

EQcorrscan
*Correlation for earthquake
detection in Python*

EQcorrscan Documentation

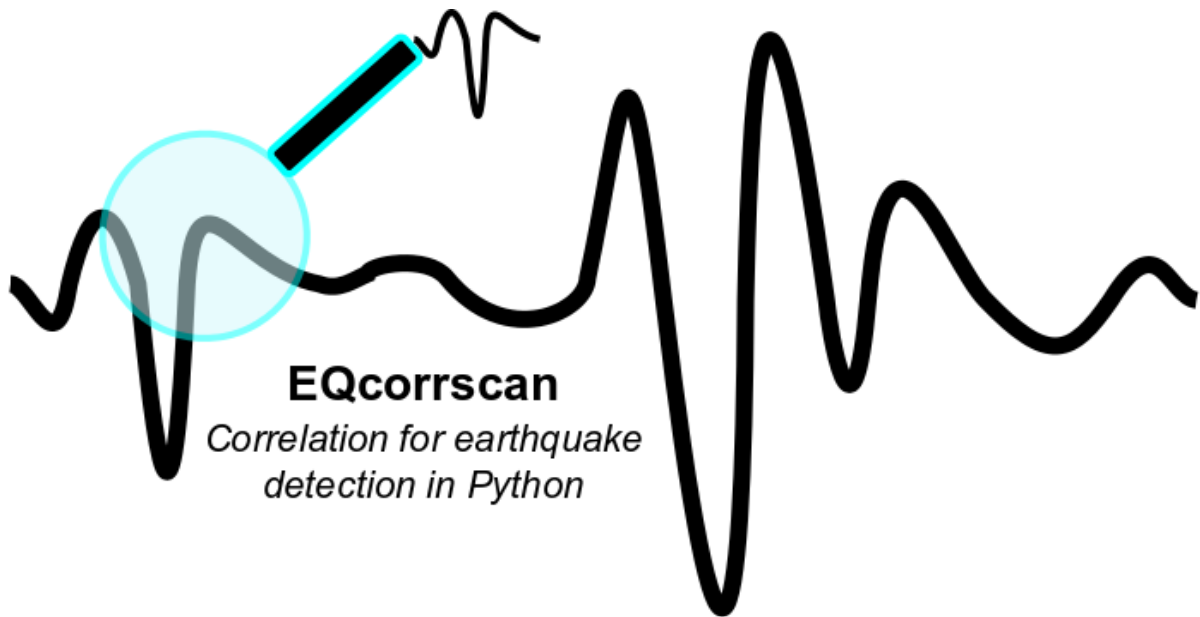
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Calum John Chamberlain

September 04, 2015

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EQCORRSCAN

A python package to conduct match-filter earthquake detections. Codes are stored on github, the bleeding edge master is [here](#), or the latest stable(ish) release can be found [here](#)

This package contains routines to enable the user to conduct match-filter earthquake detections using [Obspy](#) bindings when reading and writing seismic data, and the correlation routine in [openCV](#). Neither of these packages are installed by this software, due to a range of licences being implimented. However, both are open-source and should be installed before using this package. This package was written to impliment the matlab routines used by Chamberlain et al. (2014) for the detection of low-frequency earthquakes.

Also within this package are:

- Clustering routines for seismic data;
- Peak finding algorithm (basic);
- Automatic amplitude picker for local magnitude scale;
- [Seisan](#) S-file integration for database management and routine earthquake location;
- Stacking routines including phase-weighted stacking based on Thurber et al. (2014);
- Brightness based template creation based on the work of Frank et al. (2014)

This package is written by Calum Chamberlain of Victoria University of Wellington, and is distributed under the LGPL GNU Licence, Copyright Calum Chamberlain 2015.

REFERENCES

- CJ Chamberlain, DR Shelly, J Townend, TA Stern (2014) [Lowfrequency earthquakes reveal punctuated slow slip on the deep extent of the Alpine Fault, New Zealand](#), *G-cubed*, doi:10.1002/2014GC005436
- Thurber, C. H., Zeng, X., Thomas, A. M., & Audet, P. (2014). [PhaseWeighted Stacking Applied to LowFrequency Earthquakes](#), *BSSA*, doi:10.1785/0120140077.
- Frank, W. B., & Shapiro, N. M. (2014). [Automatic detection of low-frequency earthquakes \(LFEs\) based on a beamformed network response](#), *Geophysical Journal International*, 197(2), 1215-1223, doi:10.1093/gji/ggu058.

CONTENTS:

3.1 Introduction to the EQcorrscan package

This document is designed to give you an overview of the capabilities and implementation of the EQcorrscan python module.

3.1.1 Installation

Most codes should work without any effort on your part. However you must install the packages this package relies on yourself, this includes the following packages:

- matplotlib
- numpy
- scipy
- obspy
- joblib
- openCV (2)

This install has only been tested on Linux machines and even then has some issues when installing on 32-Bit versus 64-Bit machines. In this instance you should be prepared for small differences in the results of your correlations relating to floating-point truncation differences between 32 and 64-Bit machines.

If you plan to run the `bright_lights.py` routines you will need to have NonLinLoc installed on your machine. This is not provided here and should be sourced from [NonLinLoc](#). This will provide the Grid2Time routine which is required to set-up a lag-time grid for your velocity model. You should read the NonLinLoc documentation for more information regarding how this process works and the input files you are required to give.

3.1.2 Functions

This package is divided into sub-directories of *core*, *par* and *utils*. The *utils* directory contains simple functions for integration with `seisan`, these is the *Sfile_util.py* module and functions therein which are essentially barebones and do not have the full functionality that `seisan` can handle. *utils* also contains a simple peak-finding algorithm *find_peaks.py* which looks for peaks within noisy data above a certain threshold and within windows.

Within *par* you will find parameter files which you will need to edit for each of the *core* scripts. *core* scripts often call on multiple *par* files so be sure to set them all up. The *template_gen_par.py* script is used by all *core* modules and must be set-up. Within this you will define all your template parameters. Currently the templates must all be of the same length, but this may change in a future release.

Within *core* you will find the core routines to generate templates, (*template_gen.py*) search for likely templates (*bright_lights.py*) and compute cross-channel correlations from these templates (*match_filter.py*).

3.2 EQcorrscan tutorial

Welcome to EQcorrscan - this package is designed to compute earthquake detections using a paralleled match-filter network cross-correlation routine. The inner loop of this package is the cross-correlation of templates of seismic data with daylong seismic data. This inner function is the `openCV.match_template` function - this appears to be a well optimized cross-correlation function written in c++. Cross-correlations are computed in the frequency domain for large datasets, for which a day of seismic data usually qualifies.

Before continuing with this tutorial please check that you have installed all the pre-requisite modules, as this won't be done for you. The list of these is in the Introduction section of this documentation.

As you will see, this package is divided into three main sub-modules, the Core, Utils and Par sub-modules. The Core sub-module contains the main, high-level functions:

bright_lights A brightness based template detection routine;

template_gen A series of routines to generate templates for match-filter detection from continuous or cut data, with pick-times defined either manually, or from a *Seisan* s-file;

match_filter The main match-filter routines, this is split into several smaller functions to allow python based parallelisation;

lag_calc Routines for calculating optimal lag-times for events detected by the match-filter routine, these lags can then be used to define new picks for high accuracy reloactions.

The Par sub-module contains parameter files which are provided to allow for simple bulk processing of large datasets. These *MUST* be edited by the user for their dataset.

The Utils sub-module contains useful, but small functions. These functions are rarely cpu intensive, but perform vital operations, such as reading *Seisan* s-files, finding peaks in noisy data, converting a seisan database to hypoDD formatted files and computing cross-correlations between detections for hypoDD (a double difference reloaction software), calculating magnitudes, clustering detections, stacking detections, making pretty plots, and processing seismic data in the same way repeatedly using *Obspy*'s functionality.

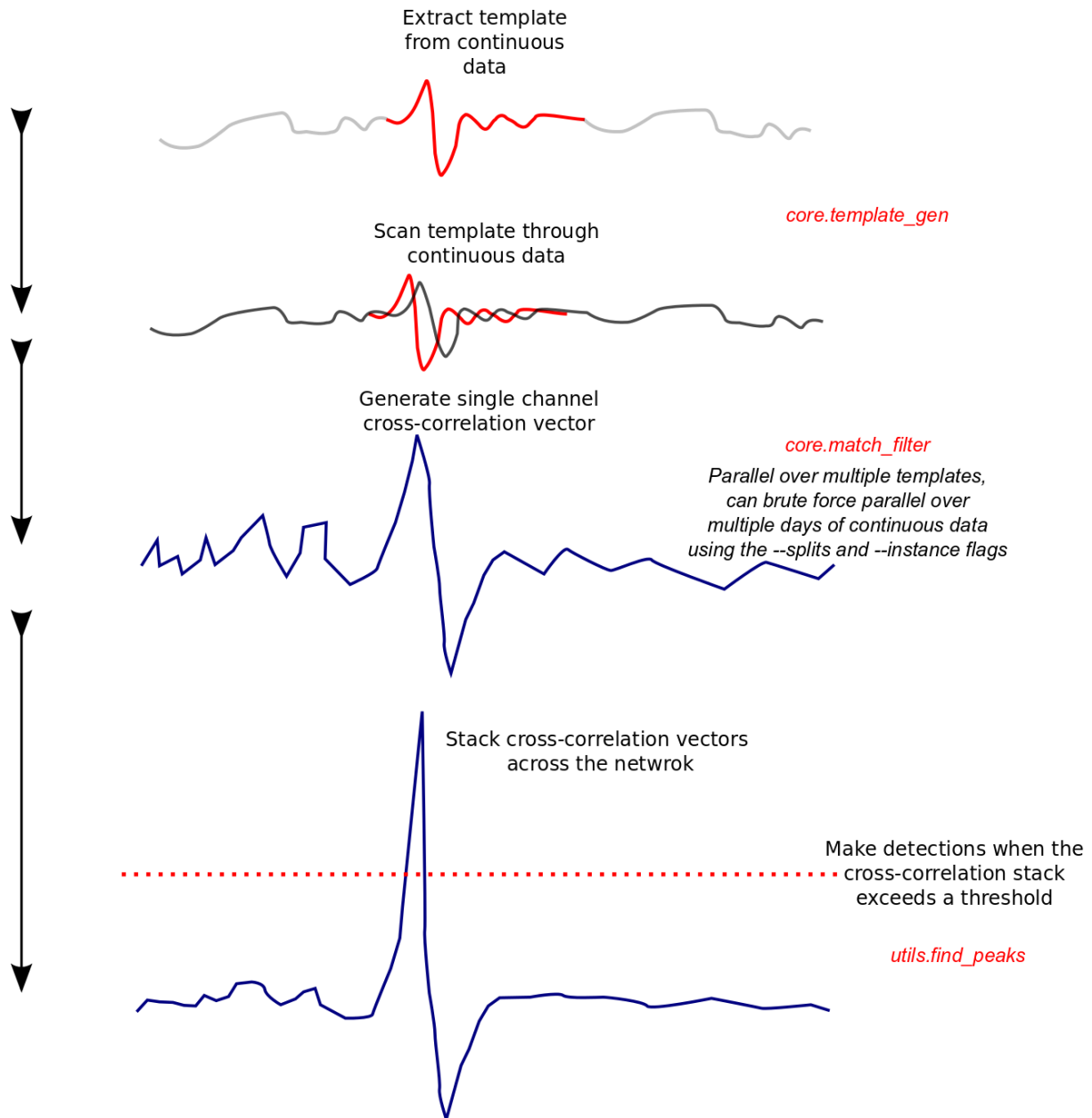
3.2.1 Match-filter detection

In this section we will discuss generating a template from a *Seisan* s-file, and using this template to scan for similar earthquakes within a day of data. This single template and single day of data does not truly exploit the parallel operations within this package however, so you would be encouraged to think about where parallel operations occur (*hint, the code can run one template per cpu*), and why there are `-instance` and `-splits` flags (*hint, if you have heaps of memory and cpus you can do some brute force day parallelisation!*).

The following script is included in the top-level directory alongside the full-scripts used by the author to generate a 6.5 year long catalogue of low-frequency earthquakes for the central Southern Alps of New Zealand.

This tutorial script highlights the ability of the match-filter method in detecting earthquakes of near-repeating nature. The dataset is a day of data taken from the New Zealand national database, and the Southern Alp Microearthquake Borehole Array (SAMBA) network (Boese et al. 2012). This day was found to contain a swarm of earthquakes, as published by Boese et al. (2014), the s-file provided is one of these events.

The main processing flow is outlined in the figure below, note the main speedups in this process are achieved by running multiple templates at once, however this increases memory usage. If memory is a problem there are flags (`mem_issue`) in the `match_filter.py` source that can be turned on - the codes will then write temporary files, which is slower, but can allow for more data crunching at once, your trade-off, your call.



3.2.2 References

- CM Boese, J Townend, E Smith, T Stern (2012). *Microseismicity and stress in the vicinity of the Alpine Fault, central Southern Alps, New Zealand*, *JGR*, doi:10.1029/2011JB008460
- CM Boese, KM Jacobs, EGC Smith, TA Stern, J Townend (2014). *Background and delayed-triggered swarms in the central Southern Alps, South Island, New Zealand*, *G-cubed*, doi:10.1002/2013GC005171

```
#!/usr/bin/python
"""
Tutorial

This script is designed as a tutorial to highlight how to call the main
functions within the EQcorrscan module. In this tutorial we will see how
to generate a template and run this through the match-filter routine.

The template will be generated from a pre-picked earthquake, however there
are other ways to generate templates, for example this package also contains
a simple brightness function that is designed to scan continuous seismic
```

data and look for impulsive energy originating from a discrete point in a seismic velocity model. The use of this brightness function is not included in this tutorial script yet because it is still in beta.

This package is distributed under the LGPL v3.0, by using this script and the functions contained within the EQcorrscan package you implicitly accept the licence. For the full wording of the licence refer to the licence.txt file.

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"""

First we import the required modules:

```
from obspy import read, Stream
from core import template_gen, match_filter
from par import template_gen_par as templatedef
from par import match_filter_par as matchdef
from utils import pre_processing, Sfile_util
import glob
```

Now we find the s-file we want to use to generate a template from
*sfiles=glob.glob('test_data/tutorial_data/*L.S*')*

Generate the template from these sfiles:

templates=[] # Open a list to be filled - only applies for multiple templates

template_names=[] # List of template names for later ID

i=0 # Template name iterator

for sfile in sfiles:

Read in the picks from the S-file, note, in the full case one fo the main
functions in template_gen would be used rather than this, but for
the tutorial we will read in the data here - also note that this
template generation is inefficient for multiple templates, if using
daylong data for multiple templates you would want to only read
the seismic data once and cut it multiple times.

picks=Sfile_util.readpicks(sfile)

for pick in picks:

if not 'wavefiles' in locals():

wavefiles=glob.glob('test_data/tutorial_data/'+
pick.station+'.')*

else:

wavefiles+=glob.glob('test_data/tutorial_data/'+
pick.station+'.')*

wavefiles=list(set(wavefiles))

for wavefile in wavefiles:

print 'Reading data from '+wavefile

if not 'st' in locals():

st=read(wavefile)

else:

```

        st+=read(wavefile)
    st=st.merge(fill_value='interpolate')
    day=st[0].stats.starttime.date
    for tr in st:
        tr=pre_processing.dayproc(tr, 1.0, 20.0, 3, 100.0,\
                                   matchdef.debug, day)
        # Apply a small amoutn of delay before the pick
        for pick in picks:
            pick.time=pick.time-0.1
        template=template_gen._template_gen(picks, st, 1.0, 'all')
        # This will generate an obspy.Stream object
        # Append this Stream to the list of templates
        templates+=[template]
        template_names.append('tutorial_'+str(i))
        # Plot the template just to check that all is well!
        template.plot(size=(800,600), equal_scale=False)
        # Save template for later
        template.write('test_data/tutorial_data/'+template_names[i]+'_template.ms',\
                      format='MSEED')

    i+=1
    del template, st

# Extract the stations from the templates
for template in templates:
    if not 'stachans' in locals():
        stachans=[(tr.stats.station, tr.stats.channel) for tr in template]
    else:
        stachans+=[(tr.stats.station, tr.stats.channel) for tr in template]

# Make this a unique list
stachans=list(set(stachans))

# Read in the continuous data for these station, channel combinations
for stachan in stachans:
    print 'Reading data from: test_data/tutorial_data/'+stachan[0]+'.*'+stachan[1][:-1]+'.*'
    # Generate a new stream object and add to it
    if not 'st' in locals():
        st=read('test_data/tutorial_data/'+stachan[0]+'.*'+stachan[1][:-1]+'.*')
    else:
        st+=read('test_data/tutorial_data/'+stachan[0]+'.*'+stachan[1][:-1]+'.*')

# Merge the data to account for miniseed files being written in chunks
# We need continuous day-long data, so data are padded if there are gaps
st=st.merge(fill_value='interpolate')

# Work out what day we are working on, required as we will pad the data to be daylong
day=st[0].stats.starttime.date

# Process the data in the same way as the template
for tr in st:
    tr=pre_processing.dayproc(tr, 1.0, 20.0, 3, 100.0,\
                              matchdef.debug, day)

# Compute detections
detections=match_filter.match_filter(template_names, templates, st,\
                                     matchdef.threshold, matchdef.threshdtype,\
                                     matchdef.trig_int, True,\
                                     'temp_0')

# We now have a list of detections! We can output these to a file to check later
f=open('tutorial_detections.csv','w')
for detection in detections:
    f.write(detection.template_name+', '+str(detection.detect_time)+\

```

```
        ', '+str(detection.detect_val)+' ', '+str(detection.threshold)+'\n',\n        ', '+str(detection.no_chans)+'\n')\n    f.close()
```

3.3 Core

Core programs for the EQcorrscan project.

3.3.1 bright_lights

Code to determine the brightness function of seismic data according to a three-dimensional travel-time grid. This travel-time grid should be generated using the `grid2time` function of the `NonLinLoc` package by Anthony Lomax which can be found here: <http://alomax.free.fr/nlloc/> and is not distributed within this package as this is a very useful stand-alone library for seismic event location.

This code is based on the method of Frank & Shapiro 2014

Part of the EQcorrscan module to integrate seismic data into a full cross-channel correlation for detection routine. EQcorrscan is a python module designed to run match filter routines for seismicology, within it are routines for integration to seismic and obspy. With obspy integration (which is necessary) all main waveform formats can be read in and output.

This main section contains a script, `LFE_search.py` which demonstrates the usage of the built in functions from template generation from picked waveform through detection by match filter of continuous data to the generation of lag times to be used for relative locations.

The match-filter routine described here was used a previous Matlab code for the Chamberlain et al. 2014 G-cubed publication. The basis for the lag-time generation section is outlined in Hardebeck & Shelly 2011, GRL. Code generated by Calum John Chamberlain of Victoria University of Wellington, 2015.

Note

Pre-requisites:

- gcc - for the installation of the openCV correlation routine
- python-cv2 - Python bindings for the openCV routines
- python-joblib - used for parallel processing
- **python-obsPy - used for lots of common seismological processing**
 - requires:
 - * numpy
 - * scipy
 - * matplotlib
- NonLinLoc - used outside of all codes for travel-time generation

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`bright_lights._cum_net_resp` (*node_lis, instance*)

Function to compute the cumulative network response by reading the saved energy .npy files

Parameters `node_lis` (*np.ndarray*) – List of nodes (ints) to read from

Returns

`class np.ndarray cum_net_resp`, list of indeces used

`bright_lights._find_detections` (*cum_net_resp, nodes, threshold, thresh_type, samp_rate, realstations*)

Function to find detections within the cumulative network response according to Frank et al. (2014).

Parameters

- `cum_net_resp` (*np.array*) – Array of cumulative network response for nodes
- `nodes` (*list of tuples*) – Nodes associated with the source of energy in the `cum_net_resp`

Returns detections as class DETECTION

`bright_lights._node_loop` (*stations, lags, stream, i=0, mem_issue=False, instance=0*)

Internal function to allow for parallelisation of brightness

Returns (*i, energy* (*np.array*))

`bright_lights._read_tt` (*path, stations, phase, phaseout='S', ps_ratio=1.68*)

Function to read in .csv files of slowness generated from Grid2Time (part of NonLinLoc by Anthony Lomax) and convert this to a useful format here.

It should be noted that this can read either P or S travel-time grids, not both at the moment.

Parameters

- `path` (*str*) – The path to the .csv Grid2Time outputs
- `stations` (*list*) – List of station names to read slowness files for.
- `phaseout` (*str*) – What phase to return the lagtimes in
- `ps_ratio` (*float*) – p to s ratio for conversion

Returns list stations, list of lists of tuples nodes, :class: 'numpy.array' lags station[1] refers to nodes[1] and lags[1] nodes[1][1] refers to station[1] and lags[1][1] nodes[n][n] is a tuple of latitude, longitude and depth

`bright_lights._resample_grid` (*stations, nodes, lags, mindepth, maxdepth, corners, resolution*)

Function to resample the lagtime grid to a given volume. For use if the grid from Grid2Time is too large or you want to run a faster, downsampled scan.

Parameters

- `stations` (*list*) – List of station names from in the form where stations[i] refers to nodes[i][:] and lags[i][:]
- `nodes` (*list, tuple*) – List of node points where nodes[i] refers to stations[i] and nodes[:,0] is latitude in degrees, nodes[:,1] is longitude in degrees, nodes[:,2] is depth in km.
- `lags` – Array of arrays where lags[i][:] refers to stations[i]. lags[i][j] should be the delay to the nodes[i][j] for stations[i] in seconds :type mindepth: float
- `mindepth` – Upper limit of volume
- `maxdepth` (*float*) – Lower limit of volume
- `corners` (*matplotlib.Path*) – matplotlib path of the corners for the 2D polygon to cut to in lat and long

Returns list stations, list of lists of tuples nodes, :class: 'numpy.array' lags station[1] refers to nodes[1] and lags[1] nodes[1][1] refers to station[1] and lags[1][1] nodes[n][n] is a tuple of latitude, longitude and depth.

`bright_lights._rm_similarlags(stations, nodes, lags, threshold)`

Function to remove those nodes that have a very similar network moveout to another lag.

Will, for each node, calculate the difference in lagtime at each station at every node, then sum these for each node to get a cumulative difference in network moveout. This will result in an array of arrays with zeros on the diagonal.

Parameters

- **stations** (*list*) – List of station names from in the form where stations[i] refers to nodes[i][:] and lags[i][:]
- **nodes** (*list, tuple*) – List of node points where nodes[i] refers to stations[i] and nodes[:,0] is latitude in degrees, nodes[:,1] is longitude in degrees, nodes[:,2] is depth in km.
- **lags** – Array of arrays where lags[i][:] refers to stations[i]. lags[i][j] should be the delay to the nodes[i][j] for stations[i] in seconds
- **threshold** – Threshold for removal in seconds

Returns list stations, list of lists of tuples nodes, :class: 'numpy.array' lags station[1] refers to nodes[1] and lags[1] nodes[1][1] refers to station[1] and lags[1][1] nodes[n][n] is a tuple of latitude, longitude and depth.

`bright_lights.brightness(stations, nodes, lags, stream, threshold, thresh_type, coherence_thresh, instance=0)`

Function to calculate the brightness function in terms of energy for a day of data over the entire network for a given grid of nodes.

Note data in stream must be all of the same length and have the same sampling rates.

Parameters

- **stations** (*list*) – List of station names from in the form where stations[i] refers to nodes[i][:] and lags[i][:]
- **nodes** (*list, tuple*) – List of node points where nodes[i] refers to stations[i] and nodes[:,0] is latitude in degrees, nodes[:,1] is longitude in degrees, nodes[:,2] is depth in km.
- **lags** – Array of arrays where lags[i][:] refers to stations[i]. lags[i][j] should be the delay to the nodes[i][j] for stations[i] in seconds.
- **data** – Data through which to look for detections.
- **threshold** (*float*) – Threshold value for detection of template within the brightness function
- **thresh_type** (*str*) – Either MAD or abs where MAD is the Median Absolute Deviation and abs is an absolute brightness.
- **coherence_thresh** (*float*) – Threshold for removing incoherent peaks in the network response, those below this will not be used as templates.

Returns list of templates as :class: `obspy.Stream` objects

`bright_lights.coherence(stream)`

Function to determine the average network coherence of a given template or detection. You will want your stream to contain only signal as noise will reduce the coherence (assuming it is incoherent random noise).

Parameters **stream** (`obspy.Stream`) – The stream of seismic data you want to calculate the coherence for.

Returns float - coherence

3.3.2 template_gen

Function to generate template waveforms and information to go with them for the application of cross-correlation of seismic data for the detection of repeating events.

Part of the EQcorrscan module to read nordic format s-files EQcorrscan is a python module designed to run match filter routines for seismology, within it are routines for integration to seisan and obspy. With obspy integration (which is necessary) all main waveform formats can be read in and output.

This main section contains a script, LFE_search.py which demonstrates the usage of the built in functions from template generation from picked waveform through detection by match filter of continuous data to the generation of lag times to be used for relative locations.

The match-filter routine described here was used a previous Matlab code for the Chamberlain et al. 2014 G-cubed publication. The basis for the lag-time generation section is outlined in Hardebeck & Shelly 2011, GRL.

Code generated by Calum John Chamberlain of Victoria University of Wellington, 2015.

Note

Pre-requisites:

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 - requires:
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`template_gen._template_gen(picks, st, length, swin)`

Function to generate a cut template in the obspy Stream class from a given set of picks and data, also in an obspy stream class. Should be given pre-processed data (downsampled and filtered)

Parameters

- **picks** – Picks to extract data around
- **st** – Stream to extract templates from
- **length** (*float*) – Length of template in seconds
- **swin** (*string*) – P, S or all

```
template_gen.from_contbase (sfile, lowcut=None, highcut=None, samp_rate=None,  
                           filt_order=None, length=None)
```

Function to read in picks from sfile then generate the template from the picks within this and the wavefiles from the continous database of day-long files. Included is a section to sanity check that the files are daylong and that they start at the start of the day. You should ensure this is the case otherwise this may alter your data if your data are daylong but the headers are incorrectly set.

Parameters

- **sfile** (*string*) – sfilename must be the path to a seisan nordic type s-file containing waveform and pick information, all other arguments can be numbers save for swin which must be either P, S or all (case-sensitive).
- **lowcut** (*float*) – Low cut (Hz), if set to None will look in template defaults file
- **highcut** – High cut (Hz), if set to None will look in template defaults file
- **samp_rate** (*float*) – New sampling rate in Hz, if set to None will look in template defaults file
- **filt_order** (*int*) – Filter level, if set to None will look in template defaults file
- **length** (*float*) – Extract length in seconds, if None will look in template defaults file.

```
template_gen.from_sfile (sfile, lowcut=None, highcut=None, samp_rate=None,  
                        filt_order=None, length=None)
```

Function to read in picks from sfile then generate the template from the picks within this and the waveform found in the pick file.

Parameters

- **sfile** (*string*) – sfilename must be the path to a seisan nordic type s-file containing waveform and pick information.
- **lowcut** (*float*) – Low cut (Hz), if set to None will look in template defaults file
- **highcut** – High cut (Hz), if set to None will look in template defaults file
- **samp_rate** (*float*) – New sampling rate in Hz, if set to None will look in template defaults file
- **filt_order** (*int*) – Filter level, if set to None will look in template defaults file
- **length** (*float*) – Extract length in seconds, if None will look in template defaults file.

3.3.3 match_filter

Function to cross-correlate templates generated by template_gen function with data and output the detections. The main component of this script is the `normxcorr2` function from the openCV image processing package. This is a highly optimized and accurate normalized cross-correlation routine. The details of this code can be found here: - http://www.cs.ubc.ca/research/deaton/remarks_ncc.html The cpp code was first tested using the Matlab mex wrapper, and has since been ported to a python callable dynamic library.

Part of the EQcorrscan module to integrate seisan nordic files into a full cross-channel correlation for detection routine. EQcorrscan is a python module designed to run match filter routines for seismology, within it are routines for integration to seisan and obspy. With obspy integration (which is necessary) all main waveform formats can be read in and output.

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class `match_filter.DETECTION` (*template_name, detect_time, no_chans, detect_val, threshold, typeofdet, chans=None*)

Information required for a full detection based on cross-channel correlation sums.

Attributes:

type `template_name` str

param `template_name` The name of the template for which this detection was made

type `detect_time`

class 'obspy.UTCDatetime'

param `detect_time` Time of detection as an obspy UTCDatetime object

type `no_chans` int

param `no_chans` The number of channels for which the cross-channel correlation sum was calculated over.

type `chans` list of str

param `chans` List of stations for the detection

type `cccsun_val` float

param `cccsun_val` The raw value of the cross-channel correlation sum for this detection.

type `threshold` float

param `threshold` The value of the threshold used for this detection, will be the raw threshold value related to the cccsum.

type `typeofdet` str

param typeofdet Type of detection, STA, corr, bright

`match_filter._channel_loop` (*templates, stream*)

Loop to generate cross channel correlation sums for a series of templates hands off the actual correlations to a sister function which can be run in parallel.

Parameters

- **templates** – A list of templates, where each one should be an `obspy.Stream` object containing multiple traces of seismic data and the relevant header information.
- **stream** – A single `obspy.Stream` object containing daylong seismic data to be correlated through using the templates. This is in effect the image

Returns New list of :class: ‘numpy.array’ objects. These will contain the correlation sums for each template for this day of data.

Returns list of ints as number of channels used for each cross-correlation

`match_filter._template_loop` (*template, chan, station, channel, i=0*)

Sister loop to handle the correlation of a single template (of multiple channels) with a single channel of data.

Parameters *i (Int)* – Optional argument, used to keep track of which process is being run.

Returns tuple of (i,ccc) with ccc as an ndarray

`match_filter.match_filter` (*template_names, templates, stream, threshold, threshold_type, trig_int, plotvar, tempdir=False*)

Over-arching code to run the correlations of given templates with a day of seismic data and output the detections based on a given threshold.

Parameters

- **templates** (*list :class: ‘obspy.Stream’*) – A list of templates of which each template is a `Stream` of obspy traces containing seismic data and header information.
- **stream** – An `obspy.Stream` object containing all the data available and required for the correlations with templates given. For efficiency this should contain no excess traces which are not in one or more of the templates.
- **threshold** (*float*) – A threshold value set based on the `threshold_type` :type threshold_type: str
- **threshold_type** – The type of threshold to be used, can be MAD, absolute or `av_chan_corr`. MAD threshold is calculated as the `threshold*(median(abs(cccsum)))` where `cccsum` is the cross-correlation sum for a given template. absolute threshold is a true absolute threshold based on the `cccsum` value `av_chan_corr` is based on the mean values of single-channel cross-correlations assuming all data are present as required for the template, e.g. `av_chan_corr_thresh=threshold*(cccsum/len(template))` where template is a single template from the input and the length is the number of channels within this template.
- **tempdir** (*String or False*) – Directory to put temporary files, or False

Returns

class ‘DETECTIONS’ detections for each channel formatted as :class: ‘obspy.UTCDateTime’ objects.

`match_filter.normxcorr2` (*template, image*)

Base function to call the c++ correlation routine from the openCV image processing suite. Requires you to have installed the openCV python bindings, which can be downloaded on Linux machines using:

- `sudo apt-get install python-openCV`

Here we use the `cv2.TM_CCOEFF_NORMED` method within openCV to give the normalized cross-correlation. Documentation on this function can be found [here](#):

- http://docs.opencv.org/modules/imgproc/doc/object_detection.html?highlight=matchtemplate#cv2.matchTemplate

Parameters **image** – Requires two numpy arrays, the template and the image to scan the template through. The order of these matters, if you put the template after the image you will get a reversed correlation matrix

Returns New :class: 'numpy.array' object of the correlation values for the correlation of the image with the template.

`match_filter.run_channel_loop(templates, stream, tempdir)`

Python helper function to run the Cythonised channel_loop function

Parameters

- **templates** (*List of :class: obspy.Stream*) – List of all the templates
- **stream** – The image stream to scan through
- **tempdir** (*String or False*) – location to put temporary files

Returns cccsums (np.ndarray), no_chans (np.ndarray)

3.3.4 lag_calc

Functions to generate lag-times for events detected by correlation.

Part of the EQcorrscan module to integrate seisán nordic files into a full cross-channel correlation for detection routine. EQcorrscan is a python module designed to run match filter routines for seismology, within it are routines for integration to seisán and obspy. With obspy integration (which is necessary) all main waveform formats can be read in and output.

This main section contains a script, LFE_search.py which demonstrates the usage of the built in functions from template generation from picked waveforms through detection by match filter of continuous data to the generation of lag times to be used for relative locations.

The match-filter routine described here was used a previous Matlab code for the Chamberlain et al. 2014 G-cubed publication. The basis for the lag-time generation section is outlined in Hardebeck & Shelly 2011, GRL.

Code generated by Calum John Chamberlain of Victoria University of Wellington, 2015.

Note

Pre-requisites:

- gcc - for the installation of the openCV correlation routine
- python-cv2 - Python bindings for the openCV routines
- python-joblib - used for parallel processing
- **python-obspy - used for lots of common seismological processing**
 - **requires:**
 - * numpy
 - * scipy
 - * matplotlib
- NonLinLoc - used outside of all codes for travel-time generation

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`lag_calc._channel_loop` (*detection, template, i=0*)

Utility function to take a stream of data for the detected event and parse the correct data to lag_gen

Parameters *i* (*int, optional*) – Used to track which process has occurred when running in parallel

Returns lagtimes, a tuple of (lag in s, cross-correlation value, station, chan)

`lag_calc.day_loop` (*detections, template*)

Function to loop through multiple detections for one template - ostensibly designed to run for the same day of data for I/O simplicity, but as you are passing stream objects it could run for all the detections ever, as long as you have the RAM!

Parameters

- **detections** (*List of obspy.Stream*) – List of all the detections for this template that you want to compute the optimum pick for.
- **template** (*obspy.Stream*) – The original template used to detect the detections passed

Returns lags - List of List of tuple: lags[i] corresponds to detection[i], lags[i][j] corresponds to a channel of detection[i], within this tuple is the lag (in seconds), normalised correlation, station and channel.

`lag_calc.lag_calc` (*detections, detect_data, templates, shift_len=0.2, min_cc=0.4*)

Overseer function to take a list of detection objects, cut the data for them to lengths of the same length of the template + shift_len on either side. This will then write out SEISAN s-file for the detections with pick times based on the lag-times found at the maximum correlation, providing that correlation is above the min_cc.

Parameters

- **detections** (*List of DETECTION*) – List of DETECTION objects
- **detect_data** (*obspy.Stream*) – All the data needed to cut from - can be a gappy Stream
- **templates** (*List of tuple of String, obspy.Stream*) – List of the templates used as tuples of template name, template
- **shift_len** (*float*) – Shift length allowed for the pick in seconds, will be plus/minus this amount - default=0.2
- **min_cc** (*float*) – Minimum cross-correlation value to be considered a pick, default=0.4

3.4 Utils

Codes to run basic utility functions for integration with seisan and to find peaks in noisy data.

3.4.1 Sfile_util

Part of the EQcorrscan module to read nordic format s-files and write them EQcorrscan is a python module designed to run match filter routines for seismology, within it are routines for integration to seisan and obspy. With obspy integration (which is necessary) all main waveform formats can be read in and output.

Code generated by Calum John Chamberlain of Victoria University of Wellington, 2015.

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class Sfile_util.**PICK** (*station, channel, impulsivity, phase, weight, polarity, time, coda, amplitude, peri, azimuth, velocity, AIN, SNR, azimuthres, timeres, finalweight, distance, CAZ*)
Pick information for seisan implimentation

Sfile_util.**blanksfile** (*wavefile, evtype, userID, outdir, overwrite=False, evtime=False*)
Module to generate an empty s-file with a populated header for a given waveform.

Parameters

- **wavefile** (*String*) – Wavefile to associate with this S-file, the timing of the S-file will be taken from this file if evtime is not set
- **evtype** (*String*) – L,R,D
- **userID** (*String*) – 4-charectar SEISAN USER ID
- **outdir** (*String*) – Location to write S-file
- **overwrite** (*Bool*) – Overwrite an existing S-file, default=False
- **evtime** (*UTCDateTime*) – If given this will set the timing of the S-file

Returns String, S-file name

Sfile_util.**populateSfile** (*sfilename, picks*)

Module to populate a blank nordic format S-file with pick information, arguments required are the filename of the blank s-file and the picks where picks is a dictionary of picks including station, channel, impulsivity, phase, weight, polarity, time, coda, amplitude, peri, azimuth, velocity, SNR, azimuth residual, Time-residual, final weight, epicentral distance & azimuth from event to station.

This is a full pick line information from the seisan manual, P. 341

Sfile_util.**readpicks** (*sfilename*)

Function to read pick informaiton from the s-file

Returns Sfile_tile.PICK

Sfile_util.**readwavename** (*sfilename*)

Convenience function to extract the waveform filename from the s-file, returns a list of waveform names found in the s-file as multiples can be present.

3.4.2 findpeaks

Function to find peaks in data above a certain threshold as part of the EQcorr package written by Calum Chamberlain of Victoria University of Wellington in early 2015.

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`findpeaks.find_peaks(arr, thresh, trig_int)`

Function to determine peaks in an array of data above a certain threshold.

EXPERIMENTAL CODE, DOES NOT WORK EFFICIENTLY, RECOMEND USING `find_peaks2`

Parameters

- **arr** (*ndarray*) – 1-D numpy array is required
- **thresh** (*float*) – The threshold below which will be considered noise and peaks will not be found in.
- **trig_int** (*int*) – The minimum difference in samples between triggers, if multiple peaks within this window this code will find the highest.

Returns peaks, locs: Lists of peak values and locations.

`findpeaks.find_peaks2(arr, thresh, trig_int, debug=0, starttime=UTCDateTime(1970, 1, 1, 0, 0), samp_rate=1.0)`

Function to determine peaks in an array of data above a certain threshold. Improvement on `find_peaks`, speed-up of approx 250x.

Parameters

- **arr** (*ndarray*) – 1-D numpy array is required
- **thresh** (*float*) – The threshold below which will be considered noise and peaks will not be found in.
- **trig_int** (*int*) – The minimum difference in samples between triggers, if multiple peaks within this window this code will find the highest.
- **debug** (*int*) – Optional, debug level 0-5

Returns peaks, locs: Lists of peak values and locations.

3.4.3 clustering

Code to compute the linkage between seismograms and cluster them accordingly

Written by Calum Chamberlain, in alpha stages of development as of 24/06/2015

Implimented to streamline templates after template detection in beamforming methods, employed by implimentation of Frank et al. code.

As such this code is designed to work only for templates with the same channels

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`clustering.SVD_2_stream_testing` (*SVectors*, *stachans*, *k*, *sampling_rate*)

Function to convert the singular vectors output by SVD to streams, one for each singular vector level, for all channels.

Parameters

- **SVectors** (*ndarray*) – Singular vectors
- **stachans** (*List of Strings*) – List of station.channel Strings
- **k** (*Int*) – Number of streams to return = number of SV's to include

Sampling_rate *Float*

Returns SVstreams, List of Obspy.Stream, with SVStreams[0] being composed of the highest rank singular vectors.

Note

IN ALPHA, not working as expected

`clustering.SVD_testing` (*templates*)

Function to compute the SVD of a number of templates and return the singular vectors and singular values of the templates.

Parameters **templates** (*List of Obspy.Stream*) – List of the templates to be analysed

Returns SVector(*ndarray*), SValues(*ndarray*) for each channel, stachans, List of String (station.channel)

Note

IN ALPHA, not working as expected

It is recommended that you align the data before computing the SVD, .e.g., the P-arrival on all templates for the same channel should appear at the same time in the trace.

`clustering.align_traces` (*traces*)

Function to align all traces in a stream based on their cross-correlations

Parameters **traces** (*List of :class: obspy.Trace*) – List of of single channels unaligned - should contain data from multiple earthquakes for a single site, channel and phase I will compute the linear stack of all traces and align the traces relative to this.

Returns List of ndarray

`clustering.cluster` (*templates*, *show=True*)

Function to take a set of templates and cluster them, will return distance matrix of grouped templates

Returns List of cluster groups, array of length len(templates), with each number relating to a cluster

`clustering.cross_chan_coherence` (*st1*, *st2*)

Function to determine the cross-channel coherency between two streams of multichannel seismic data.

Returns cross channel coherence, float - normalized by number of channels

`clustering.distance_matrix` (*templates*)

Function to compute the distance matrix for all templates - will give distance as 1-abs(cccoh), e.g. a well correlated pair of templates will have small distances, and an equally well correlated reverse image will have the same distance as apositively correlated image - this is an issue

Returns ndarray - distance matrix

`clustering.extract_detections` (*detections*, *templates*, *extract_len=90.0*, *outdir=None*, *extract_Z=True*, *additional_stations=[]*)

Function to extract the waveforms associated with each detection in a list of detections for the template, template. Waveforms will be returned as a list of `obspy.Streams` containing segments of `extract_len`. They will also be saved if `outdir` is set. The default is unset. The default `extract_len` is 90 seconds per channel.

Parameters

- **detections** (*List tuple of of :class: datetime.datetime, string*) – List of datetime objects, and their associated template name
- **templates** (*List of tuple of string and :class: obspy.Stream*) – A list of the tuples of the template name and the template Stream used to detect detections.
- **extract_len** (*float*) – Length to extract around the detection (will be equally cut around the detection time) in seconds. Default is 90.0.
- **outdir** (*Bool or String*) – Default is None, with None set, no files will be saved, if set each detection will be saved into this directory with files named according to the detection time, NOT than the waveform start time. Detections will be saved into template subdirectories.
- **extract_Z** (*Bool*) – Set to True to also extract Z channels for detections delays will be the same as horizontal channels, only applies if only horizontal channels were used in the template.
- **additional_stations** (*List of tuple*) – List of stations, chanel and networks to also extract data for using an average delay.

Returns List of :class: obspy.Stream

`clustering.group_delays` (*templates*)

Function to group template waveforms according to their delays

Parameters **templates** (*List of obspy.Stream*) – List of the waveforms you want to group

Returns List of List of obspy.Streams where each initial list is a group with the same delays

3.4.4 pre_processing

Utilities module for the EQcorrscan package written by Calum Chamberlain of Victoria University Wlelington. These functions are designed to do the basic processing of the data using `obspy` modules (which also rely on `scipy` and `numpy`).

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`pre_processing._check_daylong` (*tr*)

Function to check the data quality of the daylong file - check to see that the day isn't just zeros, with large steps, if it is then the resampling will hate it.

Return qual bool

`pre_processing.dayproc` (*tr, lowcut, highcut, filt_order, samp_rate, debug, starttime*)

Basic function to bandpass, downsample and check headers and length of trace to ensure files start at the start of a day and are daylong. Works in place on data. This is employed to ensure all parts of the data are processed in the same way.

Returns obspy.Stream

`pre_processing.shortproc` (*st, lowcut, highcut, filt_order, samp_rate, debug=0*)

Basic function to bandpass, downsample. Works in place on data. This is employed to ensure all parts of the data are processed in the same way.

Returns obspy.Stream

3.4.5 EQcorrscan_plotting

Utility code for most of the plots used as part of the EQcorrscan package.

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`EQcorrscan_plotting.Noise_plotting` (*station, channel, PAZ, datasource*)

Function to make use of obspy's PPSD functionality to read in data from a single station and the poles-and-zeros for that station before plotting the PPSD for this station. See McNamara(2004) for more details.

Parameters

- **station** (*String*) – Station name as it is in the filenames in the database
- **channel** (*String*) – Channel name as it is in the filenames in the database
- **PAZ** (*Dict*) – Must contain, Poles, Zeros, Sensitivity, Gain :type Poles: List of Complex :type Zeros: List of Complex :type Sensitivity: Float :type Gain: Float
- **datasource** (*String*) – The directory in which data can be found, can contain wild-cards.

Returns PPSD object

`EQcorrscan_plotting.cumulative_detections` (*dates, template_names, save=False, save_file=''*)

Simple plotting function to take a list of datetime objects and plot a cumulative detections list. Can take dates as a list of lists and will plot each list separately, e.g. if you have dates from more than one template it will overlay them in different colours.

Parameters

- **dates** (*list of lists of datetime.datetime*) – Must be a list of lists of datetime.datetime objects
- **template_names** (*list of strings*) – List of the template names in order of the dates

`EQcorrscan_plotting.detection_multiplot` (*stream, template, times, streamcolour='k', templatecolour='r'*)

Function to plot the stream of data that has been detected in, with the template on top of it timed according to a list of given times, just a pretty way to show a detection!

Parameters

- **stream** (*obspy.Stream*) – Stream of data to be plotted as the base (black)
- **template** (*obspy.Stream*) – Template to be plotted on top of the base stream (red)
- **times** (*List of datetime.datetime*) – list of times of detections in the order of the channels in template.

`EQcorrscan_plotting.detection_timeseries` (*stream, detector, detections*)

Function to plot the data and detector with detections labelled in red, will downsample if too many data points.

Parameters **detections** (*np.array*) – array of positions of detections in samples

`EQcorrscan_plotting.peaks_plot` (*data, starttime, samp_rate, save=False, peaks=[(0, 0)], savefile=''*)

Simple utility code to plot the correlation peaks to check that the peak finding routine is running correctly, used in debugging for the EQcorrscan module.

`EQcorrscan_plotting.pretty_template_plot` (*template, size=(18.5, 10.5), save=False, title=False*)

Function to make a pretty plot of a single template, designed to work better than the default obspy plotting routine for short data lengths.

`EQcorrscan_plotting.threeD_gridplot` (*nodes, save=False, savefile=''*)

Function to plot in 3D a series of grid points.

Parameters **nodes** (*List of tuples*) – List of tuples of the form (lat, long, depth)

`EQcorrscan_plotting.threeD_seismpoint` (*stations, nodes*)

Function to plot seismicity and stations in a 3D, movable, zoomable space using matplotlib's Axes3D package.

Parameters

- **stations** (*list of tuple*) – list of one tuple per station of (lat, long, elevation), with up positive
- **nodes** (*list of tuple*) – list of one tuple per event of (lat, long, depth) with down positive

`EQcorrscan_plotting.triple_plot` (*cccsun, trace, threshold, save=False, savefile=''*)

Main function to make a triple plot with a day-long seismogram, day-long correlation sum trace and histogram of the correlation sum to show normality

3.4.6 mag_calc

Functions to simulate Wood Anderson traces, pick maximum peak-to-peak amplitudes write these amplitudes and periods to SEISAN s-files and to calculate magnitudes from this and the information within SEISAN s-files.

Written as part of the EQcorrscan package by Calum Chamberlain - first written to implement magnitudes for the 2015 Wanaka aftershock sequence, written up by Warren-Smith [2014/15].

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```
mag_calc.Amp_pick_sfile(sfile, datapath, respdir, chans=['Z'], var_wintype=True, winlen=0.9,
                        pre_pick=0.2, pre_filt=True, lowcut=1.0, highcut=20.0, corners=4)
```

Function to read information from a SEISAN s-file, load the data and the picks, cut the data for the channels given around the S-window, simulate a Wood Anderson seismometer, then pick the maximum peak-to-trough amplitude.

Output will be put into a mag_calc.out file which will be in full S-file format and can be copied to a REA database.

Parameters

- **datapath** (*String*) – Path to the waveform files - usually the path to the WAV directory
- **respdir** (*String*) – Path to the response information directory
- **chans** (*List of strings*) – List of the channels to pick on, defaults to ['Z'] - should just be the orientations, e.g. Z,1,2,N,E
- **var_wintype** (*Bool*) – If True, the winlen will be multiplied by the P-S time if both P and S picks are available, otherwise it will be multiplied by the hypocentral distance*0.34 - derived using a p-s ratio of 1.68 and S-velocity of 1.5km/s to give a large window, defaults to True
- **winlen** (*Float*) – Length of window, see above parameter, if var_wintype is False Then this will be in seconds, otherwise it is the multiplier to the p-s time, defaults to 0.5
- **pre_pick** (*Float*) – Time before the s-pick to start the cut window, defaults to 1.0
- **pre_filt** (*Bool*) – To apply a pre-filter or not, defaults to True
- **lowcut** (*Float*) – Lowcut in Hz for the pre-filter, defaults to 1.0
- **highcut** (*Float*) – Highcut in Hz for the pre-filter, defaults to 20.0
- **corners** (*Int*) – Number of corners to use in the pre-filter

```
mag_calc._GSE2_PAZ_read(GSEfile)
```

Function to read the instrument response information from a GSE Poles and Zeros file as generated by the SEISAN program RESP.

Format must be CAL2, not coded for any other format at the moment, contact the author to add others in.

Returns Dict of poles, zeros, gain and sensitivity

```
mag_calc._find_resp(station, channel, network, time, delta, directory)
```

Helper function to find the response information for a given station and channel at a given time and return a dictionary of poles and zeros, gain and sensitivity.

Parameters

- **station** (*String*) – Station name (as in the response files)
- **channel** (*String*) – Channel name (as in the response files)
- **network** (*String*) – Network to scan for, can be a wildcard
- **time** (*datetime.datetime*) – Date-time to look for response information
- **delta** (*float*) – Sample interval in seconds
- **direcotry** – Directory to scan for response information

Returns Dictionary

`mag_calc._max_p2t` (*data*, *delta*)

Function to find the maximum peak to trough amplitude and period of this amplitude. Originally designed to be used to calculate magnitudes (by taking half of the peak-to-trough amplitude as the peak amplitude).

Parameters

- **data** (*ndarray*) – waveform trace to find the peak-to-trough in.
- **delta** (*float*) – Sampling interval in seconds

Returns tuple of (amplitude, period, time) with amplitude in the same scale as given in the input data, and period in seconds, and time in seconds from the start of the data window.

`mag_calc._sim_WA` (*trace*, *PAZ*, *seedresp*, *water_level*)

Function to remove the instrurment response from a trace and return a de-measured, de-trended, Wood Anderson simulated trace in it's place.

Works in-place on data and will destroy your original data, copy the trace before giving it to this function!

Parameters

- **trace** (*obspy.Trace*) – A standard obspy trace, generally should be given without pre-filtering, if given with pre-filtering for use with amplitude determination for magnitudes you will need to worry about how you cope with the response of this filter yourself.
- **PAZ** (*dict*) – Dictionary containing lists of poles and zeros, the gain and the sensitivity.
- **water_level** (*int*) – Water level for the simulation.

Returns *obspy.Trace*

`mag_calc.dist_calc` (*loc1*, *loc2*)

Function to calculate the distance in km between two points, uses the flat Earth approximation

Parameters **loc1** (*Tuple*) – Tuple of lat, lon, depth (in decimal degrees and km)

3.4.7 stacking

Utility module of the EQcorrscan package to allow for different methods of stacking of seismic signal in one place.

In alpha stages and only with linear stacking implimented thusfar

Calum Chamberlain 24/06/2015

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`stacking.PWS_stack` (*streams*, *weight=2*)

Function to compute the phase weighted stack of a series of streams

Parameters **weight** (*float*) – Exponent to the phase stack used for weighting.

Returns *obspy.Stream*

`stacking.linstack` (*streams*)

Function to compute the linear stack of a series of seismic streams of multiplexed data

Returns stack - Stream

3.4.8 catalogue2DD

Module written by Calum Chamberlain as part of the EQcorrscan package.

This module contains functions to convert a seisan catalogue to files ready for relocation in hypoDD - it will generate both a catalogue (dt.ct) file, event file (event.dat), station information file (station.dat), and a correlation output file correlated every event in the catalogue with every other event to optimize the picks (dt.cc).

The correlation routine relies on obspy's `xcorrPickCorrection` function from the `obspy.signal.cross_correlation` module. This function optimizes picks to better than sample accuracy by interpolating the correlation function and finding the maximum of this rather than the true maximum correlation value. The output from this function is stored in the dt.cc file.

Information for the station.dat file is read from SEISAN's STATION0.HYP file

Earthquake picks and locations are taken from the catalogued s-files - these must be pre-located before entering this routine as origin times and hypocentre locations are needed for event.dat files.

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`catalogue2DD._av_weight (W1, W2)`

Function to convert from two seisan weights (0-4) to one hypoDD weight(0-1)

Returns str

`catalogue2DD._cc_round (num, dp)`

Convenience function to take a float and round it to dp padding with zeros to return a string

Returns string

`catalogue2DD._separation (loc1, loc2)`

Function to calculate the distance between two points in the earth

Parameters

- **loc1** (*tuple (float, float, float)*) – First point location as lat, long, depth in deg, deg, km
- **loc2** (*tuple (float, float, float)*) – First point location as lat, long, depth in deg, deg, km

Returns distance in km (float)

`catalogue2DD.readSTATION0 (path, stations)`

Function to read the STATION0.HYP file on the path given. Outputs written in station.dat file.

Parameters

- **path** (*String*) – Path to the STATION0.HYP file
- **station** (*List*) – Stations to look for

Returns List of tuples of station, lat, long, elevation

`catalogue2DD.write_catalogue(event_list, max_sep=1, min_link=8)`

Function to write the dt.ct file needed by hypoDD - takes input event list from `write_event` as a list of tuples of event id and sfile. It will read the pick information from the seisan formatted s-file using the `Sfile_util` utilities.

Parameters

- **event_list** (*List of tuple*) – List of tuples of event_id (int) and sfile (String)
- **max_sep** (*float*) – Maximum separation between event pairs in km
- **min_link** (*int*) – Minimum links for an event to be paired

Returns List stations

`catalogue2DD.write_correlations(event_list, wavbase, extract_len, pre_pick, shift_len, lowcut=1.0, highcut=10.0, max_sep=4, min_link=8)`

Function to write a dt.cc file for hypoDD input - takes an input list of events and computes pick refinements by correlation

Parameters

- **event_list** (*List of tuple*) – List of tuples of event_id (int) and sfile (String)
- **wavbase** (*string*) – Path to the seisan wave directory that the wavefiles in the S-files are stored
- **extract_len** (*float*) – Length in seconds to extract around the pick
- **pre_pick** (*float*) – Time before the pick to start the correlation window
- **shift_len** (*float*) – Time to allow pick to vary
- **lowcut** (*float*) – Lowcut in Hz - default=1.0
- **highcut** (*float*) – Highcut in Hz - default=10.0
- **max_sep** (*float*) – Maximum separation between event pairs in km
- **min_link** (*int*) – Minimum links for an event to be paired

`catalogue2DD.write_event(sfile_list)`

Function to write out an event.dat file of the events

Parameters **sfile_list** (*List*) – List of s-files to sort and put into the database

Returns List of tuples of event ID (int) and Sfile name

3.5 Par

User-editable codes to input parameters for *core* files. Scripts are coded in the files with a full description of the parameters. Outline definitions for match filter python code

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Outline definitions for template generation

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