Seismic event discrimination using diffusion maps

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Abstract

Discrimination between earthquakes and explosions is an important component of the CTBT verification regime. Currently used seismic discrimination methods give a partial solution to the problem. We apply diffusion maps for constructing a geometric representation of the seismograms that capture the intrinsic structure of the signal. In the obtained low-dimensional representation, seismic events with similar source mechanism from the same region have a similar representation. This enables to discriminate earthquakes from explosions from the same region.

Diffusion maps

- A non-linear dimensionality reduction technique.
- Constructs global parameterization description of the dataset from local similarities.
- Diffusion distances provide a local preserving metric for this data.

Diffusion maps were introduced in (Coifman and Lafon, 2006). The first applications of diffusion maps in seismology may be found in (Taylor et al., 2011 and Ramirez et al., 2011).

Main idea

The distance between two points can be defined as the probability to land in the second point after a number of random steps that start at the first point.

$$\Delta(x_i, x_j) = \sum_{T \geq 0} (p(x_i, x_j) - p(x_j, x_i))^2$$

This distance measures the connectivity between the two points in the data, while taking into account all possible paths between them.

Algorithm outline

Given data points $\Gamma = \{x_1, ..., x_n\}$ in $\mathbb{R}^n$, construct a normalized kernel (Markov matrix) from the data:

$$P \propto W = e^{-\frac{1}{\sigma} \| x \|^2}.$$ The spectral decomposition of $P$, $P(x_i, x_j) = \sum_{k \geq 0} \lambda_k \psi_k(x_i) \psi_k(x_j)$ is used to construct the family of diffusion maps

$$\Psi(x_i) = (\Lambda_1 \psi_1(x_i), \Lambda_2 \psi_2(x_i), \Lambda_3 \psi_3(x_i), \cdots)$$

These embedding the data to Euclidean space.

Diffusion distances are preserved:

$$\Delta(x_i, x_j) = \sum_{T \geq 0} (p(x_i, x_j) - p(x_j, x_i))^2 = \sum_{k \geq 0} \lambda_k^2 (\psi_k(x_i) - \psi_k(x_j))^2$$

Simple example - diffusion maps embedding

Euclidean distances in the embedded space correspond to probabilistic distances in the high dimensional space.

Seismic discrimination in seismic active regions

We propose new methods for identifying seismic events as earthquakes by applying diffusion maps and using the historic seismic data from the same region. Our approach rely on the following observations:

- If seismic events have the “similar” source mechanisms, locations and magnitudes then their waveforms should be “similar” as well.
- We observe that if two events are nearly collocated and have the close magnitudes but have quite different source mechanisms then their waveforms should be quite different as well.

Dead Sea events

5 earthquakes and one underwater explosion (Fig. 2) in the northern Dead Sea area which were received at IMS stations MMAO & EIL located 150 & 230 km from the epicenters, respectively, while the maximal distance between the epicenters is 6.5 km.

Fig. 2: Dead Sea events as received at IMS stations MMAO (left) and EIL (right)

There are many similarities in the earthquake seismogram patterns at MMAO although their amplitudes are different. On the other hand, the patterns of earthquake seismograms are fully different from the pattern of explosion seismogram. Our purpose is to quantify those “similarities”. We have applied the simple cross correlations as well as even more complicated seismogram pattern recognition technique (Joswig, 1990), however we did not solve the problem. Namely, the earthquakes were assigned to different classes. Thus, a “rougher” classifier is required.

Preprocessing

We first calculate a seismogram (Joswig, 1999) by summing the power spectrum density in logarithmically scaled frequency pass bands for overlapping time windows. Fig. 3 presents the preprocessing results for the Dead Sea events at MMAO. The earthquake seismograms are similar one to other and emphasize the S phase while the explosion seismogram underlines the P phase.

Fig. 3: MMA0 sonograms for Dead Sea events normalized by frequency bands

Main processing

The diffusion maps algorithm was applied separately to each such window as the input matrix. The first diffusion maps coordinate provides a robust and consistent representation of the seismic window. Figure 4 presents the new low dimensional representation for Dead Sea events. It can be seen that the natural events, even though they are of different magnitudes, have an almost identical representation and explosion can be easily separated from them.

Fig. 4: Dead Sea events representation by the application of diffusion maps at IMS stations MMAO (left) and EIL (right)

References


Fig.1: Left: original dataset, the points are measures with diffusion distances. Right: the diffusion maps parameterization of the data. Euclidean distances correspond to diffusion distances in the original, left, image.

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