



New applications at the IDC for SHI Expert Technical Analysis

Ivan Kitov ; Mikhail Rozhkov ; Yuri Starovoyt ; Ronan Le Bras

ls1-353



PUTTING AN END TO NUCLEAR EXPLOSIONS





Expert Technical Analysis: Seismic, Hydroacoustic, and Infrasound (SHI) Technologies

Problems and related objectives

The Preparatory Commission for the CTBTO routinely operates software to process timeseries data from *seismic, hydro-acoustic, and infrasound* (SHI) stations from around the world. The data are transmitted to the IDC (International Data Centre) in Vienna in nearreal-time (within 5 minutes). The data are processed *to detect, build, locate, and screen events that may be nuclear explosions*. The observation and processing systems are required to be *sensitive to small events, especially in unusual locations*. The data with the *highest resolution* are typically provided by array stations, and *advanced signal processing methods* can significantly *improve detection* of monitoring-relevant signals, *effectively associate* them with events, and *locate* these events more *accurately and with lower uncertainty* for the purposes of the Treaty.





Expert Technical Analysis: SHI Technologies

One of the IDC services to the States Parties is Expert Technical Analysis (ETA). In particular, Paragraph 19 of the Protocol to the CTBT (Part I) says that "The IDC shall carry out, at no cost to States Parties, special studies to provide in-depth, technical review by expert analysis of data from the IMS, if requested by the Organization or by a State Party, to improve the estimated values for the standard signal and event parameters". Paragraph 20 provides that the methods for supporting data access and the provision of data shall include the following service: Assisting individual States Parties, at their request and at no cost for reasonable efforts, with **expert technical analysis** of IMS data and other relevant data provided by the requesting State Party, in order to help the State Party concerned to identify the source of **specific events**. The output of any such technical analysis shall be considered a product of the requesting

State Party but shall be available to all States Parties. According to Annex 2 to the Protocol, one of the defining parameters estimated by the IDC is the hypocentre solution based on SHI data, which includes the *origin epicentre coordinates and depth*. There are characterization parameters for International Data Centre Standard Event Screening mentioned in the same Annex: *spectral ratios of phases; focal mechanism;* relative excitation of seismic phases; comparative measures to other events and groups of events. In routine IDC processing, source location is calculated with the globally robust and steady technique providing quasi-uniform location accuracy and uncertainty which depends on the quality of relevant detections. For ETA, advanced and state-of-the-art techniques should be used to **enhance automatic and interactive location**.





Selected SHI applications (seismic)

- 1. ETA Suite Prototype for SHI data : Interactive and Automatic Spot Check Tool based on waveform cross correlation (REB/SSEB completeness and consistency)
- 2. ETA Suite Prototype for SHI data: Depth determination based on moment tensor estimation, ParMT (location, depth, focal mechanism)
- 3. Spectral discrimination of the DPRK explosions and aftershocks (nature of events)
- 4. Detection of ultra-weak aftershocks of the DPRK tests (focus on small events)
- 5. Independent component analysis (separate merged signals from different events)
- 6. Generalized approach to the master event template design (detection, association, screening)
- 7. Ambient Noise Based Methods (velocity structure, beam loss)





ETA Suite Prototype for SHI data : Interactive and Automatic Spot Check Tool based on waveform cross correlation

- *Spot Check Tool development*: to facilitate a work of the Independent Reviewer (IR)
- Underlying methodology: waveform cross correlation
- Processing stages: master selection, detection using matched filter, Local Association (LA), Conflict Resolution (CR), Spot Check, Comparison with other bulletins
- Spot Check Modes: Interactive and Automatic
 - Interactive: under flexible scenario developed by the IR
 - Automatic: on daily basis, building XSEL (cross correlation standard event list) bulletins and conducting automatic comparison with SELs (same day analysis) and REB (upon its completion) bulletins.



CONTROL PANELS, SPOT, EVENTS

 \mathcal{S}

ĹШ

 $\overline{\mathcal{O}}$

PRE

New applications at the IDC for SHI Expert Technical Analysis Ivan Kitov; Mikhail Rozhkov; Yuri Starovoyt; Ronan Le Bras



ETA Suite Prototype for SHI data: Interactive Spot Check Tool







ETA Suite Prototype for SHI data: Interactive Spot Check Tool

\leq	SCT					SCT							_
\bigcirc	Control Panel					Control Panel							
ECTI	Start time 302120111312 × C Two Oros Constitutor Detection Al regress	Ai stations +	Association		Comparison All filters +	Start time:	2021/05/14 13:10 Cross Correlation shold	Files	Detection	> ~	sociation	Comparison	
	Bulletin: FEB ¥ Start Day: 2021/05/14	X 🖬 End Day	2021/05/14	× 🗂 ORID:	v	Customise	Station Parameters						
\Box	Latitude from: -90	to:	90			Detection Wi	ndow (s):	60	Historical perfe	ormance			
						Filter # min:		2	~				
\bigcirc	Longitude from: -100	to:	180			Filter # max: Detection set	tings:	4	~				
\cup	Magnitude from: 0	to:	0			Detector type	E		~				
•••						Duration:			~				le
ဂ်	Depth from (km): 0	to (km):	700			CC SNR three Lead window	inoto: Ien before signal, s:	3					
						Signal templa	ite len, s:	8					
<u>ц</u>	Hide Advanced Perameters					Station Adv	anced Parameters						
Ā	Station configuration:	Segment Length (s):	80	Masters Max Number:	20	Hide Advanced	d Paramuterà						
		Bulletin ORID min:	1	Bulletin ORID max:	100	Master De	pendent	544V-0 640		P.u.t.			
- 1 I		Choice of Master Events by	principal characteristics			106	Magnitude 4	11.2	120.34	8.3	RMSQ value:	3	
\equiv		Proximity Type:	Smaj 🗸 🗸	Proximity Value:	3	107	3.5	10.8	110.54	5.2			
\cup		Latiliado feren:		ter.	0	108	5	21.3	133.67	6.9	SNR definition:	Standard	~
		Contract in card		-		100	-	4.51	are of		DFX detection		
		Longitude from:	0	to:	0								
<u>'</u>		Megnitude from:	0	tec	0								
\leq		Depth from:	8	to:	0								
S		 Natural Synthetic Subspace 	QC based Seismic Infrasound	□ N	zlear								





ETA Suite Prototype for SHI data: Depth determination based on moment tensor estimation, ParMT



Processing Overview



- Programs in Seismology allow for use of source-specific models; e.g., MDJ2.
- hudson96 allows us to get high-frequencies into the teleseismic body waves.

Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO







TDSearch - t*/depth search processor (MT involved)



Map widget



CTBTO.ORG

PUTTING AN END TO NUCLEAR EXPLOSIONS



62 6.0 5.8 5.6 Ň 5.2 5.0 4.8 46 48 9.6 14.4 19.2 24.0 0.178727 Depth (km) Min Max: 0.00284374 0.574955 0.004761846 0.20.30.40.50.60.7 Inint Prohab mm as M -nn -m -sha m

T

m

-Am

m

m

m

-n

52 5.0 48 4.6 ₹ 4.4 4.0 1.8 2.4 3.0 Min: 0.40271 0.6 1.2 Depth (km) Min: Max 0.003759098 0 781367 0.008389519 0.40.50.60.70.80.9 Inint Probabili 23-m im 20 s 1 -m mm -m ------Am -m -mm min -mym -NA m ----m m mm mm -no m n mo mm ~m~ m Mm m no mm m -m An mm m



Canada 2017-12-22 08:00:13 UTC 65.481°N 134.083°W 3.5 km depth



Joint Probability

Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO

m

nn

s

-Am

CTBTO.ORG









Pres. No.:

New applications at the IDC for SHI Expert Technical Analysis Ivan Kitov; Mikhail Rozhkov; Yuri Starovoyt; Ronan Le Bras











Spectral discrimination of the DPRK explosions and aftershocks



Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO

NCE AND TECHNOLOGY CONFERENC

ls.1-353

Pres. No.:





Spectral discrimination of the DPRK explosions and aftershocks



Large (100-20000) Mahalanobis, MD, distances between groups. Critical α =0.001 corresponds to MD =16.3 for df=3



Short (0.1-4.2) Mahalanobis distances within groups





Detection of ultra-weak aftershocks of the DPRK tests: multi-master method

	id	Origin time	Epoch time	Relmag	KSRS	USRK	Total	1			_	~ ~									~							~ _	_
1	2006282_0	01:35:28						1		3 3	3	565	5 6	30	2 2	2	2 2	1213	- <u>-</u>	6 8	8	8 6	50 3	2 2	5	8 8	121	2121	2
2	2009145_0	00:54:43]		1724	172(1728	1732	1133	1735	1134	1134	1810	6	1908	306	2002	2007	2008	2003	203(2032	2103	2103
3	2013043_0	02:57:51								8 8	8	8 8	8 8	8	8 8	8	8 8	8 8	8	8 8	8	8 8	8	20	30	30	202	30 30	8
4	2016006_0	01:30:00							2017266_1	7.6 13.1	_	44.2 47.8	28.2 28.	.3 17.4	15.2 13.0	11.4	15.7 20.0	4.0 9	.5 12.4	17.9 15.	5.4	10.8 15.3	8.9	7.6 7.	1 8.7	15.5 7.3	3 5.3	11.1 5.3	7.4
5	2016253_0	00:29:58	1473380998.67	5.35	25	27	52	<u> </u>	2017266_2 2017285_1	9.1 14.5 7.9 9.3	39.4 38.6	32.5 35.2	22.1 18. 18.5 29.	2 11.3 6 18.4	15.7 9.7 8.2 10.3	7.9 3 11.5	17.2 19.7 20.9 19.2	4,4 5 5.1 1	.8 19.5 .2 9.8	28.6 24.3	9.9 7.1	10.2 16.2 7.9 14.8	7.7 6.7	8.2 7. 7.3 7.	7 11.9 5 5.9	16.5 12.7 8.2 8.0	9.0	12.8 7.5 7.8 5.6	4.9
6	2016255_1	01:50:48	1473558648.01	2.86	22	23	45	$\overline{\mathbf{z}}$	2017304_1 2017335_1	3.5 2.9 2.9 3.4	3.3 22.9	3.8 3.7 19.5 9.4	3.3 4	2 5.3 .8 6.5	3.4 3.0 8.7 5.7	3.7 4.7	5.1 5.1 8.5 7.5	2.5 4.0	.7 3.0 .9 11.1	2.6 4.1 10.1 8.4	2.7 4.3	2.5 3.3 3.5 9.0	2.9	3.0 2. 5.5 4.	8 2.5 8 5.8	4.1 3.2 5.1 5.1	2.7 3 3.9	2.8 3.0 4.3 2.4	2.8 2.3
7	2017246_0	03:30:00	1504409398.92	5.94	25	22	47		2017339_1 2017340_1	6.6 9.5 5.2 6.3	26.9 11.2	24.4 32.1 8.1 9.7	21.9 5.4 17.	28.9 .7 8.8	9.2 19.1 3.2	12.4 5.7	24.7 20.1 11.7 7.8	6.5 S	.9 7.2 .7 5.5	14.4 11.0 7.8 7.1	10.8 8.0	5.1 12.6 2.5 7.0	9.8 6.2	9.7 7. 6.7 4.	2 5.9 0 4.2	7.1 7.7 3.0 3.	3.8 1 2.1	5.6 3.2 3.1 2.1	4.7
8	2017246_1	03:38:31	1504409910.45	4.11	23	14	37	<u>д</u>	2017343_1 2017343_2	2.6 2.8 2.7 5.9	9.1 14.5	5.3 5.6 15.0 10.4	4.2 10. 7.5 21	.5 9.6	3.0 5.0 7.5 11.3	3 20.1	13.3 15.7 35.5	3.8 5.7 9	.9 3.8 .5 6.9	3.7 3. 9.8 9.0	4.2	3.5 3.7 5.4 5.8	3.3 3.3	3.3 3. 4.7 3.	3 3.0 5 6.0	4.1 3.4 7.8 6.	2.3	2.1 2.1 4.3 3.4	1.9 2.9
9	2017246_2	09:31:28	1504431087.60	2.66	22	22	44		2017343_3	2.8 5.3	13.1	17.1 8.0	6.7 17.	.3 15.6	5.6 8.5	17.9	36.2	5.2 8	1.0 7.7	9.5 8.	6.5	6.5 6.3	4.7	4,4 4.	6 6.5	7.4 3.0	3,4	3.7 2.8	2.7
10	2017266_1	04:42:58	1506141777.71	3.06	22	19	41		2016255_1	2.5 4.2	3.5	7.9 3.7	3.5 4	.0 6.3	3.0 5.4	4.6 5.1	6.7 6.0	3.0	1.5 2.7	4.3 4.1	4.9 3.7	3.8 5.3	4.4	4.9 3.	1 2.9	5.4 4.5	5.6	3.4 2.6	3.8
11	2017266_2	08:29:14	1506155354.55	3.60	25	26	51		2018036_1 2018036_2	2.7 2.8	6.2	7.5 3.7	3.0 5.	.9 6.2 .1 4.4	2.4 3.6	5 4.6 5 4.1	8.7 8.4 6.6 7.1	2.8	1.9 3.5	6.7 4.3 3.7 4.0	3.8	2.4 3.7	5.0 2.8	5.9 3. 3.7 2.	1 5.2 9 3.1	8.1 5.7 4.9 Z.1	3.3	4.8 2.9 2.4 2.2	2.5
12	2017285_1	16:41:07	1507826465.00	3.27	27	27	54		2018036_3 2018037_1	2.6 3.9 4.0 2.8	6.5 7.3	7.2 3.5 4.7 5.8	4.1 5.	.4 3.0 .4 4.3	2.2 2.7 2.9 2.7	7 3.3 7 2.9	4.7 4.5	2.9	.7 2.9 .3 2.5	2.7 3.0	2.6	2.2 3.4	2.4	3.4 3. 3.8 3.	1 2.8 2 2.3	2.5 3.0	7 3.0	2.8 2.2 2.8 2.8	3.0
13	2017304_1	10:20:13	1509445213.19	2.52	12	23	35		2018037_2 2018037_3	2.4 2.5 3.0 4.0	5.6 16.0	5.0 5.0 18.2 14.3	4.4 5. 12.2 13.	.8 3.6 .4 7.6	3.0 2.9 6.3 6.6	2.6 5 5.0	4.0 4.2 10.2 10.0	2.9 4 4.5 8	1.0 2.5 1.2 7.1	3.0 3.0 6.7 6.3	3.7 3.8	2.8 4.8 5.1 7.8	2.8 6.3	3.3 3. 6.4 3.	2 2.8 8 5.9	3.3 4.4 10.9 7.0	3.3	2.5 2.1 5.0 4.4	2.5
14	2017335_1	22:45:54	1512168354.43	2.91	24	26	50		2018038_1 2018039_1	4.8 6.1 2.9 2.8	15.9 8.9	15.9 16.0 8.0 8.6	12.2 19. 6.6 10.	0 12.3 2 5.9	6.3 8.8 4.6 6.1	8 4.8 L 6.0	12.5 8.9 9.0 9.9	4.2	.5 5.1 .1 3.0	7.2 5.3	4.6	4.8 10.8 3.9 6.8	5.4 4.0	5.2 4. 5.2 4.	9 4.1 3 3.8	11.6 7.0 5.2 5.1	3.9 4.3	5.5 4.6 4.4 2.5	3.0 2.5
15	2017339_1	14:40:52	1512484851.85	3.14	23	24	47	2	2018112_1 2018112_2	2.8 3.5 2.9 3.4	11.6 15.7	12.3 8.5 15.8 15.0	7.1 8. 13.1 14.	.2 5.8 .7 8.2	4.5 3.9 6.3 7.7	9 5.7 7 6.3	8.2 10.5 9.1 9.0	4.1 5.7	.7 4.0 .4 4.9	5.4 5.9 4.6 5.0	3.7 4.3	3.4 6.5 4.6 7.3	6.6 6.7	6.2 Z. 7.1 4.	9 3.5 7 4.4	7.2 3.6 10.1 6.1	3.3 5 4.2	3.9 2.3 4.8 3.4	2.3 3.7
16	2017340_1	16:20:05	1512577204.78	2.6	11	18	29	S		9 7	- 5		m –	~ ~	15	5 5	2		5 5	19	3 =		4 9	5 5	5	~ ~	-	5 5	-
17	2017343_1	06:08:40	1512799720.05	2.79	19	23	42			016253	017246	018036	0.18036	0.18.037	018038	018035	018112	10610	19012	19158	19233	19323	019325	120071	020308	020308	020308	021108	021110
18	2017343_2	06:13:32	1512800011.25	3.41	16	24	40		2017266 1	6.9 3.8	4.7 16	5 75 .9 8.3	8.7 9.6	8.7 21	4 18.1	8 8 13.1 14.4	20.6 1	2.6 13.6	8.1 14.8	14.9 9	.7 8.7	15.2 15	5 11.2	5.7 17	.7 8.2	9.5 15.5	9.6	9.2 18.2	9.1
19	2017343_3	06:40:00	1512801600.08	3.11	24	27	51		2017266 2 2017285 1	8.6 5.9 8.5 6.5	8.0 15 3.6 14	.3 10.3	7.7 6.0 9.2 8.7	6.7 19. 8.1 20.	.8 15.5 : .0 23.7 :	11.8 16.2 15.2 12.1	16.9 1	2.0 12.5 0.6 13.9	7.1 12.7 8.6 7.4	13.3 8 9.5 6	.2 8.5 .8 4.7	12.6 12 15.4 15	.6 10.9 .8 8.5	4.9 18 5.6 10	2 8.0 .9 5.1	10.7 12.8 5.7 7.5	6.8 7.0	8.3 17.4 5.3 14.6	8.0 7.8
20	2018036_1	10:32:30	1517826749.75	2.67	17	27	44		2017304 1 2017335 1	4.8 2.7 4.9 3.7	3.0 3. 4.0 11	.6 3.3 .1 4.5	2.7 2.5 5.4 6.2	3.4 5.9 5.9 13.	9 3.8 .0 10.7	3.6 4.8 7.1 8.2	4.8	19 3.6 19 7.5	3.2 3.1 5.9 4.1	5.2 3 6.5 3	.7 3.6 .7 3.1	3.3 3. 9.0 9.	7 3.5 7 6.9	2.7 3. 3.2 5.	9 2.9 5 3.3	3.0 3.4 2.2 3.4	3.5	3.3 6.5 2.9 8.1	3.2 2.9
21	2018036_2	20:07:30	1517861249.34	2.79	17	24	41		2017339 1 2017340 1	7.9 6.0 4.5 4.2	5.4 14	.3 7.0 8 3.3	6.6 7.7 3.3 3.7	7.3 17.	.3 19.3 : 2 9.2	12.6 9.6 6.6 3.8	18.8	12.5 10 5.7	7.3 7.5	12.0 4 5.3 2	.8 5.1 .7 3.5	12.3 11	.8 7.0 5 5.6	3.6 9. 3.7 4.	4 4.1 2 2.6	4.3 5.9	43 0	4.8 15.2 2.4 7.0	5.6 3.0
22	2018036_3	21:57:35	1517867855.28	2.96	12	25	37		2017343 1 2017343 2	3.7 3.1 6.7 5.9	4.1 3.	8 3.9 6 6.7	5.9 3.1 3.8 4.1	3.6 10.	8 3.8	5.1 5.7 7.7 9.7	8.3	15 6.0	4.0 2.5 5.3 7.8	10.3 4	.1 2.9	4.6 3/ 5.9 5/	5 5.1 8 8.0	2.4 3.	3 2.6 9 3.3	4.4 7.1	4.1	3.5 10.6	5.4
23	2018037_1	04:49:36	1517892575.86	2.65	8	23	31		2017343 3 2016255 1	5./ 4.8 17.6	5.2 7. 12.8 8.	5 7.4 1 4.0	4.5 3.9 8.2 7.0	4.1 9.0	0 6.6 3 9.9	4.9 4.7	10.1	12 5.8	5.9 4.8 6.6 4.9	7.0 5	.7 3.6	7.0 8.	4 8.4 1 3.9	4.4 6.	0 3.9 7 4.1	4.5 5.6	4.3 5.2	5.1 11.0	5.7
24	2018037_2	10:12:30	1517911950.12	2.58	8	23	31	្រា	2017246_2 2018036 1	7.7 11.5 6.1 5.5	4.3	1 4.1 10.9	5.7 <u>3.0</u> 19.0 9.7	3.3 9.1 14.6 32	7 5.1 .4 23.2 :	3.3 7.4 19.5 19.0	6.6 32.7 1	17 <u>3.4</u> 2.3 21.6	3.6 3.1 8.3 14.5	4.3 3 20.2 1	.3 4.7 1.6 13.4	4.8 4. 18.4 22	8 4.2 .1 7.3	3.2 4. 6.8 27	5.1 2 16.0	5.3 4.1 11.6 21.0	4.1 8.0 1	3.5 4.3 15.5 22.4	5.9 10.1
25	2018037_3	10:53:52	1517914432.06	3.02	26	27	53		2018036_2 2018036_3	3.3 2.6 4.4 3.2	3.7 11 2.9 20	.1	6.2 2.6 6.1	4.0 14. 6.7 15.	.7 5.2 5 15.7 :	6.5 9.3 15.8 5.8	9.3 17.4	18 8.0 10 16.5	3.7 6.3 5.2 8.7	4.4 5 9.4 1	.9 7.8 8.0 5.5	6.0 8. 8.5 13	9 6.8 .5 3.6	2.3 8. 3.5 18	1 5.3 .2 6.1	6.5 7.6 4.5 130	2.6 2 3.8	5.9 5.3 7.1 6.8	4.4 3.7
26	2018038_1	21:46:23	1518039982.91	3.34	27	27	54		2018037_1 2018037_2	4.2 4.9 4.7 3.7	2.8 8. 3.2 15	0 2.5	6.0 7.2 7.7	8.3 11. 14.	.4 16.3 .2 18.7 :	8.8 4.0 13.2 6.8	15.1 18.7	13 10.5 7.5 13.8	5.8 8.7 4.1 7.7	11.7 8 12.5 10	.1 4.3 0.2 5.9	7.5 7. 8.9 12	7 2.7 .4 2.7	2.8 12 3.4 15	.6 3.7 .7 6.7	2.8 12.9 4.7 13.7	5.3 2 4.6	6.2 14.9 8.0 13.9	4.4 2.6
27	2018039_1	17:39:17	1518111556.77	2.74	23	26	49		2018037_3 2018038 1	10.9 8.3 12.7 8.6	7.9 31 5.6 25	.2 17.5	7.1 11.4 9.3 18.7	16.7 20.5 25	22.9	17.9 27.8 25.7 11.3	38.3 1 37.4 1	9.6 21.6 1.1 26.6	8.0 17.8 11.3 16.2	23.3 1	11 18.6 5.5 10.3	17.5 23 18.4 19	.5 9.9 .7 9.0	6.7 26 8.7 34	.8 19.2 .6 9.0	14.8 25.3 5.9 25.	7.9 1 3 13.7 1	17.1 22.7 13.5 42.3	8.3 13.1
28	2018112_1	19:25:08	1524425108.31	2.70	23	27	50		2018039 1 2018112 1	6.4 4.0 6.2 3.6	3.3 20 6.9 17	.6 7.4 : .9 12.1	7.1 9.6 6.6 4.6	14.2 18. 6.6 26	.6 24.7 .0 8.6 :	11.1 10.0	22.9	5.2 29.4 2.3 10.6	9.3 9.6 5.7 9.5	16.6 2 6.9 8	.3 9.1 .5 14.0	13.4 16 11.1 15	.8 5.8 .7 11.2	6.5 33 2.7 12	2 6.8 2 13.1	7.5 15.5 15.2 13.5	8.9 1 3 6.1	10.4 20.7 9.2 12.4	7.4 6.7
29	2018112_2	19:31:18	1524425477.81	2.98	27	27	54	1	2018112 2	11.4 9.5	5.7 34	.6 10.9	8.1 15.9	20.4 39.	5 33.3	23.3 19.8	1	5.8 24.8	10.9 18.0	22.6 1	5.1 17.2	24.4 27	.5 9.1	7.9 31	.8 17.6	12.1 32.5	12.8 1	18.0 24.5	12.2



Detection of ultra-weak aftershocks of the DPRK tests



Maximum SNRcc values among all templates associated with two different clusters: DPRK5/ DPRK6 for the aftershocks associated with DPRK5/ DPRK6.

Two stations are presented USRK and KSRS. The maximum SNRcc obtained by templates related to the DPRK5/DPRK6 are much larger than those related to the DPRK6.The difference between max SNRcc values illustrate the separation into two clusters.

Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO

NCE AND TECHNOLOGY CONFEE

ls.1-353

Pres. No.:





Detection of ultra-weak aftershocks of the DPRK tests



The number of associated templates at two stations for the aftershocks associated with DPRK5 and DPRK6.





Pres. No.:

Independent component analysis

Quarry blast signals separation

Quarry #1

Whentern

where we are a stand to the stand of the stand

web like way to way and plant the commence of the state of the

h h fighter car is a strategy and the state of the state

angenerstadieter van de angewerste weer ander angewerste angewerste angewerste angewerste angewerste angewerste

ety and the experiment of the second of the se

how when we wanted a second south and the second se

Separation results. Original signals, separated

(ICA) and PCs of original signals

www.weathing.com/and/anapat/ endered we developed and a difficult of the second second second second second second second second second second

server when we will be the share of the share of the state of the

and a second and a second and a second se

โดงไปไปประการจากไปไปเรื่องๆประการจะสมสาขาวที่ได้ไรการได้

mann

mannom 200 300 400 500 600 700 600 000 000 000 000 000 000 000 000

Martin Martin Martin

700 800 900

Quarry #2

hand be a second the second n mar white a market allower and an all when the she will all the states of the states r (-alger) - ter Andree en algere date alaf et bijdet het helde Angleine - et site bleker alem bei platestrates will a sold a subplate for the second states of the second s Narwales Narween and several properties of the South State of the Sout mW_logowysowwale-atomalike/oute-whates/acomatike/iterake/ie-ake -Wor Wedness - -----s Hitter Care Welcomment for the first Welder Welch Welch Constrained with the n Walan in a name and a name and a state of the Male Marin was what was a ferral what has a ferral was the

where he was a state and the second second second second ahalMangarangananahalighan Manananahanananahana

Quarry #1+ Quarry#1 signals mixture

-manine hill Wald a part in a share wind wind and the second state of th



Separation results. Original signals, separated ICA) and PCs of original signals

and the second	Englis Array Elevent Events1	-
whitehall		\sim
www.w	-1 100 200 300 400 500 600 700 800 300	1000
Marshine	Single Anay Elevent Events	
and the state of t		\sim
www.www.www	11 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1800
~Mahaman All Mar		
Northward	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	\sim
	100 201 300 400 500 600 700 800 900 100 Last independent Component	1000
wan-waarya Wan-Walaya	man	~
	110 28 300 400 500 600 700 800 500 500 Find Principle Component Event #1	1000
waynaha		~
ware when we	130 200 300 400 500 600 700 800 900 First Precipie Component Event #2	1000
Walawawalawa	· · · ································	~
100.00 ALAA		

http://www.com/align.com/glance-align.com/alig	antweethanderschellerseterssetelschele
	a fitte of the constant of the constant of the
annan alphalatain an taopan alkan dinandijadata	
\	www.www.www.www.www.www.www.www.www.ww
to-standar-andration to-state the state of the	MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
1.2mp-reveal.the of the design	-allfund have proportion and by the
Verdene-Madamber	- Mingh man and man man man man man
hansen an terreter and the station of the second	MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
ripilipishawit raikumitika (karanatarika-aporo-araba)	willing/whereberrowie-wheneberrowie-
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	MMMMmmmmmmmMmMm
500 1000 1500 2000	2508 3000 3500 4000
Quarry #1+ Quarry#	2 signals mixture (
And a local state of the	Schull Known in section of the section of the
	Instructure and a second and a second and a second and a second a second a second a second a second a second a

Quarry #1

munimperminenter MWWWWWWWWWWWWWWWWW

William Walt an and marked and a second

www.wallowallow.walan.walan.walantahatika
er
commentations and a second and a second s
//
how washing the second second was a second
588 1000 1588 2000 2568 3000 3568 4000

Comparing: ICA components (restored signals) with first principle component of the array seismogram

Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO

#### CTBTO.ORG





Separating two regional earthquakes (left to right): EQ1,  $\Delta$ =8°; EQ2,  $\Delta$ =5°; Mixture; Decomposed, 400 sec; Decomposed, 50 sec.



ndependent component analysis





Generalized approach to the master event template design

Synthetic/Subspace master event extension: dimensionality reduction with multidimensional templates + N-D noise reduction



Disclaimer: The views expressed on this presentation are thus or use during rate do not necessarily renew or use or pro-



mmmm

mmm

------

manna

-----

-------

New applications at the IDC for SHI Expert Technical Analysis Ivan Kitov; Mikhail Rozhkov; Yuri Starovoyt; Ronan Le Bras



N-D Structures: Tensors and Quaternions PCA and Dimensionality and Noise Reduction

For any tensor  $\mathcal{A} = \mathcal{S} \times_1 U^{(1)} \times_2 U^{(2)} \dots \times_N U^{(N)}$ , the MPCA (Multilinear Principle Component Analysis) objective is to define a multilinear transformation that maps the original tensor space  $R^{I_1} \otimes R^{I_2} \dots \otimes R^{I_N}$  into a tensor subspace  $R^{P_1} \otimes R^{P_2} \dots \otimes R^{P_N}$  (with  $P_n < I_n$  for n = 1, ..., N)

Then the dimensionality reduction can be performed through the truncation of U and S terms and building the restored tensor  $\mathcal{A}_{red}$  through the block term decomposition (BTD) which approximates a tensor by a sum of low multilinear rank terms.

$$\mathcal{A}_{red} = \sum_{r=1}^{R} \mathcal{S}^{(r)} \bullet_1 U^{(r,1)} \bullet_2 U^{(r,2)} \bullet_3 \dots \bullet_1 \mathbf{N} U^{(r,N)}$$

Input tensor NORSAR slice-1	Reduced tensor NORSAR slice-1
www.www.www.www.www.www.www.www.www.ww	han
	40
and the second	
and the second sec	
A second state of the s	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	30
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	25 march Man Son March M
	20
	15
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
	2
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	
······································	
200 200 400 500 500 700 900 900 1000	100 200 300 400 500 600 700 800 900 16
200 400 400 000 700 000 700 300 1000	A

A tensor containing records of N events from the M arrays of vertical sensors can be thought as a 3D cube sliced to N slices. and the reduced tensor - to R slices where R corresponds to meaningful the part of 4D cube eigenevent. can represent the same of 3C array, or a network of L arrays. Such N-D reduction provides significant N-D noise reduction (compare left and right figures)



Quaternions



For the quaternions, which are a 4-D  $\mathbb{R}$  -algebra,  $q = q_1 + q_2 \mathbf{i} + q_3 \mathbf{j} + q_4 \mathbf{k} \in \mathbb{H}$ ,  $q_1, q_2, q_3, q_4 \in \mathbb{R}$ , with the multiplication table:  $\mathbf{i}\mathbf{j} = -\mathbf{j}\mathbf{i} = \mathbf{k}$ ,  $\mathbf{j}\mathbf{k} = -\mathbf{k}\mathbf{j} = \mathbf{i}$ ,  $\mathbf{k}\mathbf{i} = -\mathbf{i}\mathbf{k} = \mathbf{j}$ ,  $\mathbf{i}^2 = \mathbf{j}^2 = \mathbf{k}^2 = -1$ . a quaternion SVD  $\mathbf{A} = \sum_{n=1}^{r} \mathbf{u}_n \mathbf{v}_n^{\triangleleft} \sigma_n$ , can be defined where  $\mathbf{u}\mathbf{n}$  are the left singular vectors and  $\mathbf{v}\mathbf{n}$  the right singular vectors,  $\sigma$ are the real singular values, and the quaternion principle components can be extracted from the pure-quaternion ( $\mathbf{i}$ - $\mathbf{j}$ - $\mathbf{k}$ ) seismic records to be used in a hypercomplex master-event template design



Example quaternion principle components. Left: input 3C seismogram, Center: pure quaternion i, j, and k components of first principal component, Right: first complex quaternion component of first 3 principle components.





- The model for 3 (and 4 = 3+pressure) signals based on quaternion algebra provides a simple notation for vector signal manipulation and processing.
- Quaternion model allows to include wave polarization in algorithms and to take advantage of the signal redundancy on its components. The existence of phase shifts (elliptical polarization or dispersion of waves) between the components does not increase the rank of signal subspace in SVDQ approach, whereas it does in the SVD component-wise approach.
- It can be used for polarized wave separation on vector-sensor arrays, and its superiority upon the component-wise approach (over R) has been shown in papers.
- The SVDQ technique may also be interesting to recover the component of a signal that is lost in noise.
- A natural extension of the proposed method would include higher order statistics (ICA-like technique) in order to enhance the separation results and release the constraint of uncorrelation to higher order independence.
- SVDQ is in fact linked with PCA and could be seen as the standardization step in a blind source separation algorithm. As perspective, the study of sensors/arrays with an arbitrary number of components *l* could be investigated. The use of hypercomplex number of dimension *l* to encode could there be used, as well as the use of Clifford Algebras. These algebras have already been used to develop pattern recognition algorithm on hyperspectral images.





#### Potential beam loss due to variation in geological structure



The large amplitude variations at NVAR. Figure shows the configuration of the short-period elements of the array and raw data from a 5.7 magnitude event that occurred in California. *From Petru T.* Negraru "Application of Seismo-Acoustic Signals to the Study of Local Site Effects", Acta Geophysica, 2010

Ambient noise based methods for refining local velocity models at IMS stations:

Ambient Noise
Tomography, ANT
The horizontal-to-vertical spectral ratio,
HVSR





# **Ambient Noise Tomography (ANT)**

- Passive exploration techniques based on ANT, HVSR comprise an efficient toolbox for refinement of velocity models underneath sensors deployment.
- This tool is useful for enhancement: ParMT results, as well as for improvement of IDC regional locations and OSI_ Seismic Aftershocks Monitoring System (SAMS).
- Velocity models restoration is based on known inversion algorithms of surface waves dispersion.
- This technique could be widely utilized for **IMS seismic arrays** for restorations of velocity model of the underlying crust.





#### **Examples of surface deployment**



Array of MEMS sensor, flat to acceleration. >650 sites. Total Combined deployment along 7 linear strings and randomly plotted seismic noise elements for vertical-well measurements on hydrofracturing sites.

 $\Delta$  along each linear string is ~20m

Example: Two spatial correlation patterns along linear strings





# **Ambient Noise Tomography**

"Zero-depth" velocity map revealed from Bessel function for frequency range 2-4Hz (horizontal-well hydrofracturing site, geophone deployment )







**HVSR** involves analyzing measurements of ambient seismic noise in three dimensions to determine the fundamental site resonance frequency RF. Resonance is excited by the interaction of surface waves (Rayleigh and Love) and body waves (vertically incident shear) with the high-contrast acoustic impedance boundary at the bedrock-sediment interface. RF has been shown to be proportional to the thickness of unconsolidated sediments (Nakamura 1989; Bonnefoy-Claudet and others 2006; van der Baan 2009). **HVSR can help imaging complex structures, involving multiple layers with active faults.** 

We conducted just preliminary studies to estimate availabile free software, and processed data from 3 US CTBTO arrays: NVAR, TXAR and PDAR with the Geopsy package. More work required to make it in complience with the SESAME European Project Guidelines (SESAME: Site EffectS assessment using AMbient Excitations)



Extracting modes by Geopsy. Results on NVAR are very close to the ones in Alfaro-Diaz, R., and T. Chen (2021) conducted for NTS. All sites demonstrate different RF, that can be inverted into the layered structure.

#### PUTTING AN END TO NUCLEAR EXPLOSIONS





### CONCLUSION

The number of new algorithms and applications related to the recovery of structure, wave propagation, characterization of source functions, and discrimination of events is rapidly growing in the realm of global and applied seismology. The IDC has to select and test algorithms and applications most appropriate for monitoring purposes. At the same time, the exclusive CTBTO mandate requires development of very specific tools and applications driven by IMS data. We presented our experience with a few openly available applications as well as those developed at the IDC.

Future usage of these applications depends on the results of extensive testing and support of the monitoring community.