SnT 2021

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

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PREPARATORY COMMISSION

New applications at the IDC for SHI Expert Technical Analysis

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

Is1-353

ORAL PRESENTATION

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

Problems and related objectives

The Preparatory Commission for the CTBTO routinely operates software to process time-series 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 near-real-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.

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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***.

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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**)**

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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.

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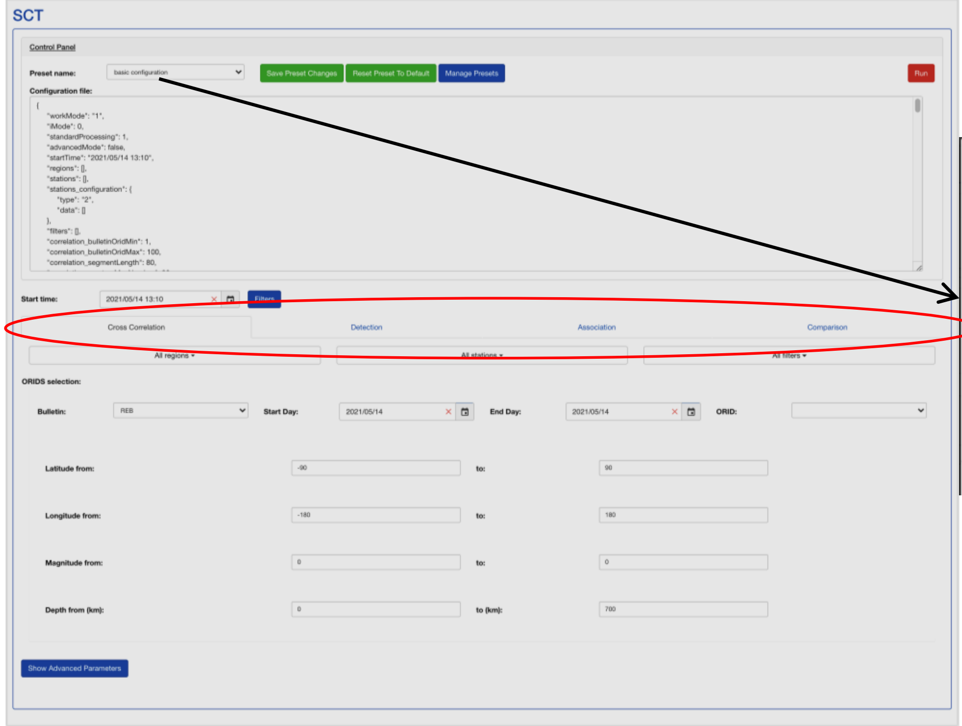
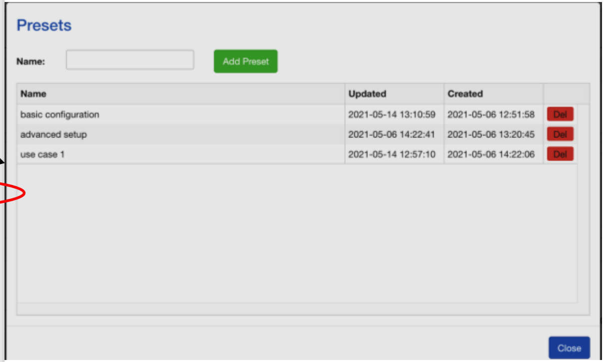
ETA Suite Prototype for SHI data: Interactive Spot Check Tool

CONTROL PANELS, SPOT, EVENTS, PRESETS



Details: P3.5-355



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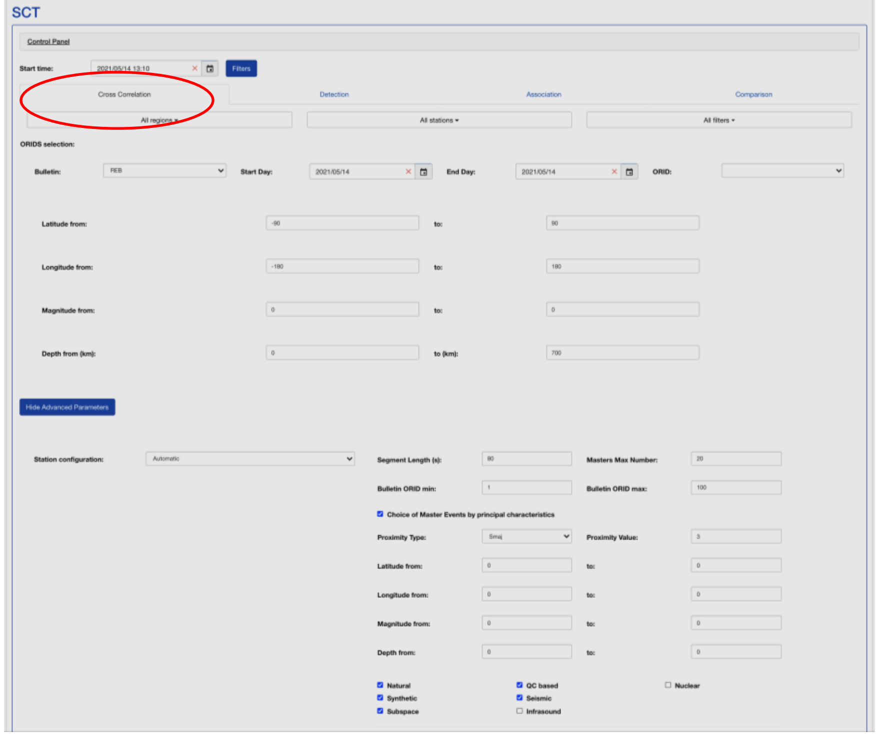
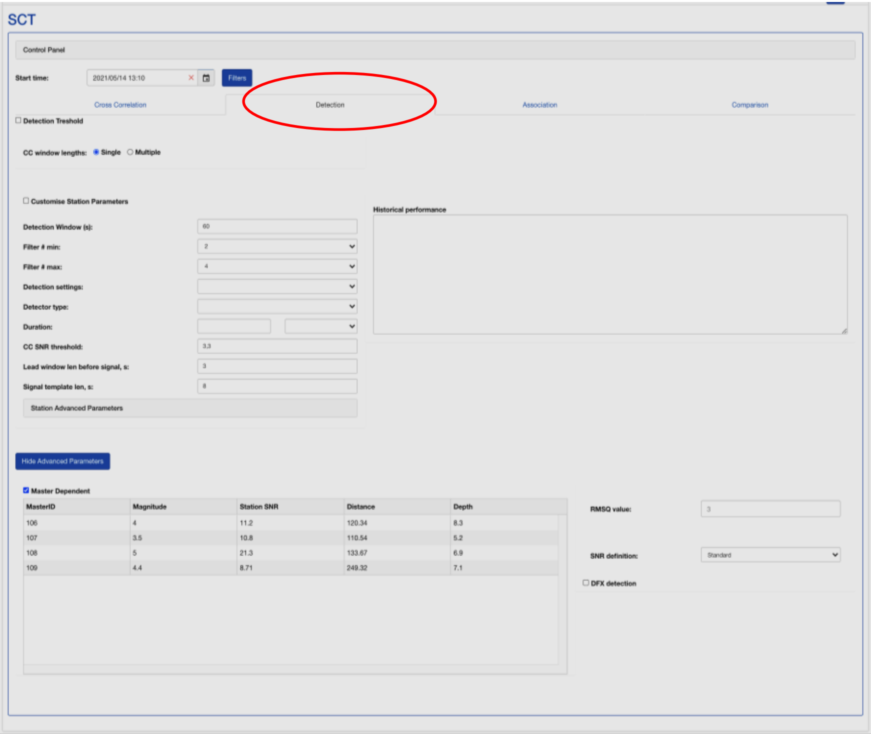
ETA Suite Prototype for SHI data: Interactive Spot Check Tool

CONTROL PANELS: CC, DETECTION





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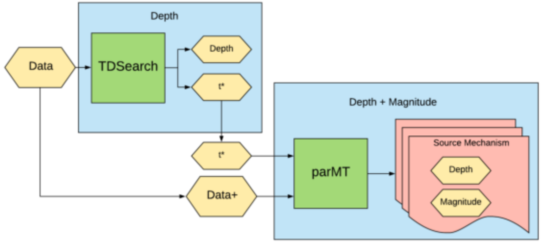
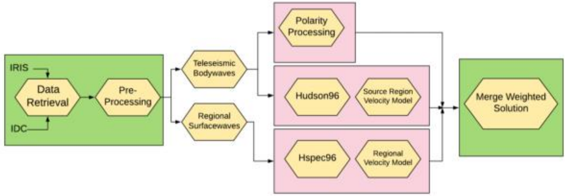
ETA Suite Prototype for SHI data: Depth determination based on moment tensor estimation, ParMT



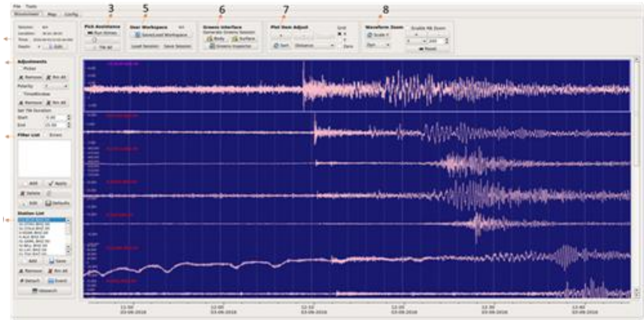
Processing Overview



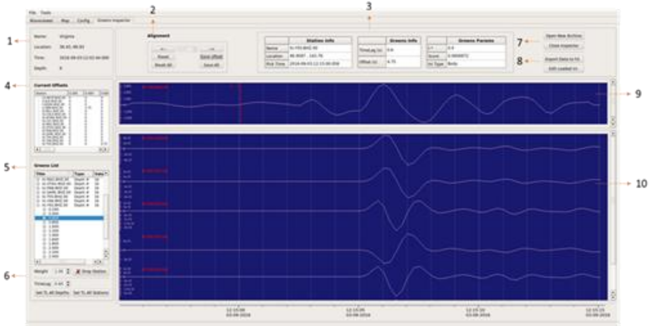
- Programs in Seismology allow for use of source-specific models; e.g., MDJ2.
- hudson96 allows us to get high-frequencies into the teleseismic body waves.

ETA Tool

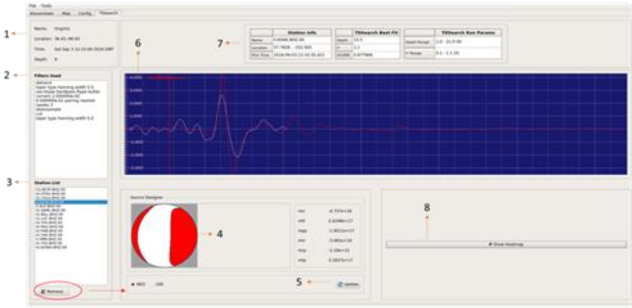
Waveform Viewer – browsing and preprocessing



Green's Inspector – synthetics manager and browser



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



Map widget

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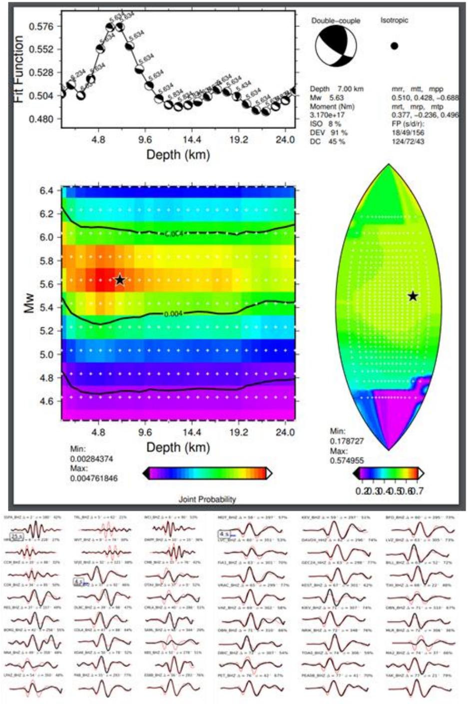
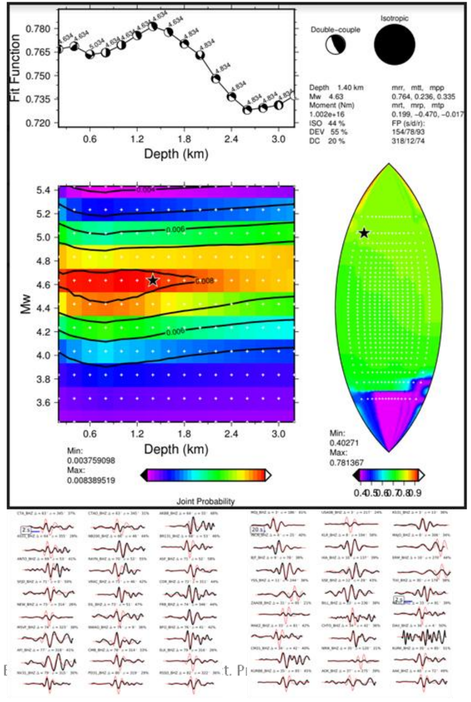
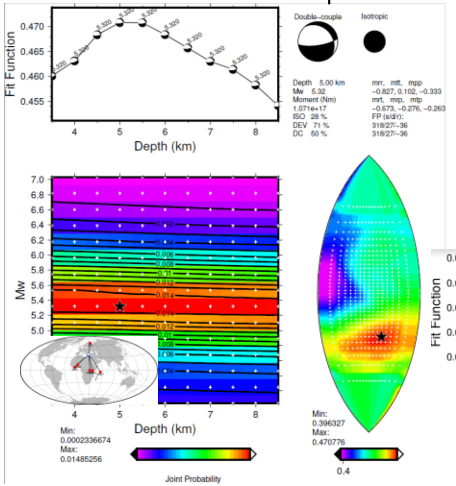
Virginia EQ 2011 M5.7



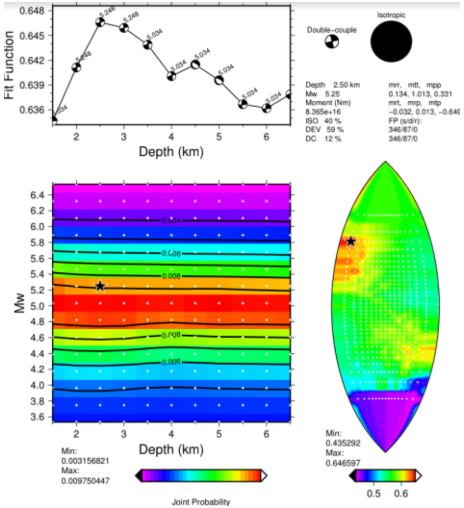
DPRK 2016b



Turkey 2017-11-24 21:49:15 UTC
37.085°N 28.622°E 5.2 km depth



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



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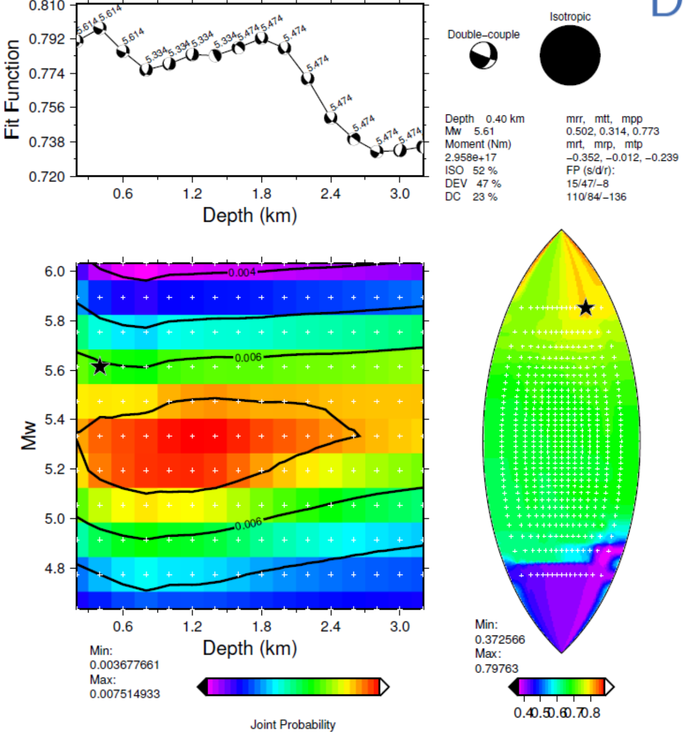
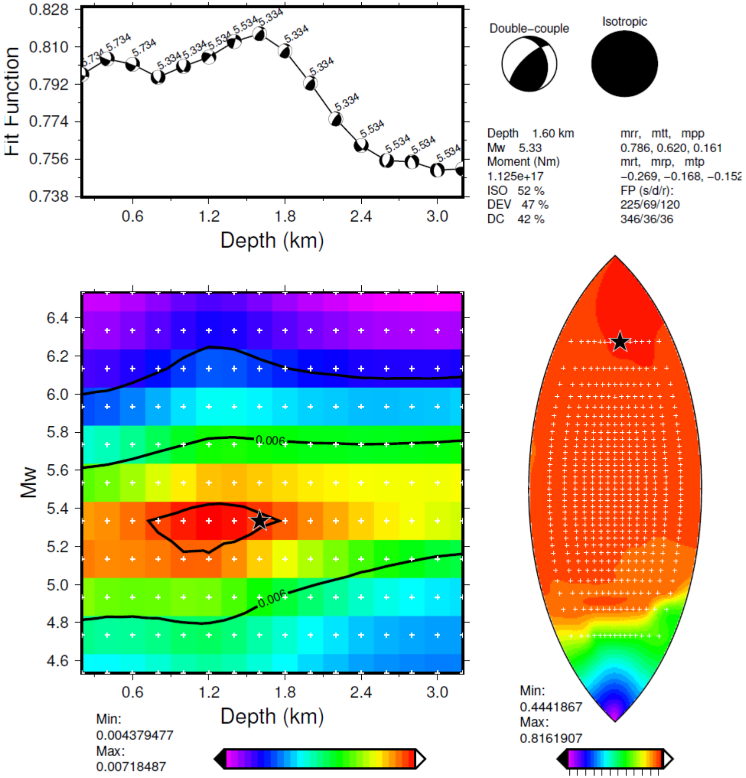
DPRK2017

Depth= 0.4 km



Depth= 1.6 km



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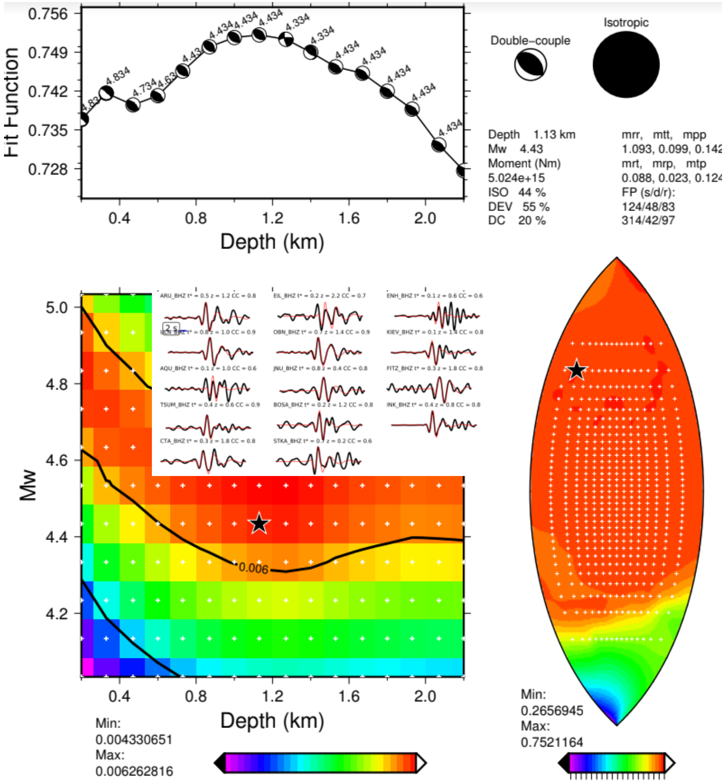
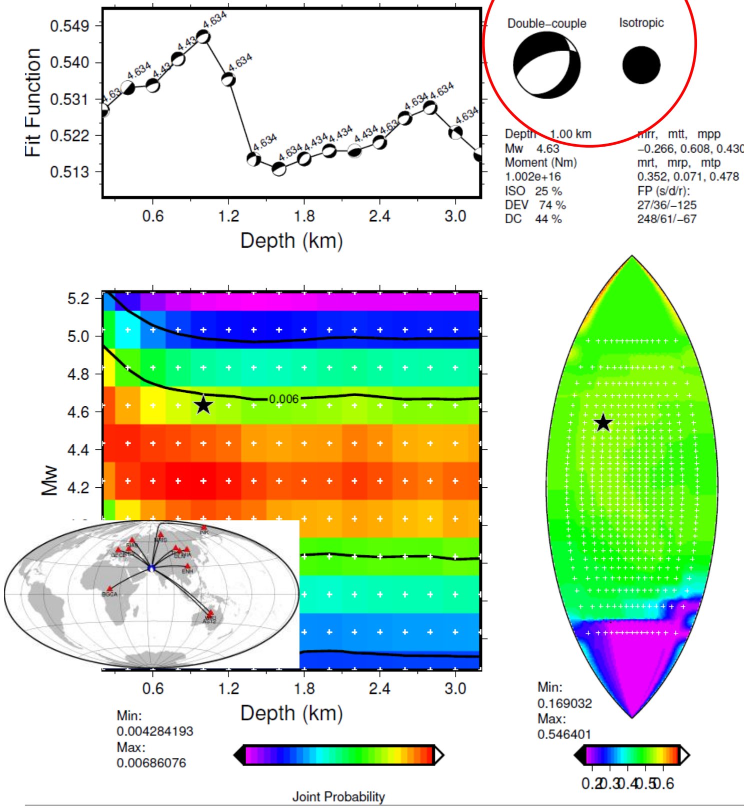
SHAKTI explosion (India 1998-05-11:10:13:42.000)



Chagai-I explosion (Pakistan 1998-05-28:10:16:15.000)



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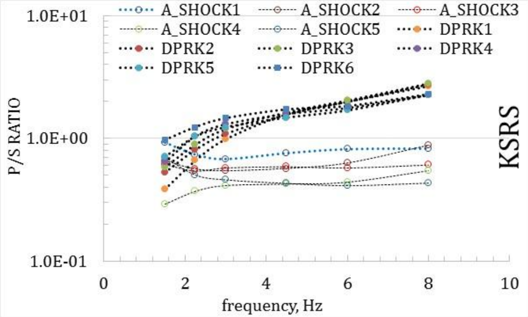
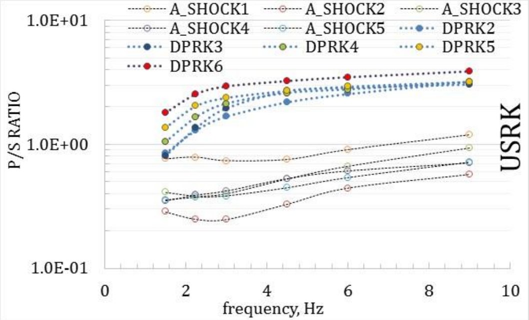
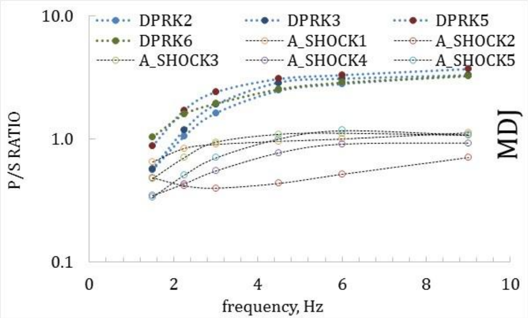
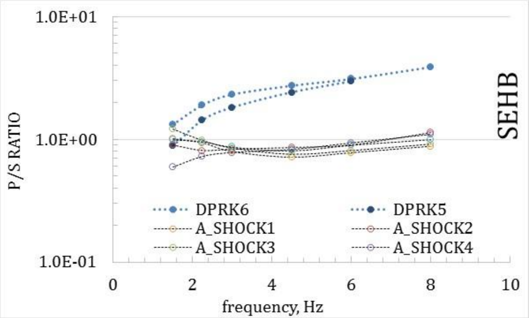
Spectral discrimination of the DPRK explosions and aftershocks

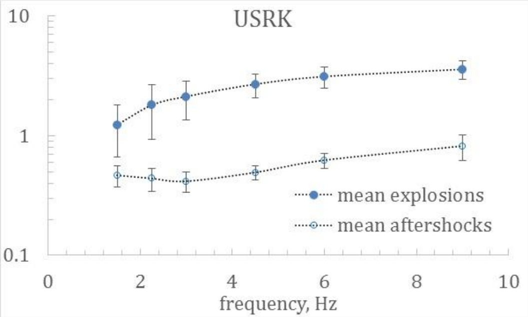


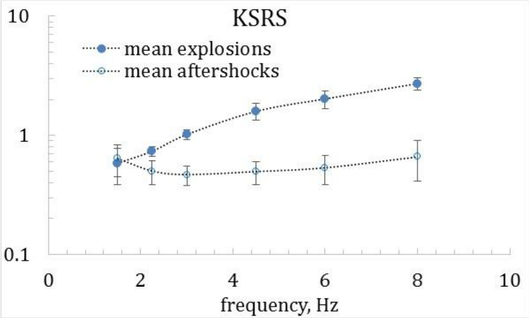






Average and st.dev.





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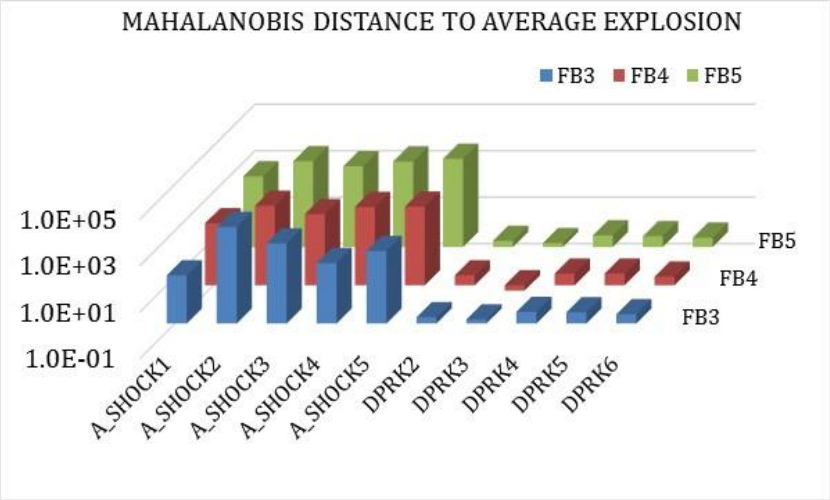
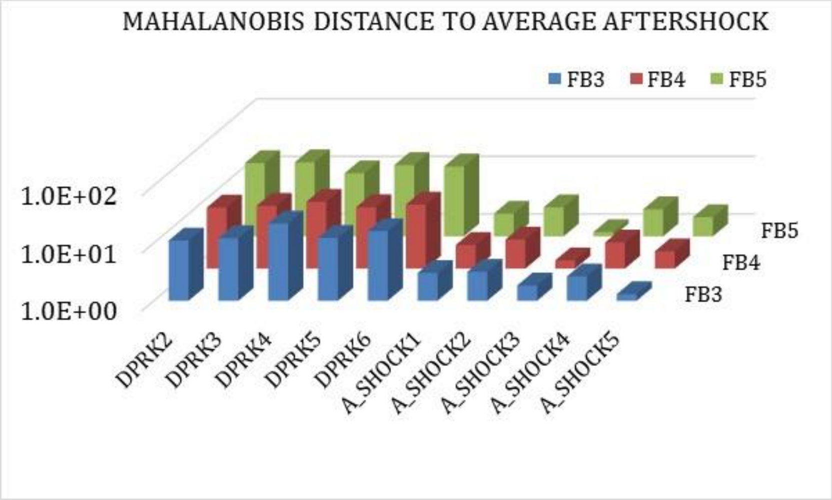
Spectral discrimination of the DPRK explosions and aftershocks



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

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

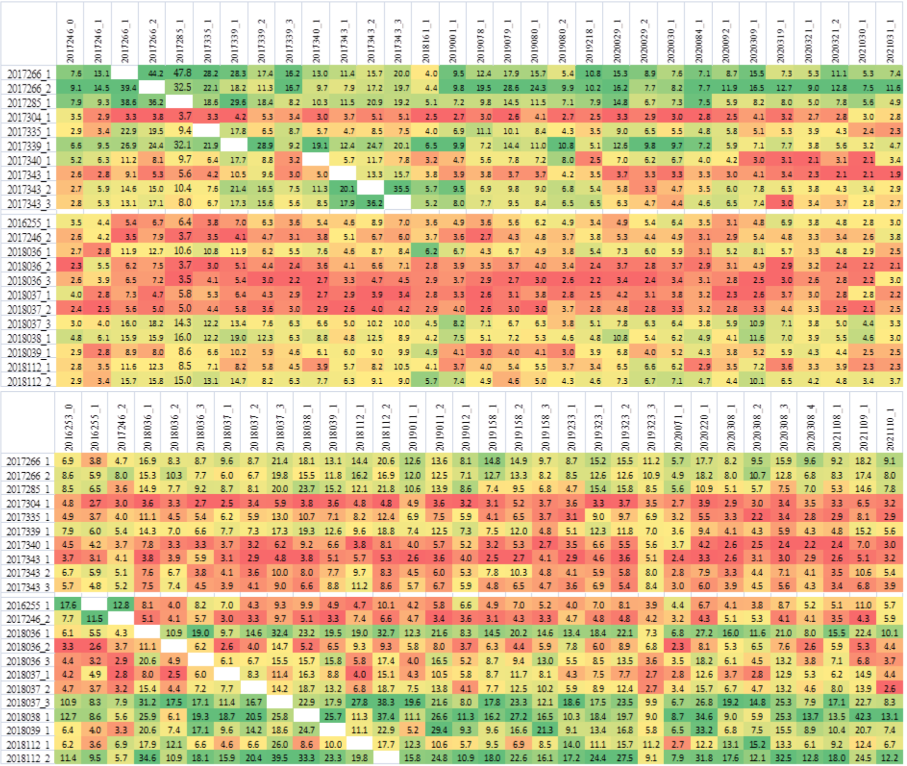
29 master events

	id	Origin time	Epoch time	Relmag	KSRS	USRK	Total
1	2006282_0	01:35:28					
2	2009145_0	00:54:43					
3	2013043_0	02:57:51					
4	2016006_0	01:30:00					
5	2016253_0	00:29:58	1473380998.67	5.35	25	27	52
6	2016255_1	01:50:48	1473558648.01	2.86	22	23	45
7	2017246_0	03:30:00	1504409398.92	5.94	25	22	47
8	2017246_1	03:38:31	1504409910.45	4.11	23	14	37
9	2017246_2	09:31:28	1504431087.60	2.66	22	22	44
10	2017266_1	04:42:58	1506141777.71	3.06	22	19	41
11	2017266_2	08:29:14	1506155354.55	3.60	25	26	51
12	2017285_1	16:41:07	1507826465.96	3.27	27	27	54
13	2017304_1	10:20:13	1509445213.19	2.52	12	23	35
14	2017335_1	22:45:54	1512168354.43	2.91	24	26	50
15	2017339_1	14:40:52	1512484851.85	3.14	23	24	47
16	2017340_1	16:20:05	1512577204.78	2.6	11	18	29
17	2017343_1	06:08:40	1512799720.05	2.79	19	23	42
18	2017343_2	06:13:32	1512800011.25	3.41	16	24	40
19	2017343_3	06:40:00	1512801600.08	3.11	24	27	51
20	2018036_1	10:32:30	1517826749.75	2.67	17	27	44
21	2018036_2	20:07:30	1517861249.34	2.79	17	24	41
22	2018036_3	21:57:35	1517867855.28	2.96	12	25	37
23	2018037_1	04:49:36	1517892575.86	2.65	8	23	31
24	2018037_2	10:12:30	1517911950.12	2.58	8	23	31
25	2018037_3	10:53:52	1517914432.06	3.02	26	27	53
26	2018038_1	21:46:23	1518039982.91	3.34	27	27	54
27	2018039_1	17:39:17	1518111556.77	2.74	23	26	49
28	2018112_1	19:25:08	1524425108.31	2.70	23	27	50
29	2018112_2	19:31:18	1524425477.81	2.98	27	27	54

DPRK6

USRK

DPRK5



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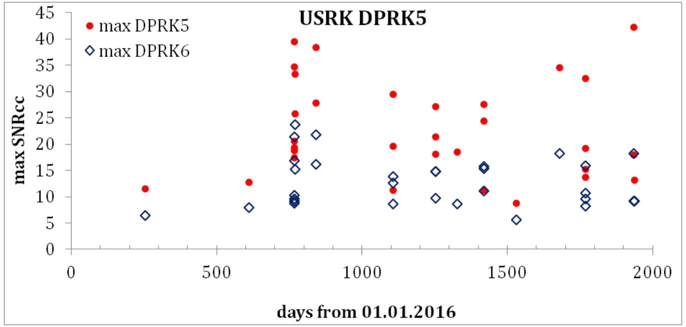
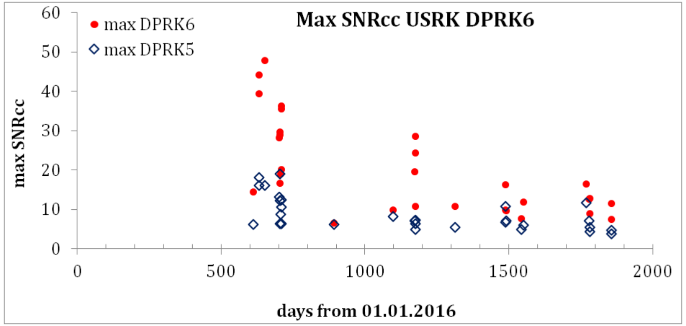
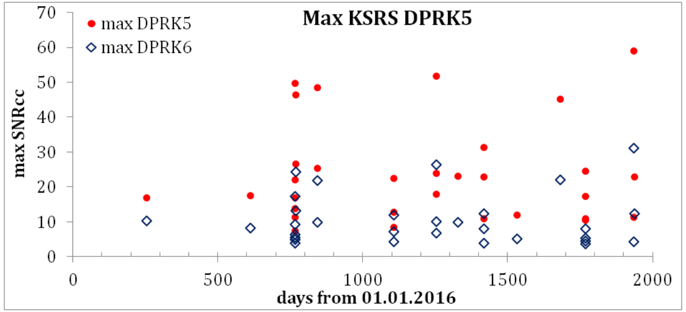
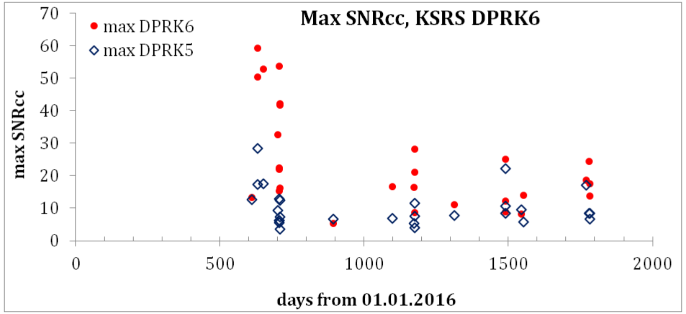
Detection of ultra-weak aftershocks of the DPRK tests









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.

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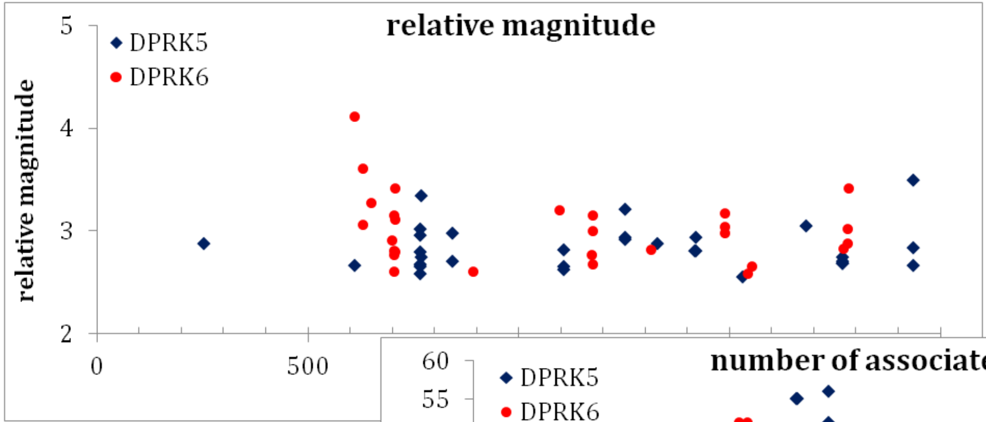
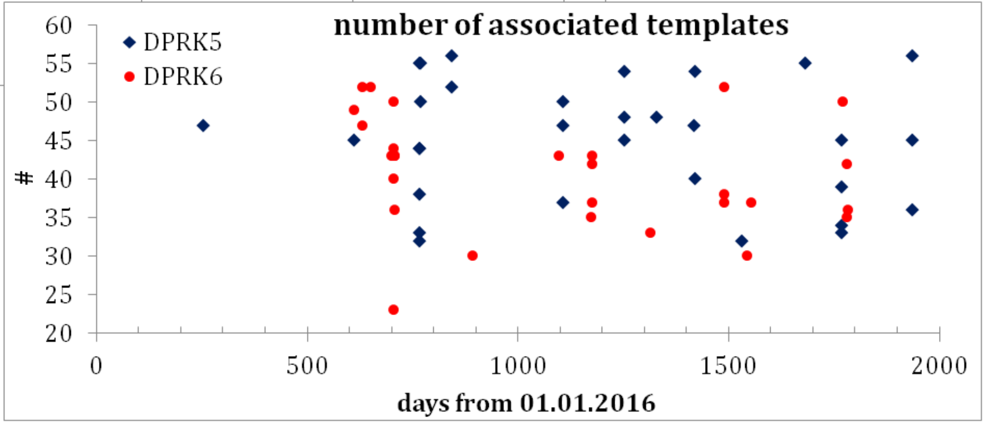
Detection of ultra-weak aftershocks of the DPRK tests



Relative magnitudes of the aftershocks associated with DPRK5 and DPRK6



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

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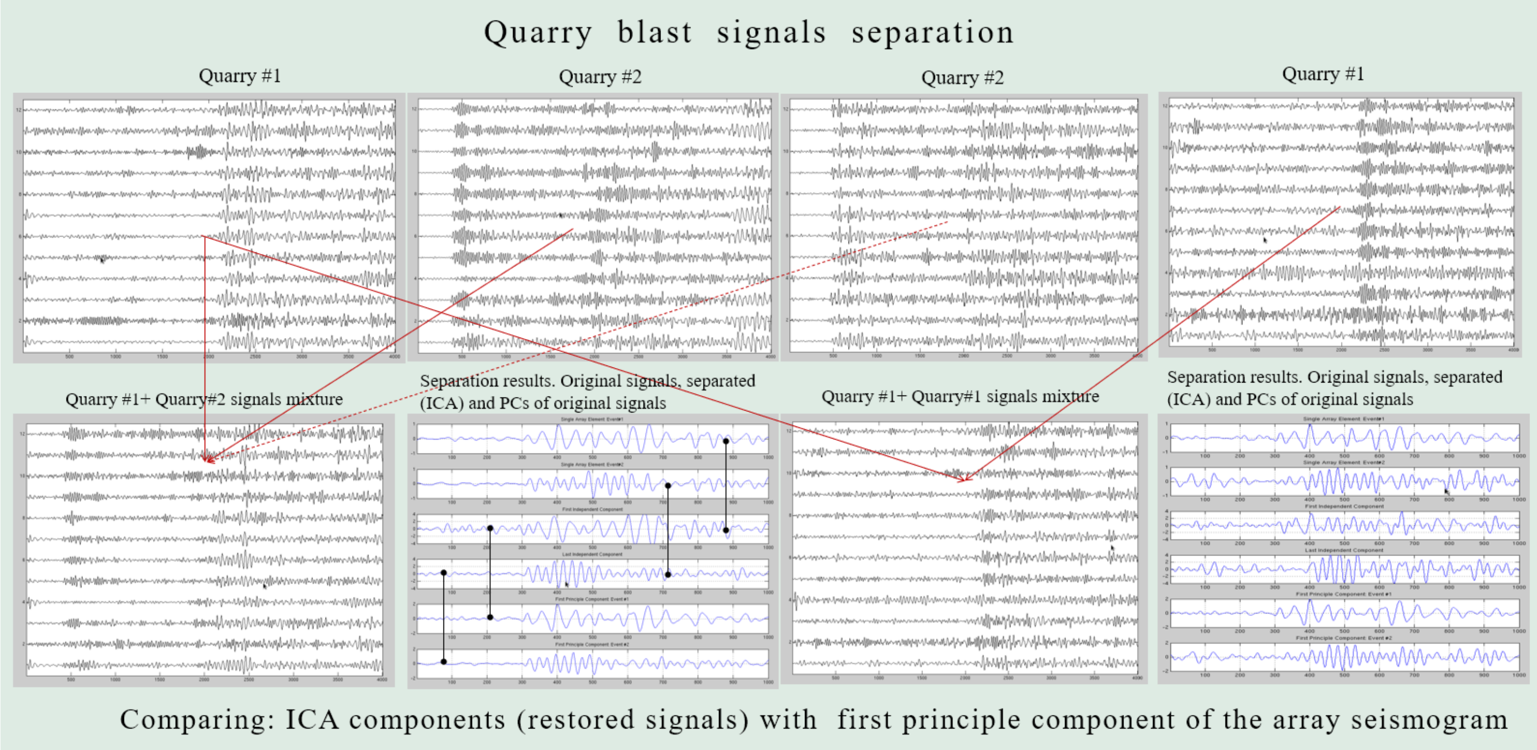
Independent component analysis



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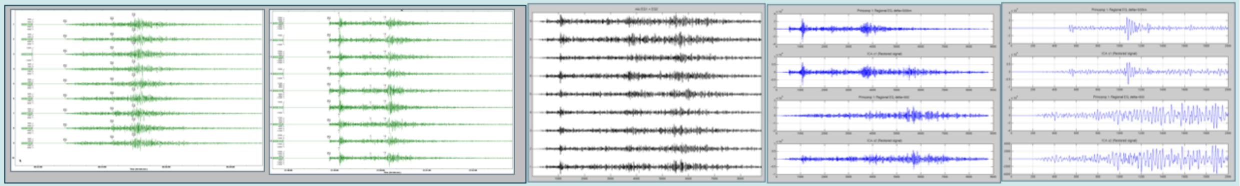
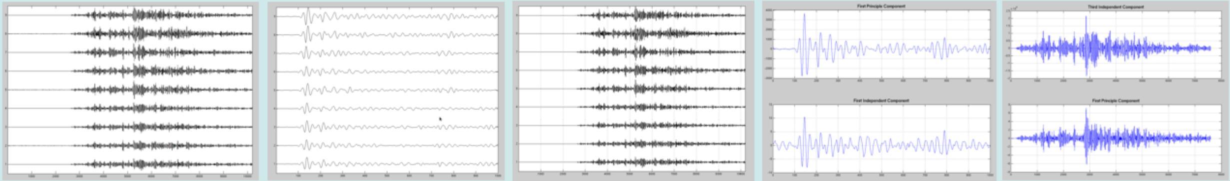
Independent component analysis

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



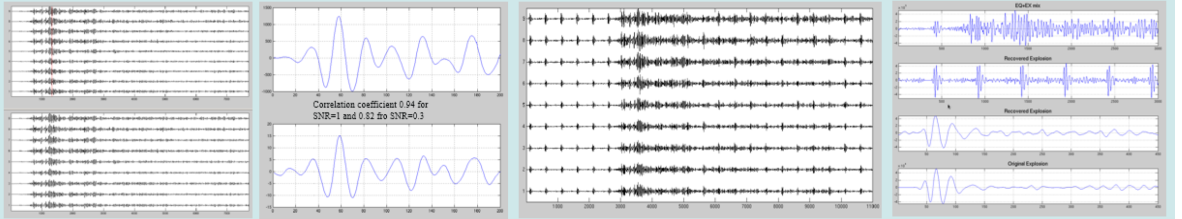
Separating events with close azimuths from the mix: DPRK-2013, Feb-2013 Mb=4.9 (scaled up to Mb=7) test and Tohoku, March 2011 Mw=9.0 EQ.

Earthquake waveforms at MKAR IMS array | DPRK-2013 test at MKAR array | A mix of both events | Recovered EX signal (bottom) and first PC | Recovered EQ signal (top) and first PC



A case of separation of events with different back-azimuths from the mix: DPRK-2013, Feb-2013 Mb=4.9 (scaled up to Mb=7) test and Sumatra, April 2012 Mw=8.6 earthquake

Earthquake waveforms at MKAR array (top) and mix with DPRK-2013 test | Recovered test signal (top) and first PC | Repeatable mix of the synthetic DPRK-2013 array seismogram with the EQ array seismogram, MKAR IMS array | EQ and synth-DPRK-2013 mix, restored explosion in different time scales, and 1st PC of the original



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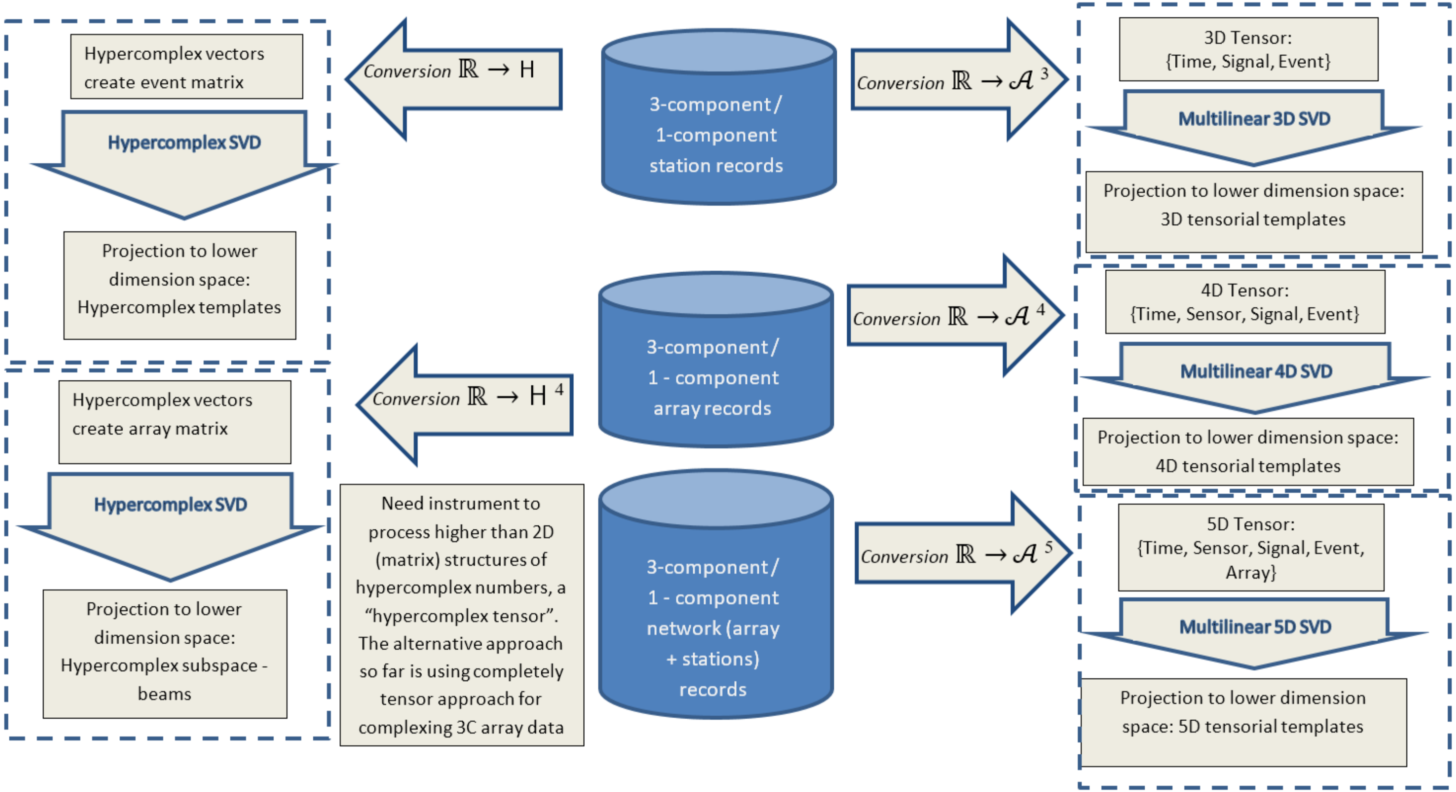
Generalized approach to the master event template design

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



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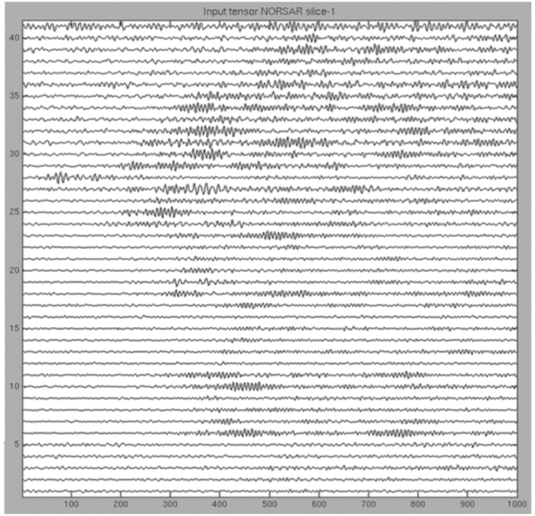
Tensors

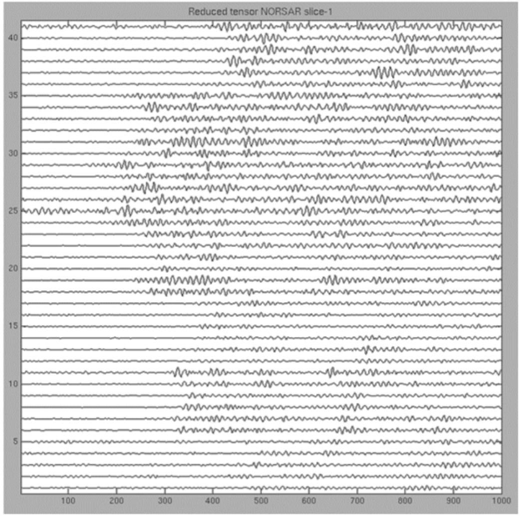
N-D Structures: Tensors and Quaternions PCA and Dimensionality and Noise Reduction

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 $n = 1, \dots N$)

Then the dimensionality reduction can be performed through the truncation of U and $\mathcal{S}$ 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.

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





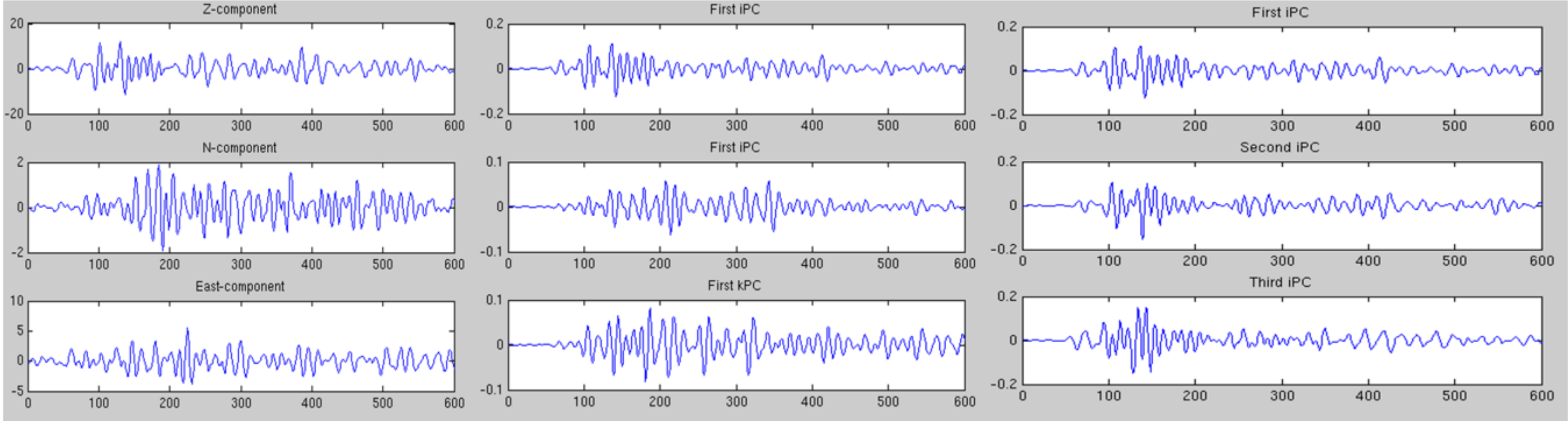
A tensor containing records of N events from the M arrays of vertical sensors can be thought as a 3D cube sliced to N slices, and the reduced tensor – to R slices where R corresponds to the meaningful part of eigenevent. 4D cube can represent the same of 3C array, or a network of L arrays. Such N-D reduction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

Quaternions

For the quaternions, which are a 4-D $\mathbb{R}$ -algebra, $\boldsymbol{q} = q_1 + q_2\boldsymbol{i} + q_3\boldsymbol{j} + q_4\boldsymbol{k} \in \mathbb{H}$, $q_1, q_2, q_3, q_4 \in \mathbb{R}$,

with the multiplication table: $\boldsymbol{ij} = -\boldsymbol{ji} = \boldsymbol{k},\ \boldsymbol{jk} = -\boldsymbol{kj} = \boldsymbol{i},\ \boldsymbol{ki} = -\boldsymbol{ik} = \boldsymbol{j},\ \boldsymbol{i}^2 = \boldsymbol{j}^2 = \boldsymbol{k}^2 = -1.$

a quaternion SVD $\mathbf{A} = \sum_{n=1}^{r} \mathbf{u}_n \mathbf{v}_n^{\triangleleft} \sigma_n$, can be defined where **un** are the left singular vectors and **vn** the right singular vectors, σ are the real singular values, and the quaternion principle components can be extracted from the pure-quaternion (i-j-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.

New applications at the IDC for SHI Expert Technical Analysis
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Quaternions

- 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.

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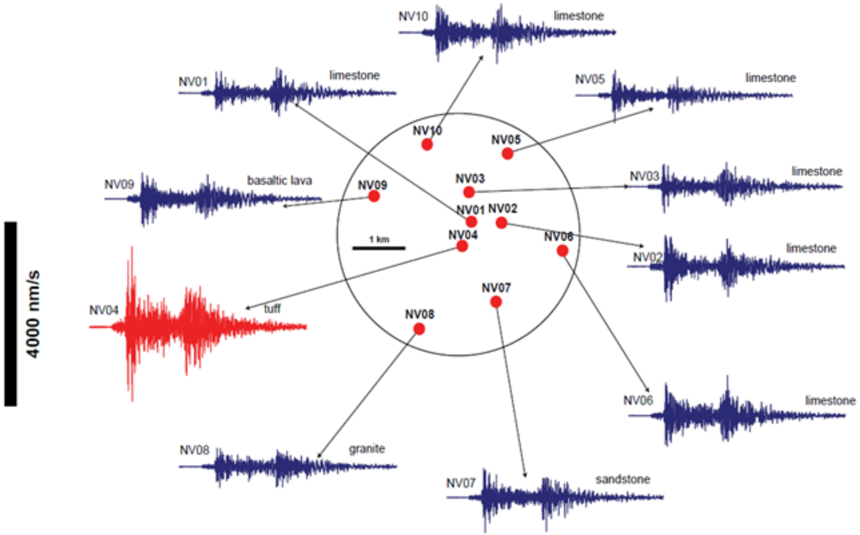
Potential beam loss due to variation in geological structure



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

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

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.

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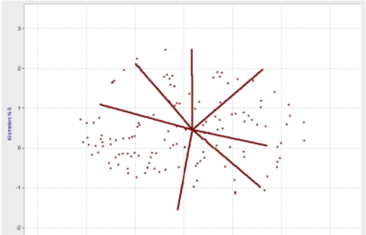
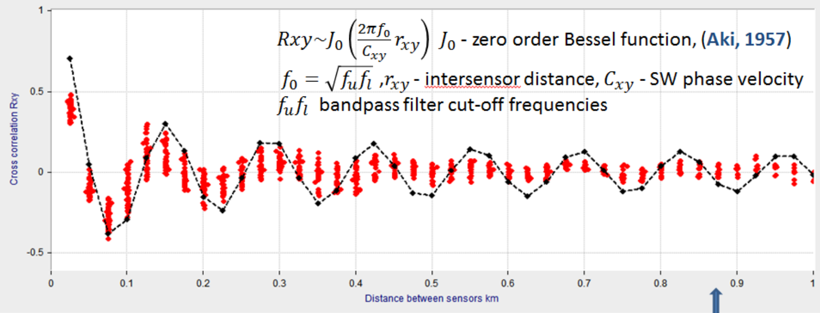
Examples of surface deployment



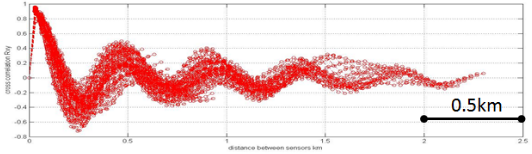
Array of MEMS sensor, flat to acceleration. Total >650 sites. Combined deployment along 7 linear strings and randomly plotted elements for seismic noise measurements on vertical-well hydrofracturing sites.

Δ along each linear string is ~20m

Example: Two spatial correlation patterns along linear strings **2-4Hz band filtered**



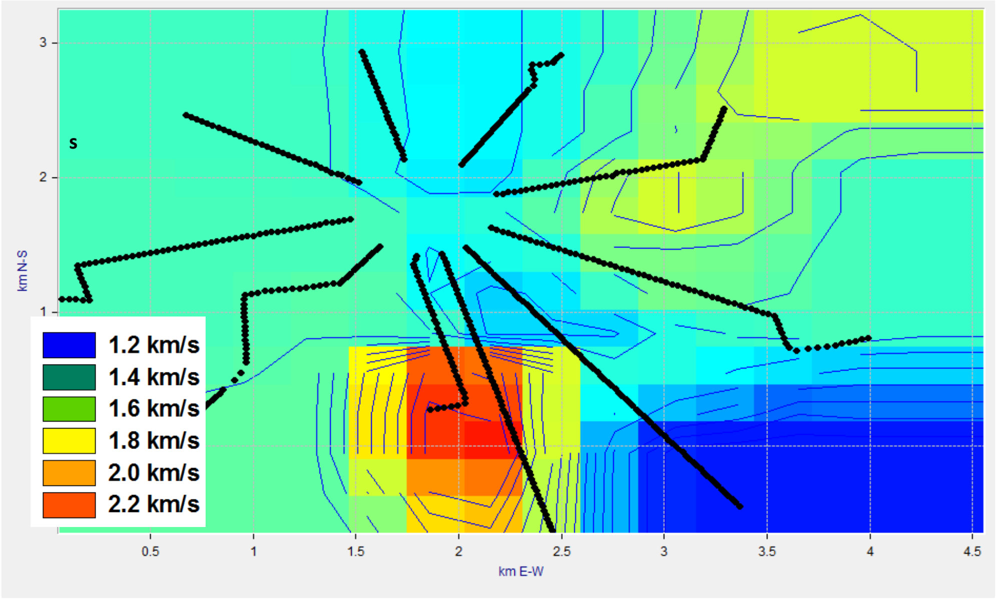
MEMS deployment



Geophones

Ambient Noise Tomography

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



New applications at the IDC for SHI Expert Technical Analysis

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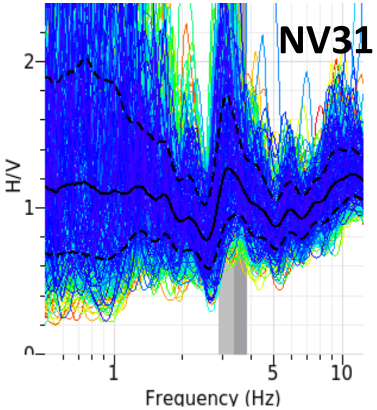
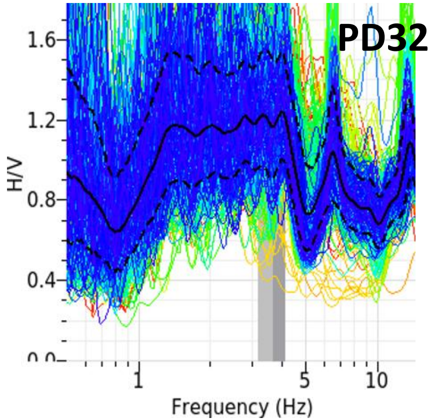
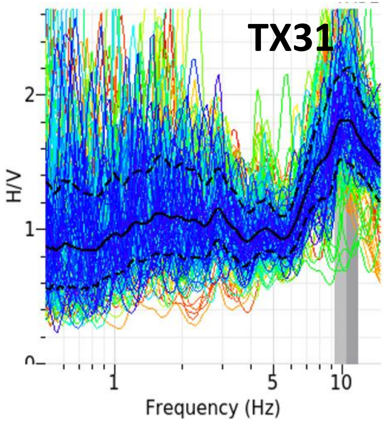
HVSR involves analyzing measurements of ambient seismic noise in three dimensions to determine the fundamental site resonance frequency RF. Resonance is excited by the interaction of surface waves (Rayleigh and Love) and body waves (vertically incident shear) with the high-contrast acoustic impedance 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.

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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.