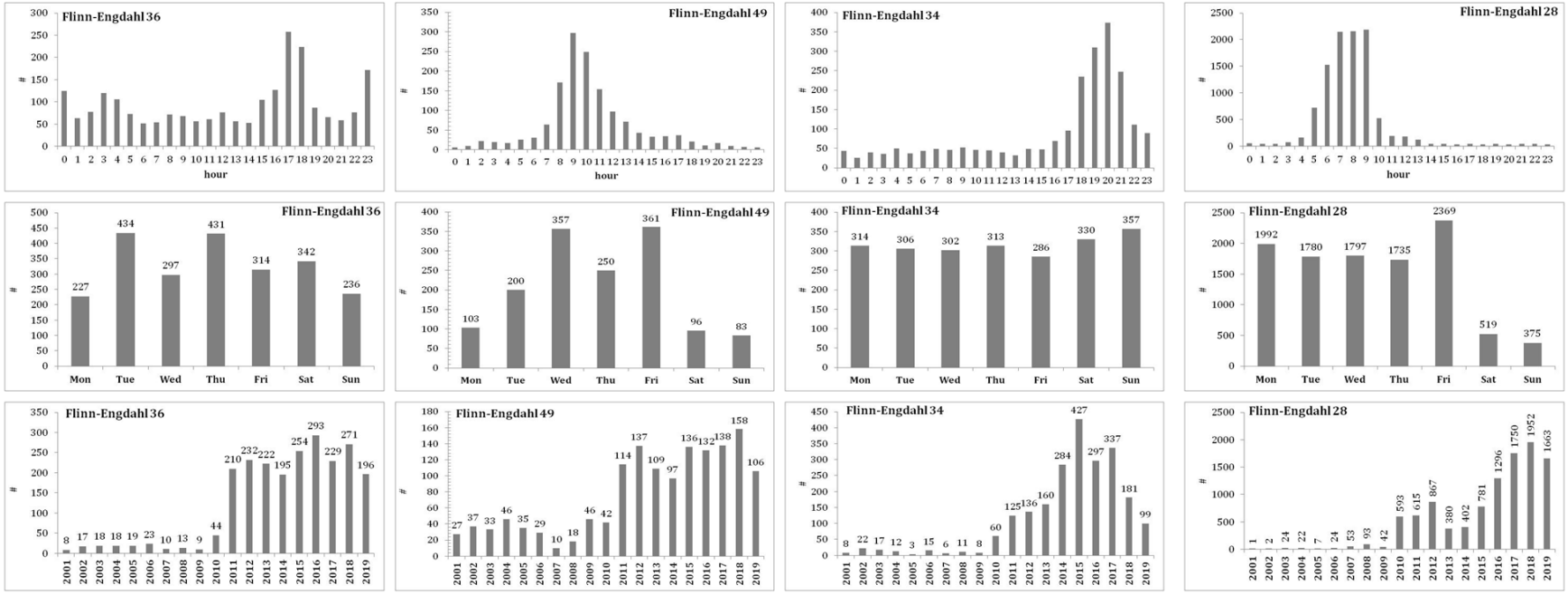


There are mining areas with repeating events without infrasound arrivals. For some open mines, wind conditions make infrasound detection seasonal and then pure seismic events are built. There are also areas with highly *repeatable natural seismic events* within continents. All these areas are can be processed by WCC-based methods using a large number of the REB as master events.

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

REB MINING EVENTS **WITHOUT** INFRASOUND



The number of highly repeating seismic REB events within continents has also been increasing since 2010-2014. These events can be mining blasts as well as shallow earthquakes: there are some events out of the narrow time slots and they are more often on weekends. Many of these pure seismic events are from the same mines as the events with infrasound.

SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

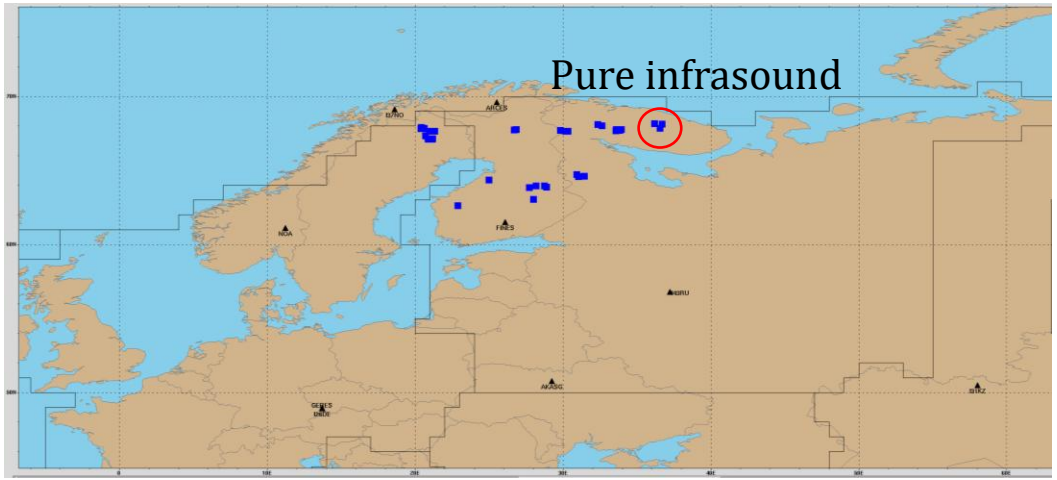
Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION

Region: 62°N to 72°N: 16°E to 37°E

Infrasound has to be processed



From 36 events 20 (not black in the Table) have less than 3 primary seismic stations and need infrasound arrival to match the REB EDC.
From these 20:

- 9 have at least one auxiliary station SPITS, HFS (blue)
- 3 are pure infrasound REB events (bold red)

#	orid	origine time	lat, deg	lon, deg	nass	mb	Jdate	Sreg	Evid/SEL3
1	15460810	1518422405	63.93	28.20	5	-999.0	2018043	49	15460810
2	15460101	1518432181	67.71	33.84	**10**	-999.0	2018043	49	**15416420**
3	15460147	1518435351	63.03	28.01	8	-999.0	2018043	49	**15416590**
4	15464563	1518611392	63.87	28.90	6	-999.0	2018045	49	15452317
5	15461488	1518688804	64.70	30.93	6	-999.0	2018046	49	15461488
6	15461558	1518711867	67.76	26.85	4	-999.0	2018046	49	15461555
7	15446540	1518741690	67.80	20.61	**12**	3.4	2018047	36	**15432230**
8	**15461785**	1518782073	68.14	36.21	3	-999.0	2018047	49	15461785
9	15465072	1518784614	63.93	28.76	7	-999.0	2018047	49	15435172
10	15465075	1518804101	67.11	20.90	7	-999.0	2018047	36	15461560
11	15464346	1518835811	67.75	33.95	**16**	3.3	2018048	49	**15437043**
12	15477198	1518853414	67.89	20.43	9	-999.0	2018048	36	15477191
13	15479674	1518865668	67.71	29.83	6	-999.0	2018048	49	**15438858**
14	15464786	1518866839	67.65	30.17	6	-999.0	2018048	49	15456932
15	**15478144**	1518873754	67.83	36.58	4	-999.0	2018048	49	15478144
16	**15479611**	1518874264	68.13	36.71	3	-999.0	2018048	49	**15439950**
17	15478154	1518876626	68.00	32.64	6	-999.0	2018048	49	15478154
18	15478348	1518879206	67.65	20.95	9	-999.0	2018048	36	15440239
19	15463023	1518919307	67.14	20.90	9	-999.0	2018049	36	15442049
20	15997904	1530844569	67.12	21.18	**10**	-999.0	2018187	36	**15987652**
21	16001147	1530844747	67.82	20.61	**11**	-999.0	2018187	36	16001147
22	16002926	1530854864	67.32	20.72	5	-999.0	2018187	36	16002925
23	16011059	1530870324	67.64	21.34	6	-999.0	2018187	36	15989782
24	16001788	1530871783	67.72	26.71	4	-999.0	2018187	49	16001787
25	16010674	1530876561	63.84	27.74	5	-999.0	2018187	49	16010674
26	16007335	1530905854	67.76	33.61	**10**	-999.0	2018187	49	15990807
27	16006190	1530961668	67.63	30.34	8	-999.0	2018188	49	**15991887**
28	16006243	1530962474	67.67	33.58	8	-999.0	2018188	49	16006243
29	16011281	1531127203	64.35	25.00	7	-999.0	2018190	49	16011281
30	16015821	1531216818	64.61	31.44	8	-999.0	2018191	49	16002796
31	16015125	1531233197	62.61	22.90	7	-999.0	2018191	49	16015125
32	16014477	1531242059	67.10	21.14	7	-999.0	2018191	36	16004425
33	16024168	1531351746	67.85	20.58	7	-999.0	2018192	36	16024168
34	16032016	1531390277	64.58	31.07	7	-999.0	2018193	49	16026194
35	16026586	1531399184	68.11	32.36	5	-999.0	2018193	49	16026586
36	16031667	1531437704	67.82	20.41	**12**	-999.0	2018193	36	**16013104**

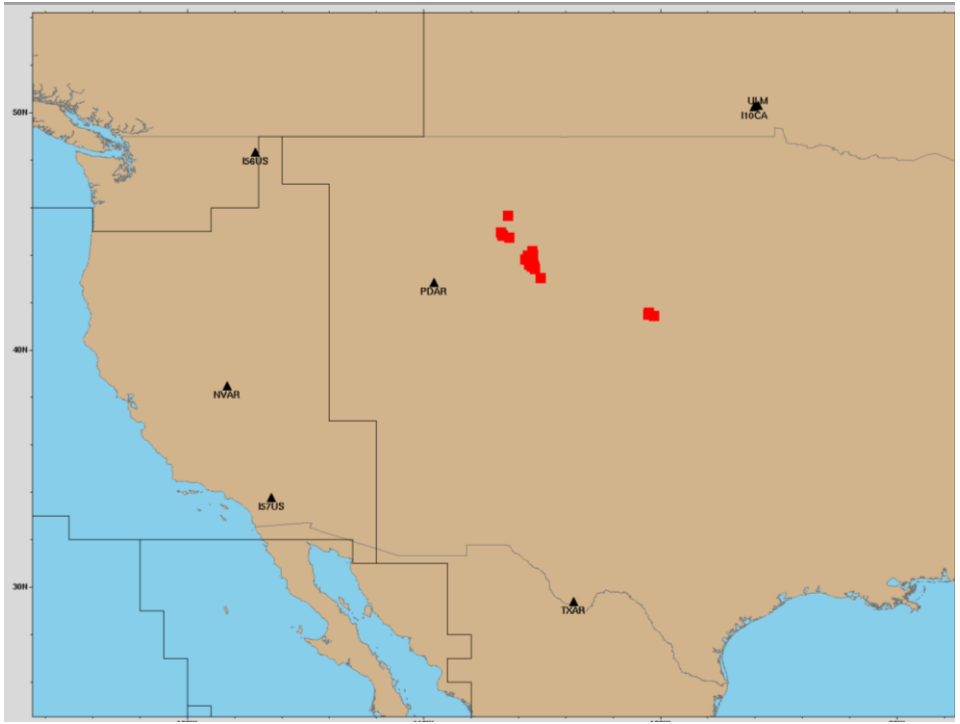
SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION

Region: 40°N to 46°N: 100°W to 110°W



From 23 events, 11 have less than 3 seismic and at least 1 infrasound defining arrival

#	orid	origine time	lat, deg	lon, deg	nass	mb	Jdate	Sreg	Evid/SEL3
1	15672162	1522869781	44.81	-106.65	5	-999.0	2018094	34	15672162
2	15668168	1522877668	43.73	-105.54	**11**	3.9	2018094	34	**15645522**
3	15677616	1523040923	43.83	-105.47	6	-999.0	2018096	34	15654668
4	15682212	1523210757	43.57	-105.34	**11**	3.7	2018098	34	**15662320**
5	15682288	1523213616	43.03	-105.05	5	-999.0	2018098	34	**15661792**
6	15681451	1523266427	41.42	-100.26	**16**	3.5	2018099	34	**15665462**
7	15693519	1523303087	44.83	-106.68	5	-999.0	2018099	34	15681548
8	15694154	1523304089	43.40	-105.30	7	4.0	2018099	34	**15666258**
9	15693452	1523305921	43.48	-105.31	5	-999.0	2018099	34	***15666838***
10	15693552	1523310220	43.51	-105.43	5	-999.0	2018099	34	15693552
11	15681453	1523360468	41.47	-100.49	**19**	4.0	2018100	34	**15668862**
12	15694447	1523375352	41.56	-100.48	9	2.7	2018100	34	15670599
13	15699901	1523386918	43.98	-105.59	**13**	4.0	2018100	34	15671054
14	16138713	1533687435	44.15	-105.39	6	-999.0	2018220	34	16125880
15	16137075	1533749757	45.64	-106.43	6	-999.0	2018220	34	16137075
16	16141739	1533846931	44.95	-106.73	5	-999.0	2018221	34	16141739
17	16141745	1533847238	43.79	-105.45	5	-999.0	2018221	34	16141745
18	16152603	1534014675	43.99	-105.37	**11**	-999.0	2018223	34	**16130484**
19	16152008	1534092652	44.72	-106.38	6	-999.0	2018224	34	16134994
20	16152895	1534179711	43.89	-105.55	5	-999.0	2018225	34	16152895
21	16153500	1534183290	43.79	-105.55	7	3.8	2018225	34	16152901
22	16152974	1534200979	43.60	-105.54	4	-999.0	2018225	34	16152974
23	16157491	1534278614	43.80	-105.71	9	-999.0	2018226	34	16157491

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

REB events to find: overview

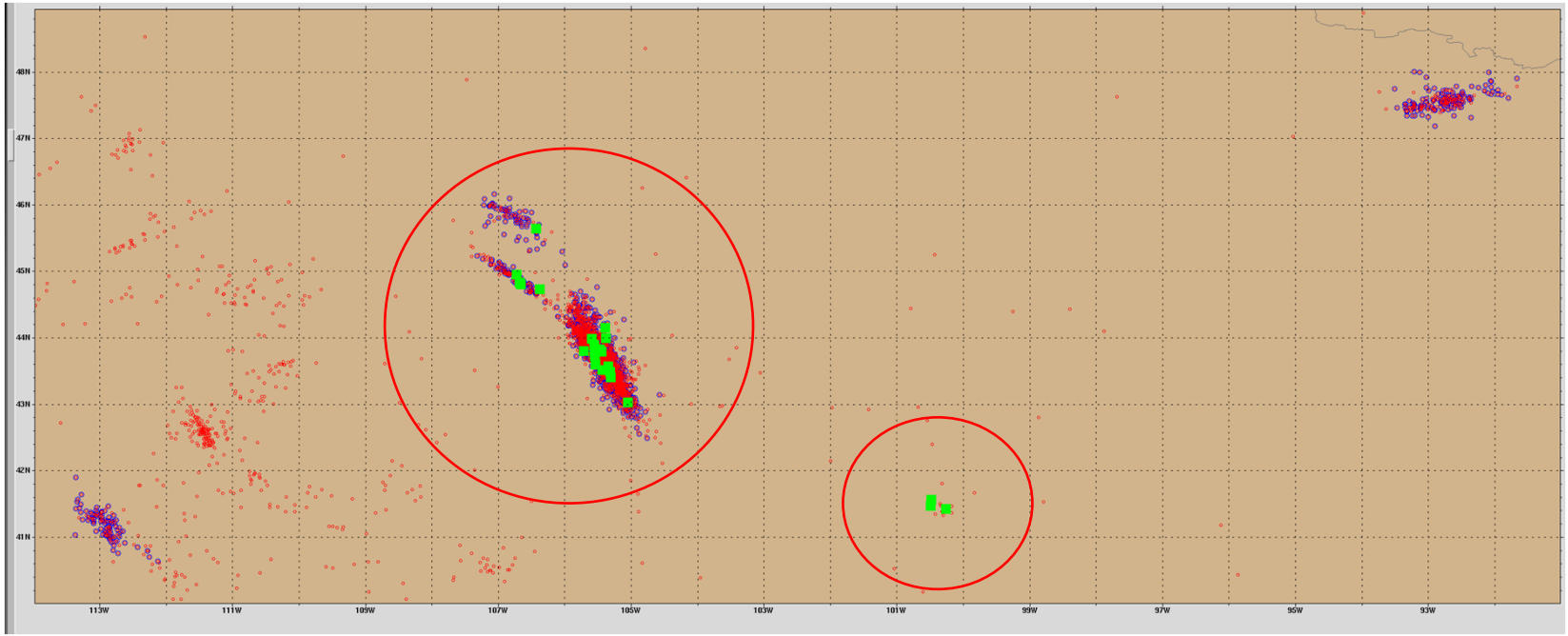
There are 59 events in the REB, which were found in two designated regions during the studied period. The latter was selected as two different weeks having larger number of events in 2018.

1. Many events have no m_b magnitude and were found by 3-4 closest IMS stations: seismic and infrasound
2. Events with the largest m_b are likely not mining blasts (to be excluded?)
3. All events have zero depth
4. 31 from 59 events (52%) have 2 or less seismic stations with associated phases. These events do not exist without infrasound detections
5. 3 events are pure infrasound (all in Scandinavia)
6. Only 17 from 59 events (29%) have SEL3 events with the same *evid, i.e.* they have seed events for interactive analysis
7. 42 events have to be added by analysts and built from scratch, *i.e.* with highly increased workload (specialized analysts)

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

POTENTIAL MASTER EVENTS

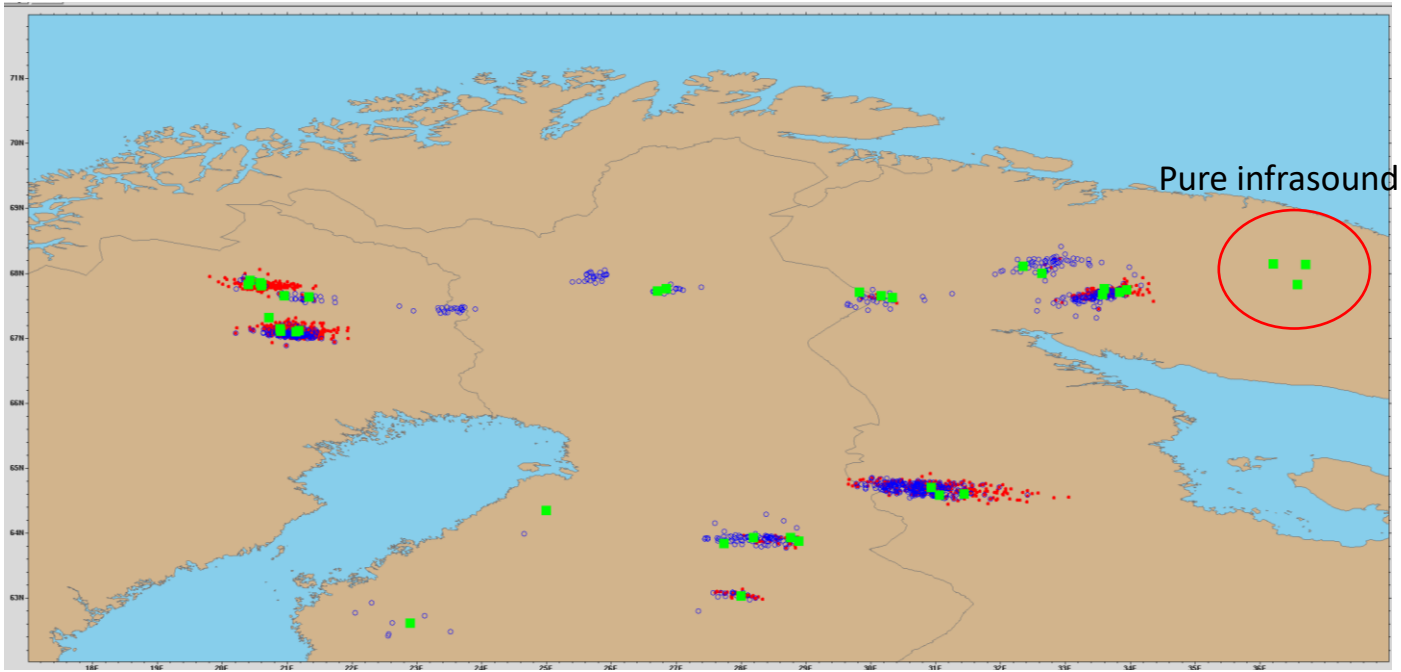


There are many regions with mining events, including those detected by infrasound stations. In this study , we focus on the region with the highest number of historical events. Green – REB events to find.

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

POTENTIAL MASTER EVENTS



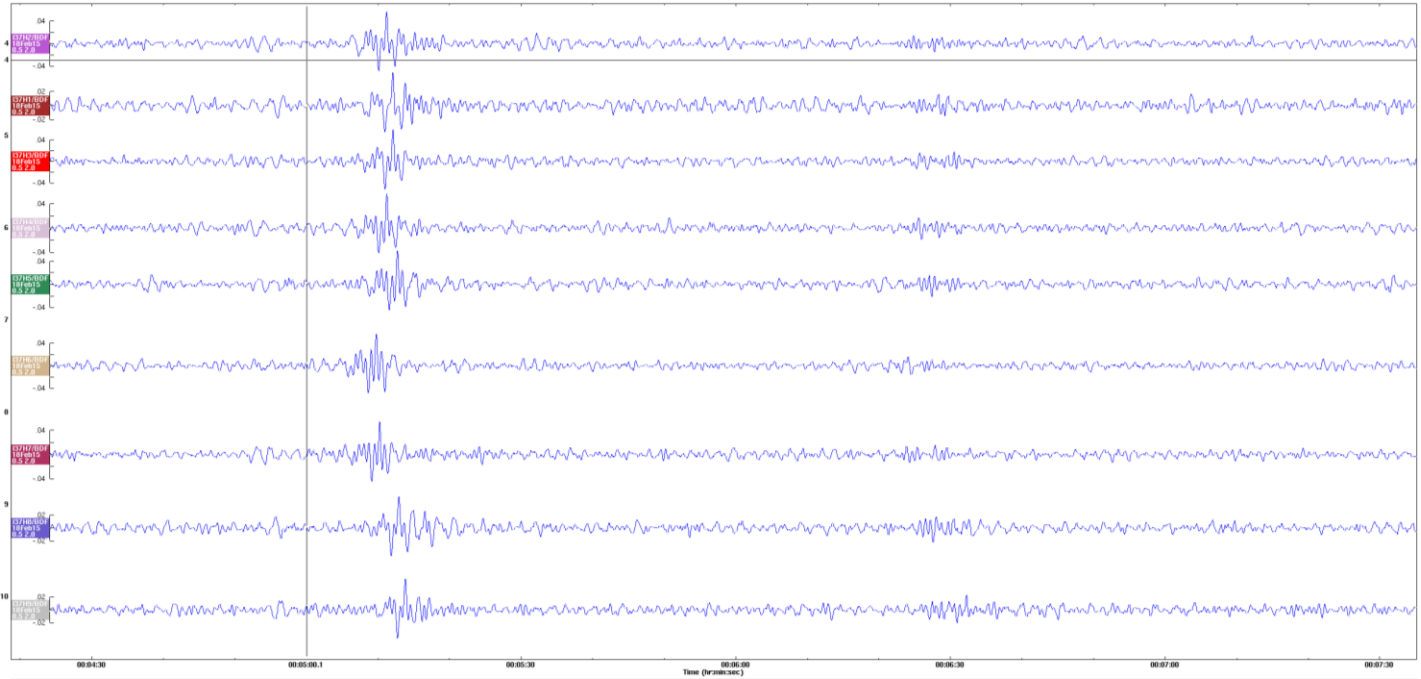
The events to find are within quarries with historical blasts. Some mines are detected by seismic and infrasound stations *(e.g.*, Aitik mine). There are underground mines with blasts detected only by seismic stations *(e.g.*, Kiruna). There are areas with repeating **pure infrasound** events. No masters are made for such places yet.

SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION



Infrasound station
I37NO
Filter: 0.5 Hz – 2 Hz
9 channels

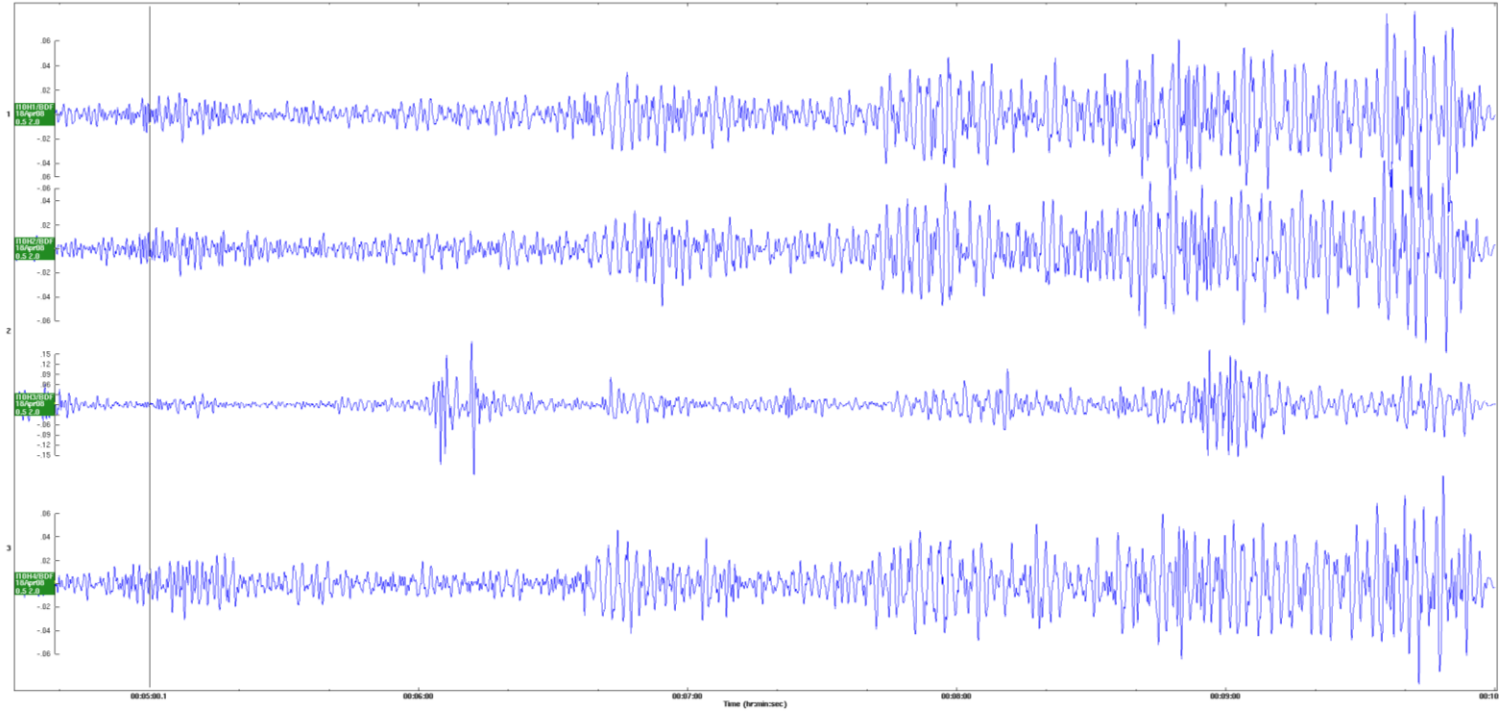
Infrasound signal associated with mining events in Scandinavia. Proper templates have to be selected.

SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Poster No.: P3.2-356

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CTBTO PREPARATORY COMMISSION



Infrasound station I10CA: 4 channels

Infrasound signals at I10CA have large amplitude.

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

Standard XSEL processing

WCC detection

1. Varying template length
2. Varying # of working channels (arrays and 3C)
3. Frequency bands: 0.75 Hz to 8 Hz. Choice depends on station: ARCES vs. CMAR
4. Adaptive detection (SNRcc=STA/LTA) threshold for CC traces
5. STA and LTA definition
6. STA and LTA length
7. FK using CC-traces
8. Standard detection and FK for array stations (e.g., for screening of CC-detections)

Local Association

1. Area of master responsibility
2. Spacing between nodes of virtual event locations
3. Minimum number of associated stations (e.g., ndef=3)
4. Association window (e.g., 20 s)
5. Origin time residual for defining/ associated arrivals (e.g., ±3 s)
6. Weight of XSEL events > W_{min} as a sum of station probabilities (from the REB empirical statistics)
7. Quality of detections SNRcc
8. Quality of detections SNR
9. Residual of relative magnitude at stations

Conflict Resolution

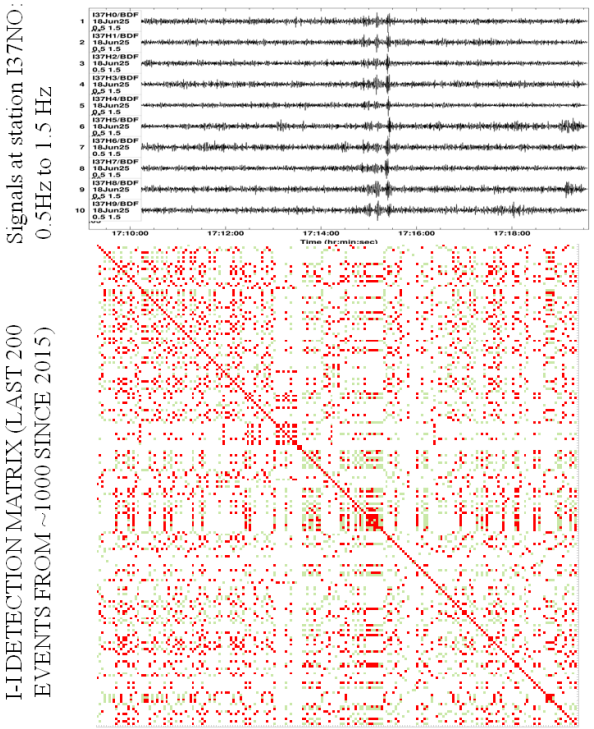
When two XSEL events from the same of different masters have detections at the same station within tolerance limit (LA tuning parameter), 20 s :

- Compare weights, Wi and Wj, of the competing XSEL events and save this detection with the bigger event.
- When Wi and Wj are equal – the number of associated stations wins
- When both above equal - standard deviation of the origin time (scattering) of the competing XSEL events
- Then remove events with parameters below EDC

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

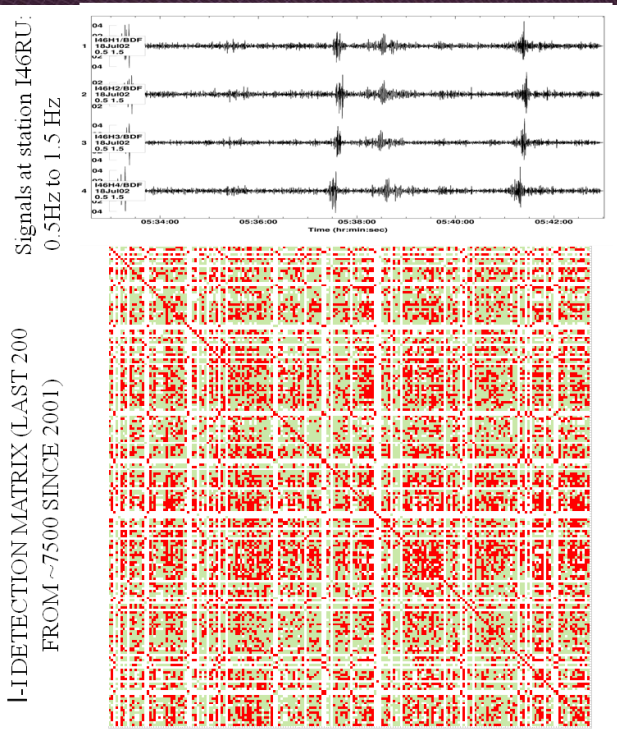
Ivan Kitov

Experience with infrasound



Detection (red dot) threshold SNRcc> 4.5. Distance to REB events from 3 to 15 degrees. 9 sensors

1. The observed repeatability of infrasound signals from quarry blasts together with high quality seismic signals at regional primary seismic stations allow automatic finding and identifying mining activity.
2. The performance of infrasound IMS stations in building REB events depends on epicentral distance, seasonal propagation efficiency and the number of sensors in infrasound arrays.
3. When seismic stations are not available at regional distances or have poor sensitivity due to high seismic noise, infrasound stations, which are very close to mining areas (like I47ZA or I46RU), can be used instead of seismic stations and.



Detection threshold SNRcc> 4.5. Distance to events from 1 to 14 degrees.

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

#	orid	origine time	lat, deg	lon, deg	nass	mb	Jdate	Sreg	evid	infra match	pure seismic	60 s
1	15460810	1518422405	63.93	28.20	5	-999.0	2018043	49	15460810	1	0	1
2	15460101	1518432181	67.71	33.84	10	-999.0	2018043	49	15416420	1	0	1
3	15460147	1518435351	63.03	28.01	8	-999.0	2018043	49	15416590	0	0	1
4	15464563	1518611392	63.87	28.90	6	-999.0	2018045	49	15452317	1	0	1
5	15461488	1518688804	64.70	30.93	6	-999.0	2018046	49	15461488	1	1	1
6	15461558	1518711867	67.76	26.85	4	-999.0	2018046	49	15461555	0	0	0
7	15446540	1518741690	67.80	20.61	12	3.4	2018047	36	15432230	1	1	1
8	15461785	1518782073	68.14	36.21	3	-999.0	2018047	49	15461785	0	0	0
9	15465072	1518784614	63.93	28.76	7	-999.0	2018047	49	15435172	0	1	1
10	15465075	1518804101	67.11	20.90	7	-999.0	2018047	36	15461560	1	1	1
11	15464346	1518835811	67.75	33.95	16	3.3	2018048	49	15437043	0	0	1
12	15477198	1518853414	67.89	20.43	9	-999.0	2018048	36	15477191	1	1	1
13	15479674	1518865668	67.71	29.83	6	-999.0	2018048	49	15438858	0	0	1
14	15464786	1518866839	67.65	30.17	6	-999.0	2018048	49	15456932	0	0	1
15	15478144	1518873754	67.83	36.58	4	-999.0	2018048	49	15478144	0	0	0
16	15479611	1518874264	68.13	36.71	3	-999.0	2018048	49	15439950	0	0	1
17	15478154	1518876626	68.00	32.64	6	-999.0	2018048	49	15478154	0	0	1
18	15478348	1518879206	67.65	20.95	9	-999.0	2018048	36	15440239	0	1	1
19	15463023	1518919307	67.14	20.90	9	-999.0	2018049	36	15442049	1	1	1
20	15997904	1530844569	67.12	21.18	10	-999.0	2018187	36	15987652	0	1	1
21	16001147	1530844747	67.82	20.61	11	-999.0	2018187	36	16001147	1	0	1
22	16002926	1530854864	67.32	20.72	5	-999.0	2018187	36	16002925	0	0	1
23	16011059	1530870324	67.64	21.34	6	-999.0	2018187	36	15989782	1	0	1
24	16001788	1530871783	67.72	26.71	4	-999.0	2018187	49	16001787	0	0	0
25	16010674	1530876561	63.84	27.74	5	-999.0	2018187	49	16010674	0	0	1
26	16007335	1530905854	67.76	33.61	10	-999.0	2018187	49	15990807	0	0	1
27	16006190	1530961668	67.63	30.34	8	-999.0	2018188	49	15991887	1	0	1
28	16006243	1530962474	67.67	33.58	8	-999.0	2018188	49	16006243	1	0	1
29	16011281	1531127203	64.35	25.00	7	-999.0	2018190	49	16011281	0	0	0
30	16015821	1531216818	64.61	31.44	8	-999.0	2018191	49	16002796	1	1	1
31	16015125	1531233197	62.61	22.90	7	-999.0	2018191	49	16015125	1	0	1
32	16014477	1531242059	67.10	21.14	7	-999.0	2018191	36	16004425	1	1	1
33	16024168	1531351746	67.85	20.58	7	-999.0	2018192	36	16024168	0	1	0
34	16032016	1531390277	64.58	31.07	7	-999.0	2018193	49	16026194	1	1	1
35	16026586	1531399184	68.11	32.36	5	-999.0	2018193	49	16026586	1	0	1
36	16031667	1531437704	67.82	20.41	12	-999.0	2018193	36	16013104	1	1	1

Because of weak Pg/Pn arrivals at seismic stations from mining events the measured arrival times are subject to larger uncertainty and sometimes are not matched by 10 s rule. We extend the match rule by 60 s origin time difference well fit to the time spacing between mining events.

From 36 events in the area we match **30** with masters obtained from repeated (>30 within 0.5 degree) seismic/infrasound events. The XSEL shows good results. From 3 pure infrasound events no one was matched (I18DK templates are not built yet), but there was one alternative event close to the origin time of **15479611**. Infrasound IMS stations have significant input with 16 events would not be matched (2 stations or origin time within 60 s) without I-phase

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

#	orid	origine time	lat, deg	lon, deg	nass	mb	Jdate	Sreg	evid	infra match	pure seismic	60 s
1	15672162	1522869781	44.81	-106.65	5	-999.0	2018094	34	15672162	0	0	**1**
2	15668168	1522877668	43.73	-105.54	**11**	3.9	2018094	34	**15645522**	1	1	**1**
3	15677616	1523040923	43.83	-105.47	6	-999.0	2018096	34	15654668	1	1	**1**
4	15682212	1523210757	43.57	-105.34	**11**	3.7	2018098	34	**15662320**	1	1	**1**
5	15682288	1523213616	43.03	-105.05	5	-999.0	2018098	34	**15661792**	0	1	**1**
6	15681451	1523266427	41.42	-100.26	**16**	3.5	2018099	34	**15665462**	0	1	**0**
7	15693519	1523303087	44.83	-106.68	5	-999.0	2018099	34	15681548	1	0	**1**
8	15694154	1523304089	43.40	-105.30	7	4.0	2018099	34	**15666258**	1	0	**1**
9	15693452	1523305921	43.48	-105.31	5	-999.0	2018099	34	***15666838***	1	0	**1**
10	15693552	1523310220	43.51	-105.43	5	-999.0	2018099	34	15693552	0	0	**1**
11	15681453	1523360468	41.47	-100.49	**19**	4.0	2018100	34	**15668862**	0	1	**1**
12	15694447	1523375352	41.56	-100.48	9	2.7	2018100	34	15670599	0	1	**1**
13	15699901	1523386918	43.98	-105.59	**13**	4.0	2018100	34	15671054	1	1	**1**
14	16138713	1533687435	44.15	-105.39	6	-999.0	2018220	34	16125880	0	0	**1**
15	16137075	1533749757	45.64	-106.43	6	-999.0	2018220	34	16137075	0	0	**1**
16	16141739	1533846931	44.95	-106.73	5	-999.0	2018221	34	16141739	0	1	**1**
17	16141745	1533847238	43.79	-105.45	5	-999.0	2018221	34	16141745	1	1	**1**
18	16152603	1534014675	43.99	-105.37	**11**	-999.0	2018223	34	**16130484**	1	1	**1**
19	16152008	1534092652	44.72	-106.38	6	-999.0	2018224	34	16134994	1	1	**1**
20	16152895	1534179711	43.89	-105.55	5	-999.0	2018225	34	16152895	0	1	**1**
21	16153500	1534183290	43.79	-105.55	7	3.8	2018225	34	16152901	1	1	**1**
22	16152974	1534200979	43.60	-105.54	4	-999.0	2018225	34	16152974	1	1	**1**
23	16157491	1534278614	43.80	-105.71	9	-999.0	2018226	34	16157491	1	1	**1**

From 23 events in the area we match **22** with masters obtained from repeated (>30 within 0.5 degree) seismic/infrasound events. The XSEL shows good results.

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

Results: Lake Issyk-Kul – Lake Baikal

period	start	end	# REB events with infra	# of REB events with >2 seismic stations	Total number of events	# of REB events matched by XSEL: masters with infra	Infra events % matched	Total events % matched
week 1	2018043	2018049	95	94	104	85	0.89	0.82
week 2	2018094	2018100	33	34	37	29	0.88	0.78
week 3	2018187	2018193	55	57	59	47	0.85	0.80
week 4	2018200	2018226	50	47	50	44	0.88	0.88

- The number of events with infrasound stations is larger then in Scandinavia and Eastern North America
- Master events with infrasound are able to find from 85% to 89% of REB events with infrasound by two station match. Infrasound station I46RU is very close to the mining area.
- When only master events with infrasound stations are used, the WCC method is able to find from 78% to 88% of all REB events by two station match
- Auxiliary array stations KURK and BVAR are used as a primary station to calculate event weight

Finding repeating mining events using waveform cross correlation at seismic and infrasound IMS stations

Ivan Kitov

CONCLUSION

- Waveform cross correlation (WCC) is used to find seismic and seismic-infrasound events in the current IMS data, which are similar to one or more events from the historical REB (>600,000 events)
- Mining events (seismic and seismic-infrasound) and repeated events within continents are processed separately in order to use the advantage of source similarity for the co-located master events
- The XSEL match rate in all studied regions is between 85% and 96%