

# Coda Wave Interferometry detection of velocity changes user guide



This application calculates possible velocity changes using the Coda Wave Interferometry Techniques. The application calculates the delay time between the coda waves of a pair of seismograms by applying cross-correlation at subsequent lapse times. Requires SAC format seismograms from different earthquakes recorded by the same component of the same station. For any given pair of seismograms which passed the correlation threshold selection, the output consists of percent velocity changes (and associated uncertainties) which occurred in between the two earthquakes. This can be combined with industrial data (e.g., rate of extraction / injection, front advance, etc.) to ascertain if the propagation medium suffered any significant variation of elastic properties.



## REFERENCES [Document Repository](#)

**CATEGORY** Source Parameter Estimation

**KEYWORDS** Coda Wave Interferometry, Velocity changes, Subsoil monitoring

**CITATION** Please acknowledge use of this application in your work: IS-EPOS. (2019). *Data Processing Applications* [Web applications]. Retrieved from <https://tcs.ah-epos.eu/>

## Introduction

Two earthquakes exhibiting very similar waveforms (doublet) are representative of the subsequent activation of a source whose mechanism and location do not change over time. In a doublet, while ballistic (i.e., P- and S-waves) arrivals match, the coda can lose coherency, since multiply scattered waves are sensitive to small changes in the medium. The earthquake coda, composed of multiply scattered waves, samples the medium more effectively than the direct (ballistic) arrivals. For identical co-located sources, acting at different times, any observed difference in waveforms is related to a change in the elastic properties of the medium. The coda wave interferometry technique (CWI) uses multiply scattered waves to detect temporal changes in a medium by using the medium as an interferometer, i.e. comparing scattered waves that sample the medium at different times. Following these principles, this app applies the Coda Wave Interferometry technique in order to estimate possible velocity changes between pairs of similar earthquakes.

## Method

The app examines a list of seismograms from the same component of the same station. At first, all the independent pairs of seismograms are cross-correlated, in order to identify doublets of repeating earthquakes. A doublet is defined as a pair of seismograms whose correlation is larger than a threshold input parameter. For any identified doublet, the app then applies the CWI method. This consists in evaluating the cross-correlation function (CCF) at subsequent lapse times  $T$  along the coda waves of the two similar earthquakes. For any window position, the time lag  $\tau$  corresponding to the maximum of the CCF is a measurement of the mean perturbation in traveltimes of one event with respect to the other. Therefore, the behaviour of  $\tau$  with lapse time along the coda allows identifying the source of the perturbation. In fact, when the perturbation is generated by a (small) displacement of scatterer or source location,  $\tau$  oscillates around 0 (Snieder, 2006). If, instead, the perturbation is due to a homogeneous velocity change over the medium sampled, then the time separation between the two waveforms will increase (decrease) linearly for later times in the coda. As a first approximation, this trend may be fitted by a linear regression curve, thus the relative velocity change measurement in terms of percentage variation corresponds to the slope of  $\tau / T$  changed in sign.

## Internal Flux

This is the description of the code's internal flux. All these steps are transparent to the user; information on how to run the App are in the next Section 4. Terms in **bold** refer to the input parameters required by the App (see Table 1)

1. Reading seismograms from the same component of the same seismic station;
2. Preconditioning: trend and mean removal, tapering;
3. Band-pass filtering over the [***fmin***, ***fmax***] frequency band;
4. Calculation of the  $N(N-1)/2$  cross-correlations between all the independent seismogram pairs;
5. Selection of the NG seismogram pairs for which the correlation coefficient is larger than the ***threshold*** parameter;
6. For each pair of similar seismograms:
  - Alignment of the two time series according to the delay time estimated by crosscorrelation;
  - Starting at ***tstartcwi*** seconds after largest amplitude, and spanning a total duration of ***tlencwi*** seconds, performing of the CWI loop for subsequent lapse times  $T$ :
    - a. Calculation of the CCF over a window of length ***wl*** second;
    - b. Interpolation of the CCF by fitting the 3 samples encompassing the CC maximum with a parabola;
    - c. Evaluation of the lag time  $\tau$  from the maximum of the interpolating function, with a precision of 1/10 of the original sampling rate;
    - d. Storing the time lag  $\tau$  and corresponding maximum of the CCF;
    - e. Shifting the correlation window ***wl*** by 50% of its length;
    - f. Goto point (a)
7. The  $\tau$  vs  $T$  relationship is then fitted to a straight line using a robust, L1-*norm* approach implemented through the IRLS algorithm (Aster et al., 2013).
8. The percent velocity change  $\Delta v = -\tau / T$  is finally evaluated from the slope of the fitting line.

Figure 1 illustrates a pictorial view of the procedure, with specification of some of the relevant parameters.

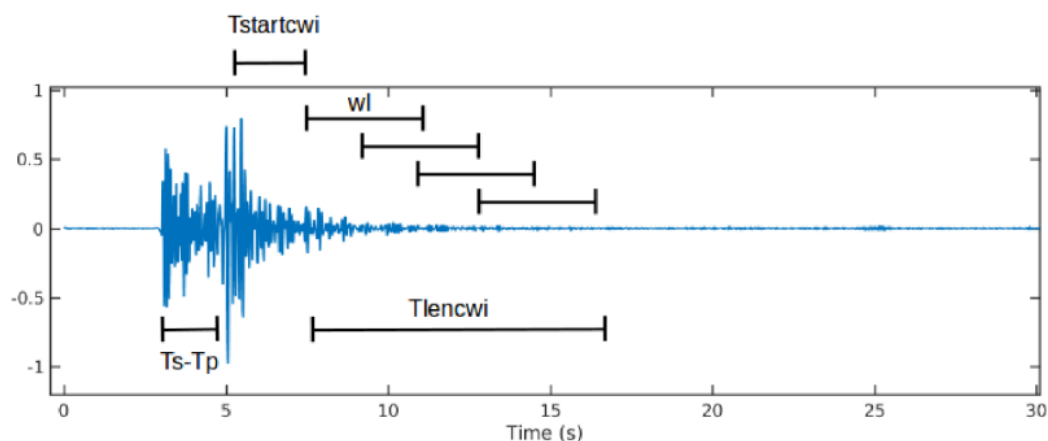


Figure 1. Main parameters mentioned in the text.

**Explanation:**  $T_s-T_p$  is the delay time between the S and P waves arrival.  $T_{startcwi}$  is the time lag after the maximum amplitude (usually associated with the S-wave arrival) at which starting the CWI analysis.  $wl$  is the length of the time window for correlation estimates.  $T_{lencwi}$  is the time interval (in s) after  $T_{startcwi}$  over which extending CWI analysis.

## Step by Step

## Obtaining the SAC files

### Selection of the episode of interest

From the list of episodes on the EPISODES Platform, select the one of your interest (in this case, the Song Tranh reservoir). You'll be redirected to the page of the selected episode (Figure 2). Click on the link 'Event Related Waveform' within the data section.

### Episode: SONG TRANH

SONG TRANH: deep water reservoir

#### Description

Seismic activity linked to Song Tranh 2 hydropower plant and the reservoir containing backed up water of Tranh river in central Vietnam. The reservoir volume is 740 million cubic meters and the water level varies between 140 and 175 m. Seismic activity in the reservoir region, previously known as aseismic, began in 2011, soon after filling of the reservoir.

Episode integrated in the framework of:

- IS-EPOS project, Digital Research Space of Induced Seismicity for EPOS Purposes No. POIG.02.03.00-14-090/13
- EPOS IP project, European Plate Observing System Implementation Phase. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 676564

If you use data from this episode in a publication, then you must cite the data source as follows:  
 IS-EPOS (2017), Episode: SONG TRANH, [https://tcs.ah-epos.eu/#episode:SONG\\_TRANH](https://tcs.ah-epos.eu/#episode:SONG_TRANH), doi:10.25171/InstGeoph\_PAS\_ISEPOS-2017-002

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#### Status details

Impacting factor:	Reservoir impoundment
Region:	Vietnam, Quang Nam Province
Project association:	IS-EPOS, EPOS-IP

#### Data

DATA RELEVANT FOR THE CONSIDERED HAZARDS

SEISMIC

- Catalog** Two seismic catalogues:
  - 1) Seismic catalog since 24/08/2013, some 250 events per month, magnitude range ML: -0.6 to 3.6
  - 2) Moment tensors (MT) were obtained by inversion of the P- and S-wave amplitudes in the time domain. Method is an extension of the method used in FOCI app ([https://tcs.ah-epos.eu/#app:FOCI\\_APP](https://tcs.ah-epos.eu/#app:FOCI_APP)). The capability of VERIS seismological network for moment tensor inversion was first determined with the use of synthetic data tests. Uncertainties of the estimated MT are estimated through the normalized root-mean-square (RMS) error between theoretical and estimated amplitudes. RMS error of full MT solution not higher than 0.3 was set as a rule of the solution acceptance along with coherent RMS errors and nodal plane orientations of the trace null and double-couple solutions.
- Event Related Waveforms** Event related waveforms available since 24/08/2013
- Parts of continuous waveforms for specific dates and stations are available through 'Waveform download tool' in Applications
- Seismic Network** Locations and parameters of seismic stations in Songh Trahn 2 reservoir area, Vietnam

Figure 2. Episode view.

### Selection of the recordings

All the data files (seismic recordings) related to this episode will be listed (Figure 3). Select the ones of your interest (in this case, the first 10 files from the Song Tranh episode).

**Data Search**

Impacting Factor: SONG TRANH: deep water res Seed Signal Country Start End

**Results**

Name	Start	End	Data type				
<input checked="" type="checkbox"/> SONG_TRANH_signal000001.seed	2013 Aug 24 17:35:24	2013 Aug 24 17:37:27	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000002.seed	2013 Aug 24 18:01:01	2013 Aug 24 18:03:07	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000003.seed	2013 Aug 24 18:01:05	2013 Aug 24 18:03:11	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000004.seed	2013 Aug 28 17:37:57	2013 Aug 28 17:40:01	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000005.seed	2013 Aug 28 20:28:40	2013 Aug 28 20:30:46	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000006.seed	2013 Aug 28 21:44:34	2013 Aug 28 21:46:39	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000007.seed	2013 Aug 29 18:08:16	2013 Aug 29 18:10:20	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000008.seed	2013 Aug 29 18:09:02	2013 Aug 29 18:11:06	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000009.seed	2013 Aug 31 03:13:45	2013 Aug 31 03:15:50	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000010.seed	2013 Sep 02 00:26:22	2013 Sep 02 00:28:24	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000011.seed	2013 Sep 03 00:08:04	2013 Sep 03 00:10:05	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000012.seed	2013 Sep 03 19:32:10	2013 Sep 03 19:34:14	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000013.seed	2013 Sep 03 21:13:14	2013 Sep 03 21:15:21	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000014.seed	2013 Sep 04 18:05:40	2013 Sep 04 18:07:45	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000015.seed	2013 Sep 04 19:50:00	2013 Sep 04 19:52:02	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000016.seed	2013 Sep 04 19:51:58	2013 Sep 04 19:54:04	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>

**Figure 3. Listing of files related to the episode.**

## Adding selected files to your workspace

Once files have been selected, click on the 'ADD SELECTED TO WORKSPACE' button, at the bottom left of the window. You'll be prompted for specifying the directory where files should be copied (Figure 4). Select the appropriate directory. (It is suggested to make sure that the directory where the User is putting data is empty.)

**Results**

Name	Start	End	Data type				
<input checked="" type="checkbox"/> SONG_TRANH_signal000001.seed	2013 Aug 24 17:35:24	2013 Aug 24 17:37:27	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000002.seed	2013 Aug 24 18:01:01	2013 Aug 24 18:03:07	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000003.seed	2013 Aug 24 18:01:05	2013 Aug 24 18:03:11	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000004.seed	2013 Aug 28 17:37:57	2013 Aug 28 17:40:01	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000005.seed	2013 Aug 28 20:28:40	2013 Aug 28 20:30:46	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000006.seed	2013 Aug 28 21:44:34	2013 Aug 28 21:46:39	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000007.seed	2013 Aug 29 18:08:16	2013 Aug 29 18:10:20	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000008.seed	2013 Aug 29 18:09:02	2013 Aug 29 18:11:06	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000009.seed	2013 Aug 31 03:13:45	2013 Aug 31 03:15:50	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input checked="" type="checkbox"/> SONG_TRANH_signal000010.seed	2013 Sep 02 00:26:22	2013 Sep 02 00:28:24	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000011.seed	2013 Sep 03 00:08:04	2013 Sep 03 00:10:05	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000012.seed	2013 Sep 03 19:32:10	2013 Sep 03 19:34:14	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000013.seed	2013 Sep 03 21:13:14	2013 Sep 03 21:15:21	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000014.seed	2013 Sep 04 18:05:40	2013 Sep 04 18:07:45	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000015.seed	2013 Sep 04 19:50:00	2013 Sep 04 19:52:02	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000016.seed	2013 Sep 04 19:51:58	2013 Sep 04 19:54:04	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000017.seed	2013 Sep 04 20:00:00	2013 Sep 04 20:02:04	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000018.seed	2013 Sep 04 20:02:08	2013 Sep 04 20:04:12	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>
<input type="checkbox"/> SONG_TRANH_signal000019.seed	2013 Sep 04 20:04:16	2013 Sep 04 20:06:20	Seed Signal	<input type="button" value="VIEW FILE"/>	<input type="button" value="VIEW EPISODE"/>	<input type="button" value="ADD TO WORKSPACE"/>	<input type="button" value="MORE"/>

Choose directory where the file should be created

/

DATA

OK CANCEL

**Figure 4. Choice of workspace directory to place the files.**

## Format conversion and data checking

Once all the data files have been copied into the selected destination, you must proceed to the '[SEED to SAC converter](#)' application and click on 'ADD TO WORKSPACE' button to add converter to the User's workspace. You will be asked for a location where creating the folder associated with the application (it has a default name: 'SeedtoSac'). The application starts automatically with the following input form (Figure 5):

**SEED to SAC converter** ACTIONS

File: SeedToSac Description: Converts SEED volume to SAC. Resulting SAC file contains sensitivity information... [EXPAND](#)

**INPUTS**

Seed Waveform ⓘ   
Required 1+

Remove response ⓘ ☐

⚠ Missing or invalid input files: Seed Waveform

☐ Enable autorun

Status: New ⓘ

**Figure 5. The "Seed to SAC converter" application input form.**

By clicking on the '**Select Files**' button, you'll be asked for selecting data files to be converted (Figure 6).

**SEED to SAC converter** ACTIONS

File: SeedToSac

**INPUTS**

Seed Waveform ⓘ   
Required 1+

⚠ Missing or invalid input files: Seed Waveform

☐ Enable autorun

Status: New ⓘ

**OUTPUTS**

**Select files** X

Individual files Files from chosen directory Application output Application input Automatic choice

Choose a directory from which all files with matching data types will be added as inputs.

/

- DATA
- SeedToSac

**Figure 6. Selection of files to be converted.**

Select the '**Files from chosen directory**' option, and then select the directory where the SEED data files to be converted reside (in this example, it is the DATA directory). Again: this directory must contain **ONLY** the data files you want to finally process.

Run the app by clicking on the '**RUN**' button (Figure 7). You should see a '**Status: Running**' message, and the progressive growing of output file names within the '**OUTPUTS**' window at the bottom of the page. At the end of the process, all the newly converted data files will be stored in the 'SeedToSac' directory.

Now it's a good moment for checking your data. From the directory tree at the left, go to the 'SeedToSac' directory and click on one of the newly-converted data files. The corresponding seismogram will be displayed (Figure 7). Here you can get information that are necessary for the subsequent selection of input parameters to the the Coda Wave Interferometry, such as sampling rate, seismogram duration, etc.

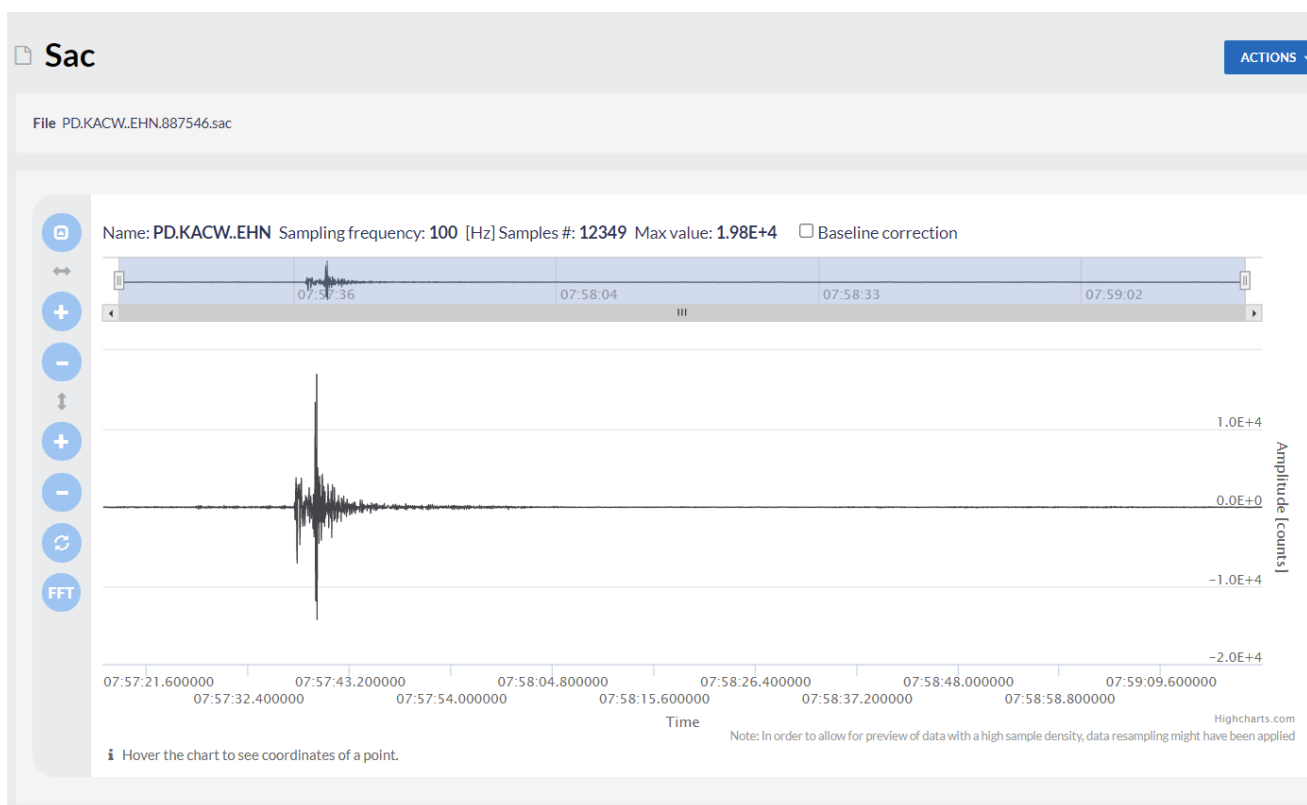


Figure 7. Display of the selected seismogram.

## Running the Coda Wave Interferometry

After adding the 'Coda Wave Interferometry detection of velocity changes' application to the workspace, the following window appears on the screen (Figure 8):

Figure 8. Input window of the application.

# EPOS Thematic Core Service Anthropogenic Hazards

Click on the 'SELECT FILES' button. A new menu window appears; select the '**Individual files**' option, and then select the SAC files of interest (at least two are required, they should be from the same station and showing the same channel). Alternatively, you may want to choose the '**Application Output**' or '**Files from chosen directory**' option and select the 'SeedToSac' folder name. This directory must contain ONLY the data files you want to process.

Finally, you have to select the rest of the parameters as explained in the Table reported in the next Section.

## Understanding the Input Parameters

<b>seislist</b>	List of SAC format input seismograms. These must be from the <u>same component</u> of the <u>same seismic station</u> , with the <u>same sampling rate</u> .
<b>Filter frequency fmin</b> (Hz)	Low corner frequency of the filter. It must be significantly greater than the <i>frequency</i> inverse of the length of the seismograms under analysis. For instance, if the time series are 10-s-long, than <b>fmin</b> must be larger than 0.1 Hz. Usually, for microearthquakes at local distances, a value <b>fmin = 2-4 Hz</b> is appropriate.
<b>Filter frequency fmax</b> (Hz)	High corner frequency of filter. It must be greater than the low-corner <i>frequency</i> frequency <b>fmin</b> and lower than the Nyquist frequency $F_n$ of the time series ( $F_n$ is equal to half the sampling frequency). For earthquake signals, Values in the order of $F_n/2$ are generally appropriate. Thus, if the sampling frequency is 100 Hz, $F_n=50$ Hz and <b>fmax=25 Hz</b> can be a good choice.
<b>Correlation threshold</b> [0.0, 1.0]	Correlation threshold for analysing seismogram pairs (range: 0-1). Seismogram pairs are analysed through the CWI algorithm if their overall correlation is above the threshold value. Since the CWI method relies on the assumption that the analysed seismogram pairs are issued by the same source, a high value of the correlation threshold is recommended (e.g., > 0.75)
<b>Window length wl</b> (s)	Length of time window for coda wave interferometry analysis. <b>wl</b> should be 2 times larger than the longest period of the signal to be analysed (i.e. $2 / fmin$ ).
<b>CWI starting time tstart cw</b> (s)	Starting time (after max amplitude of traces) for CWI analysis. <b>tstartcw</b> should be on the order of the S-P delay time. Since this quantity is not known a priori, a preliminary visual inspection of the seismograms is recommended. For cases where hypocenters are distributed within a vast region, therefore exhibiting a large variability of the S-P delay times, <u>this quantity can be set equal to 0.</u>
<b>CWI data segment length tlen cw</b> (s)	Length of data segment for CWI analysis. <b>tlencw</b> should extend throughout the duration of the coda. Since this quantity is not known a priori, a reasonable choice can only be made by a preliminary inspection of seismograms. In any case, <b>tlencw</b> cannot exceed the time interval in between the seismogram's maximum amplitude + <b>tstartcw</b> and the ending time of the seismogram.

## Caveats

- CWI window length **wl** cannot be longer than seismogram length;
- CWI window length **wl** cannot be longer than the time interval **tlencw** selected for the analysis;
- The ending time of the analysis (**tlencw** + **tstartcw**) cannot exceed the ending time of the seismogram;
- A reasonable choice for the CWI window length **wl** is twice the low-pass period, i.e. **wl** =  $1 / fmin$ ;
- The low-frequency corner of the filter **fmin** must satisfy the relationship : **fmin** >  $1/T$ , where T is the time length of the seismogram (e.g., for a 10-s-long seismogram, **fmin** must be greater than 0.1 Hz);
- The high-frequency corner of the filter **fmax** must be lower than the Nyquist frequency : **fmax** <  $0.5 F_s$ , where  $F_s$  is the sampling frequency of the seismograms (i.e., for a seismogram sampled at 100 Hz, **fmax** must be lower than 50 Hz);
- The input seismograms must be in SAC format, with the KSTNM (station name) and KCMPNM (component name) header field properly filled-in;
- The input seismograms must be from the same component of the same station.

## Application outputs

The main output is a text file (*cwi.results.txt*) containing a row for each pair of seismograms which have been analysed with the following data:

ind1 ind2 name1 name2 tstart1 tstart2 deltaV errdeltaV

ind1= index of the first seismogram, with respect to the original list

ind2= index of the second seismogram, with respect to the original list name1 = name of seismogram 1 name2 = name of seismogram 2

tstart1 = starting time of seismogram 1

tstart2 = starting time of seismogram 2

deltaV = percent velocity change derived from CWI errdeltaV = error in percent velocity change estimate

In addition, two set of figures are produced:

- A record section (png image, named *cwi.recordsection.png* with **all** the analysed seismograms prior to correlation thresholding (Figure 9)
- A *png* picture for each of the seismogram pair which passed the correlation threshold, illustrating the linear fitting of the delay time vs lapse time (named *cwi.outfig.??? .png*); see Figure 10.

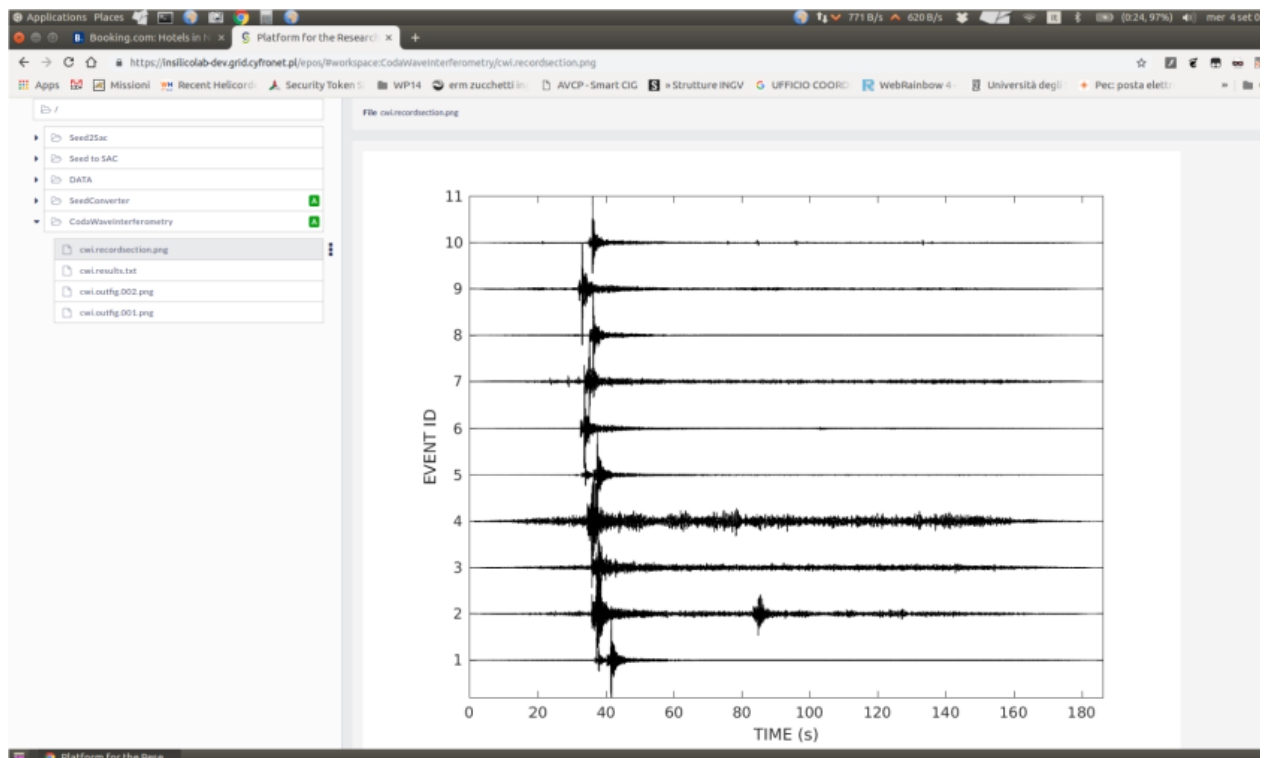


Figure 9. The Record Section plot, illustrating all the seismograms selected for the analysis.

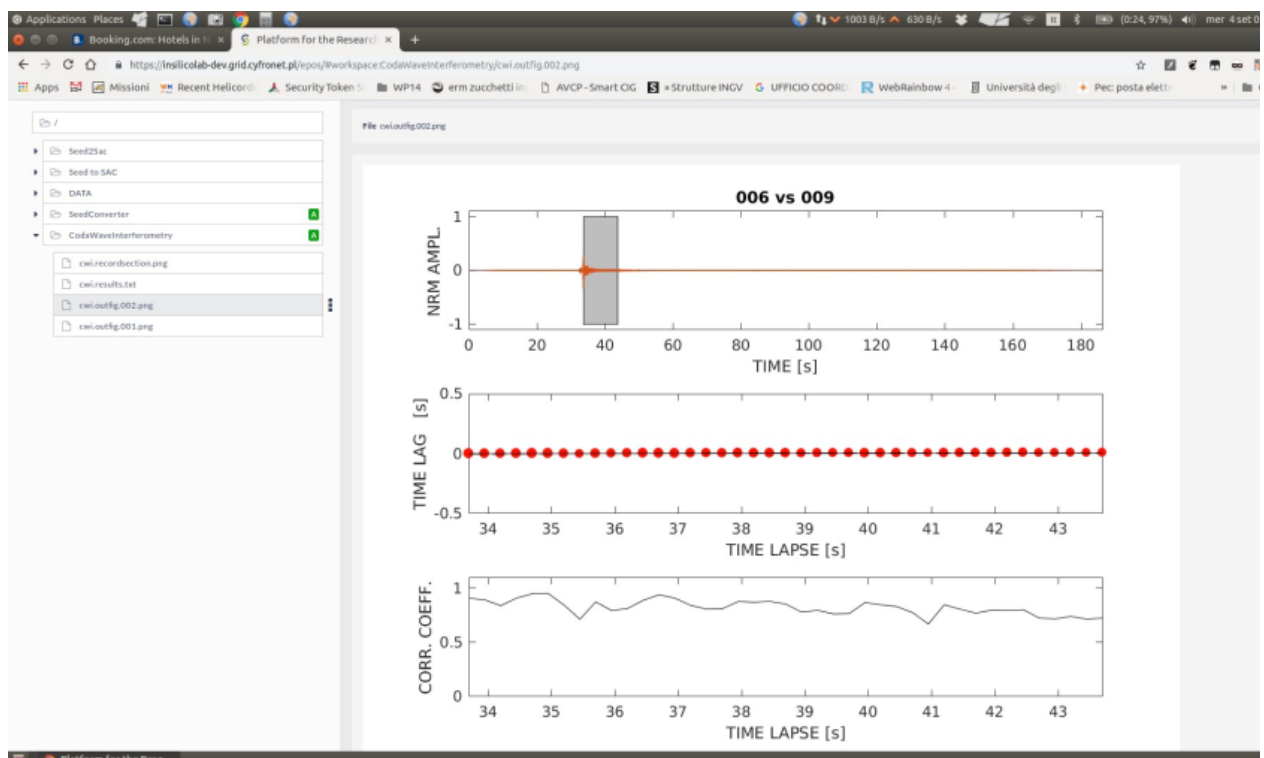


Figure 10. Results from the CWI analysis.

Top: the two earthquakes selected for the processing. The dashed area marks the time interval selected for the evaluation of the lag time vs lapse time relationship. Middle plot: Time lags as a function of lapse times. The continuous line is the line bestfitting the data in the L1-norm sense. The two dashed lines are the error bounds. Bottom plot: maximum of the cross correlation function evaluated at subsequent lapse times.

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