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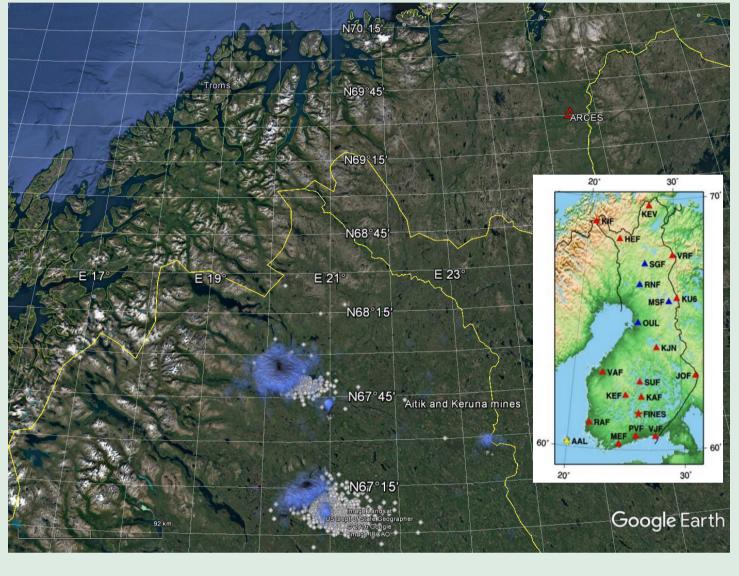
Automatic identification of repeated industrial seismicity in the Reviewed Event Bulletin

Abstract

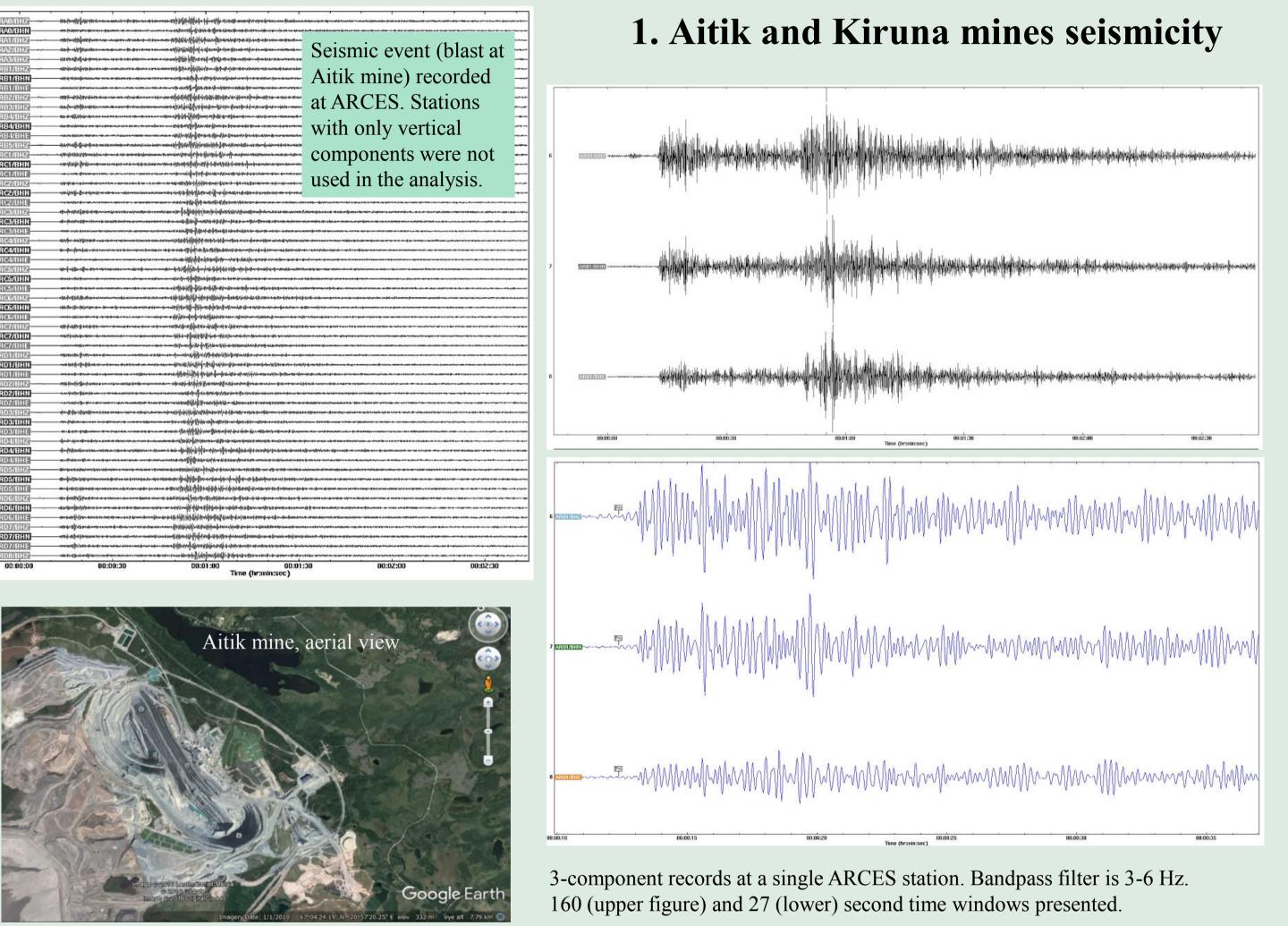
system every year. According to the CTBTO's signals from the Aitik and Kiruna mines in Sweden arrivals with seismic events, relative location and Overall, the developed method can reduce the The Reviewed Event Bulletin (REB) produced by monitoring mandate, these events represent measured at the closest IMS array stations ARCES, magnitude estimation. A prototype pipeline is overall IDC analysts' workload by several background noise, which demands human and FINES, NOA, and HFS we develop a method of currently tested at the IDC. We present select resources for interactive and automatic automatic event formation and identification based results of detection, relative location and mine comprehensive monitoring. Our method can Organization (CTBTO) includes thousands of processing. It can also increase the overall detection on waveform cross correlation (WCC). Real-time identification obtained since January 1, 2017. applied to smaller blasts detected only by local and industrial explosions detected by the primary threshold. Most of these blasts are repeated events automatic processing includes signal detection and Worldwide, there are tens of mines with hundreds near-regional seismic networks. the International monitoring generating similar signals. Using an extended set of characterization, local association of the detected of events per year, which are present in the REB.

We have conducted a study on template selection for further location of seismic events by the waveform cross-correlation method using regional quarry blast data recorded at 3-component IMS seismic array ARCES. One of reasons for this study was the difference in location conducted by the IDC and presented in the REB, and the location results presented by the International Seismological Center, ISC, based on data from the seismographic network of the University of Helsinki (UH, inlay on a Google Earth map below). The blast clusters by the IDC are white balls for both mines; the UH results are blue

In total, 122 seismic events from the Aitik (copper) and Kiruna (iron) mines were studied at 19 3-component stations of ARCES.



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3. Tensor Templates Test

We have conducted a number of tests with the obtained reduced tensor components in order to evaluate DCT, (3) HOSVD, and (4) tensor interpolation. Different template lengths were used from 10 to 30 seconds. performance of the cross correlation detector with these components used as templates. Complete sets of The best results were produced by the MD DCT and interpolation templates for average SNR; the minimum components for the 3C array were produced with 4 methods: tensor interpolation, DCT, 2DSVD and SNR_{CC} over all tested signals for a given template, which has to be above 3.5; and the average CC. The HOSVD. In this study, the 3D templates were reduced to 1D vectorized case ([Z,NS,WE]) and we applied a overall difference in detection rates is not large. Similar tests were also carried out with the eigenimages well established system of tests. Selected results are presented on figures below. The first test was based on (instead of reduced back-projections) produced for the HOSVD (PC cell array in TPCA algorithm). It was cross correlation (CC) of the developed templates with continuous waveforms measured from the set of 122 found that the algorithm destroys the proper channel alignment in sensor triads and move-outs related to events and determining the detection rate based on SNR threshold (see poster S51A-2758 for details, also different stations of the array and the test results were not impressive. In case of single 3-C station, it does Bobrov, et al. 2012): the percentage of detections having SNR_{CC}>3.5. Then, we tested 46 events not not make any difference since all the channels in a training set are aligned by default and there no is need to included into the training set of 122. In this test, the ten first reduced tensor components were used for keep the move-outs so the regular SVD/PCA case works fine. detection, i.e. 40 components were tested altogether as presented on figures below: (1) 2D SVD, (2) MD



tensor decomposition and tried our own truncated reconstruction of the reduced tensor set. The detection rate was the same as for the best methods above, and the smallest SNR_{CC} was even larger (4.2 against 3.5). More work has to be conducted to find the optimal multidimensional template design.

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Left figure: 4 methods, 10 templates in each method, variable time window length

Left figure: 2 methods, 10 templates in each method, 5 filter bands: 2-4 Hz, 4-8 Hz, 3-6 Hz, 6-12 Hz, 8-16 Hz.

Left figure: HOSVD tests nonstandard truncated reconstruction of the reduced tensor set

Introduction. Here, we introduce an approach to construct master event templates for further cross-correlation-based Following basic principles of the 1D PCA, we approach to this projection with analyzing the core tensor location with data recorded at multichannel seismic installations, such as 3-C seismic arrays of the International \mathcal{S} . It's eigenvalues (for station array NORSAR) corresponding to the dimensions (station; signal; event) Monitoring System (IMS) of the CTBTO. Dealing with the tensor representation of seismic wavefields can simplify are represented on a figure below. Only 5 eigenvalues are meaningful, so dimensionality reduction can be in certain sense the multidimensional approach to data processing, in particular, to the data set which was the same as performed to the decomposed tensors order of 5. used for the single component processing. Multichannel data corresponding to a seismic event from the Aitik and Kiruna quarries in Sweden can be rearranged as a 3-mode tensor, where first mode is time, or sample number, the second mode is station, or sensor number, and the third mode is the direction of ground motion (Z, N and E). Then, a complete test data set would consist of a 4-mode tensor with the event number corresponding to the 4th dimension. Event eigenvalues in Considering a 3-component seismic array as a multitude of observations with a tensor description (not the tensor field lin-lin scale. Red line in general sense), the corresponding data tensor, formally, can be regarded as a tensor product of 3 vector spaces, indicates reduction level each with its own coordinate system. Then we could apply tensor operations to the data recorded by such arrays gaining certain benefits from utilizing joint volumetric (sensor) and spatial (array) information. Further dimensionality reduction of tensor data produces a basis for the multidimensional waveform templates. Note that a Event (log-lin scale first-mode, or first-order tensor is a vector, a second-order tensor is a matrix, and tensors of higher orders are higher-Signal (log-lin scale) Station (log-lin scale) order tensors.

General approach. Traditional approaches to finding lower dimensional representations of tensor data include flattening the data and applying matrix factorizations such as principal components analysis (PCA) or employing tensor decompositions such as the CANDECOMP/PARAFAC (canonical polyadic decomposition with parallel factor analysis) and Tucker decompositions, which may be regarded as a more flexible PARAFAC model. Tucker decomposition, which we use in this work, decomposes a tensor into a set of matrices and one core tensor. Then the eigenimages can be extracted for resizing the input tensor to lower dimensions. There are more approaches to the multimodal dimensionality reduction we explored in this study, such as the multidimensional Discrete Fourier Transform (DCT) mostly used in image processing (JPEG, for instance), 2D SVD (based on low rank approximation of the matrix), and tensor interpolation (for example, Hotz, et al, 2010, Tensor Field Reconstruction Based on Eigenvector and Eigenvalue Interpolation). With this, we make an accent on the Tucker tensor decomposition made with the alternating least squares (ALS) method.

 $\mathcal{A} = \mathcal{S} \times_1 U^{(1)} \times_2 U^{(2)} \dots \times_N U^{(N)}$, where $U^{(n)} = (U_1^{(n)} U_2^{(n)} \dots U_{I_n}^{(n)})$ is an orthogonal $(I_n \times I_n)$ matrix (H. Lu, K.N. Plataniotis, and A.N. Venetsanopoulos (2006), Multilinear principal component analysis for tensor objects for classification). A visual representation of this decomposition in the third-order case is shown on next figure:

A matrix representation of this decomposition can be obtained by unfolding \mathcal{A} and \mathcal{S} as:

where \otimes denotes the Kronecker product and S is a core tensor of size $R_1 \times R_2 \times \cdots \times R_N$. The decomposition can also be written as

i.e., any tensor can be written as a linear combination of $I_1 \times I_2 \times \cdots \times I_N$ rank-1 tensors. This decomposition is used in the following to formulate a multilinear projection for dimensionality reduction.

Association and relative location For all valid arrivals, which are found with a given master event, origin times, OTij, are calculated. The empirical travel times from the master event to the relevant primary stations, TT*ij*, are subtracted from the arrival times, AT*ij*.

wh

11ij - 11jEmpirical travel times from a master event to seismic stations are characterized by ZERO modelling errors and very low measurement errors. These conditions allow extremely accurate *relative* location. **Relative loc**

Disclaimer: The views expressed on this poster are those of the authors and do not necessary reflect the views of the PTS CTBTO

Conclusion
Continuous detection of signals
sing cross waveform correlation
with several master events is likely
he most reliable method of
letection and creation of seismic

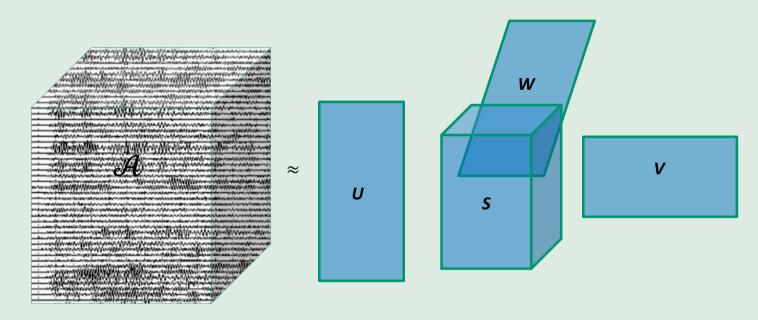
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events association procedures related to the WCC method.

a design

2. Tensor Approach to Seismic Array Data Processing

Math formalism. Following standard multilinear algebra, any tensor can be expressed as the product



 $\mathbf{A}_{(n)} = \mathbf{U}^{(n)} \cdot \mathbf{S}_{(n)} \cdot (\mathbf{U}^{(n+1)} \otimes \mathbf{U}^{(n+2)} \dots \otimes \mathbf{U}^{(N)} \otimes \mathbf{U}^{(1)} \otimes \mathbf{U}^{(2)} \otimes \dots \otimes \mathbf{U}^{(n-1)})^T$

$$\mathcal{A} = \sum_{i_1=1}^{I_1} \sum_{i_2=1}^{I_2} \dots \sum_{i_N=1}^{I_N} \mathcal{S}(i_1 i_2, \dots, i_N) \times \mathbf{u}_{i_1}^{(1)} \circ \mathbf{u}_{i_2}^{(2)} \circ \dots \circ \mathbf{u}_{i_N}^{(N)}$$

4. Continuous detection, association and relative location

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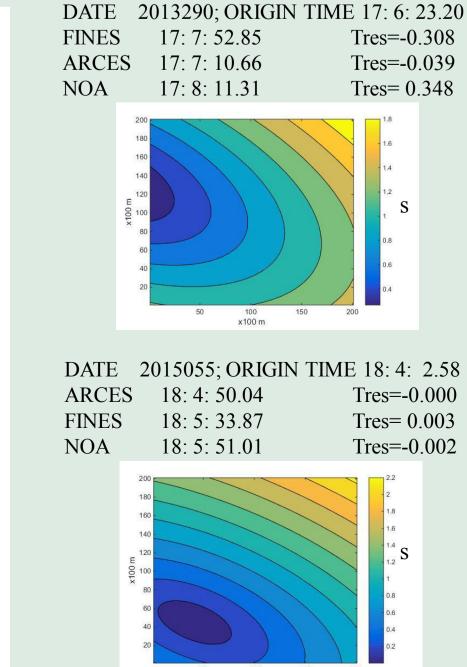
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or
$$ij = ATij - TTij$$

ere *i* is arrival index at station *j*.
 $TTii = TTi$

ve location grid 	$dt_{k} = \mathbf{S} \cdot \mathbf{d}_{k} - \text{travel time}$ correction $OT^{k}_{ij} = AT_{ij} - TT_{j} + dt_{jk} - $ corrected origin time k nodes, rectangular of circle; grid size from 1 to 100 km;
0 0 5 10 0 -5 -5 -6 -6 -6 -6 -6 -6 -6 -6	spacing from meters to 10- 15 km Average OT and RMS OT residual are calculated in each node

Ground truth events for Aitik mine There are 97 GT events confirmed by local infrasound measurements, from which 33 (see table below) are missing in the REB. All were found by cross correlation at ARCES. FINES and NOA

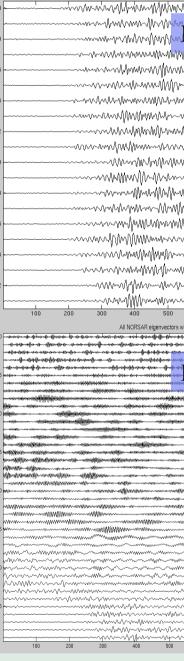


We perform a dimensionality reduction through the truncation of U and S terms and building the restored tensor \mathcal{A}_{red} through the block term decomposition (BTD) which approximates a tensor by a sum of low multilinear rank terms

Multimodal dimensionality reduction with other methods. The multidimensional discrete (MD) cosine transform (DCT-II and DCT-III for inverse) is popular compression structures for MPEG-4, H.264, and HEVC (high efficiency video coding), and is accepted as the best suboptimal transformation since its performance is very close to that of the statistically optimal Karhunen-Loeve transform

 $X(k_1, k_2, \dots, k_r = \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} \dots \sum_{n_r=0}^{N_r-1} x(n_1, n_2, \dots, n_r) \cdot \cos \frac{\pi (2n_1+1)k_1}{2N_1} \dots \cos \frac{\pi (2n_r+1)k_r}{2N_r} ,$

where $k_i = 0, 1, ..., N_i$ -1 and i = 1, 2, ..., r. Inverse truncated MD DCT returns the reduced tensor array with the required number of components used for cross correlation template construction.

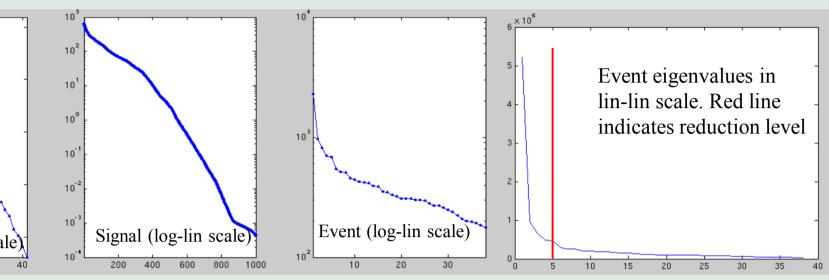






arrav was considered as a 3-order tensor so the training data set turned to 4-

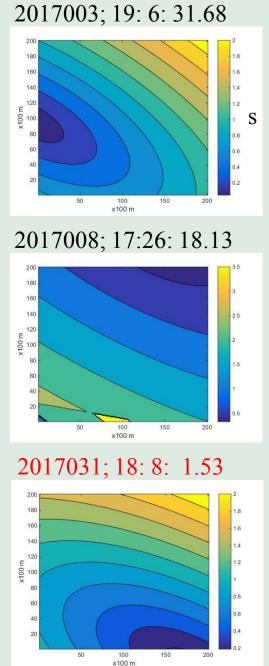
order tensor. The following methods tested: (1) high-order SVD transform (MD DCT), (3) two dimensional SVD (2D SVD), and (4) tensor interpolation.

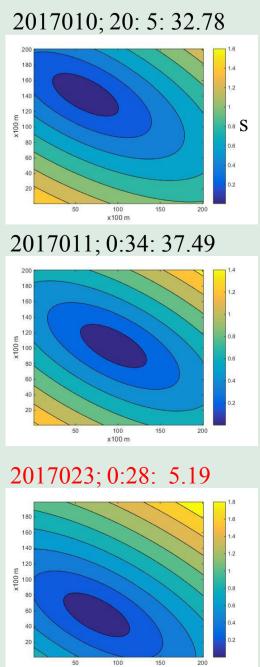


 $\mathcal{A}_{red} = \sum \mathcal{S}^{(r)} \bullet_1 U^{(r,1)} \bullet_2 U^{(r,2)} \bullet_3 \dots \bullet_1 N U^{(r,N)}$

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**Continuous association and location of Aitik and Kiruna blasts** Continuous detection with cross correlation uses 14 master events: 7 from Aitik mine and 7 from Kiruna. The WCC method finds all REB (black date and time) events and many events not in the REB (red date and time)





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