# User Guide

## Content

## 1. Requirements

SplitRacer currently works on Linux and Windows (64-bit). Please download the appropriate file for your operational system.

MATLAB 2015b-2016b is needed. If you have the Parallel Processing Toolbox, the program will work considerably faster.

## 2. License



## 3. Installation

To install SplitRacer, simply unzip the package and copy it into your MATLAB folder. Start the program by executing start_SplitRacer.m. All functions are stored in separate folders depending on where they are used. Folders are **main**, **defaults**, **download**, **pre-processing**, and **splitting**.

# 4. Introduction

SplitRacer is a program for teleseismic shear-wave splitting analysis. This user guide is a manual to the program itself. If you are unfamiliar with shear-wave splitting, please see the accompanying paper for further information. Below is a work flow of the program.

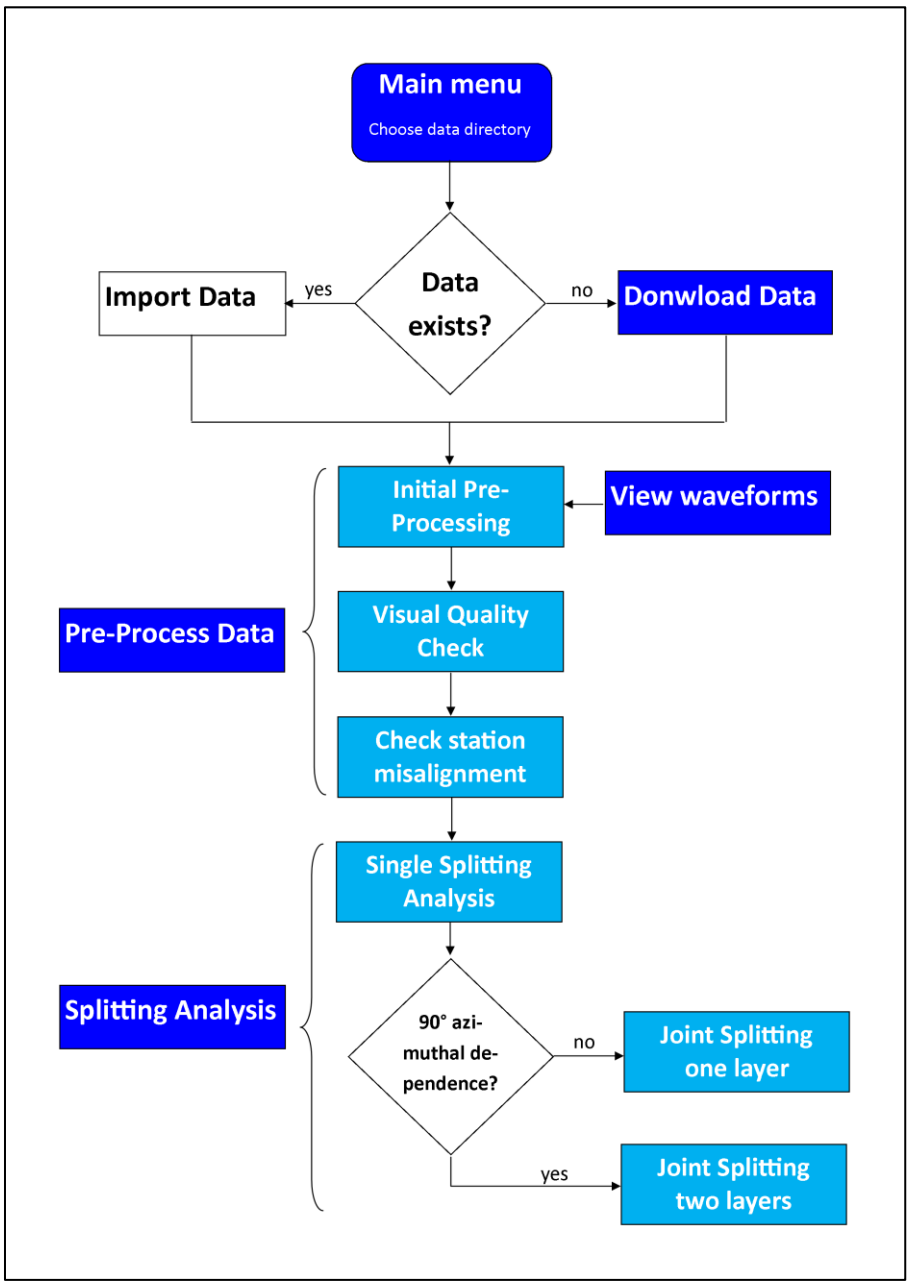



Figure 1 Work Flow

The following chapters will walk you through every processing step and available options.

SplitRacer works with data libraries, which are built as the program runs through the different processing steps. Below is a summary of which folders are created and their content. As a user, you do not need to access any of the folders. Through out all processing stages, different statistic, results and waveforms can be exported. All files can be found in the folder graphics_output. Please see Chapter 9 for an overview and description.

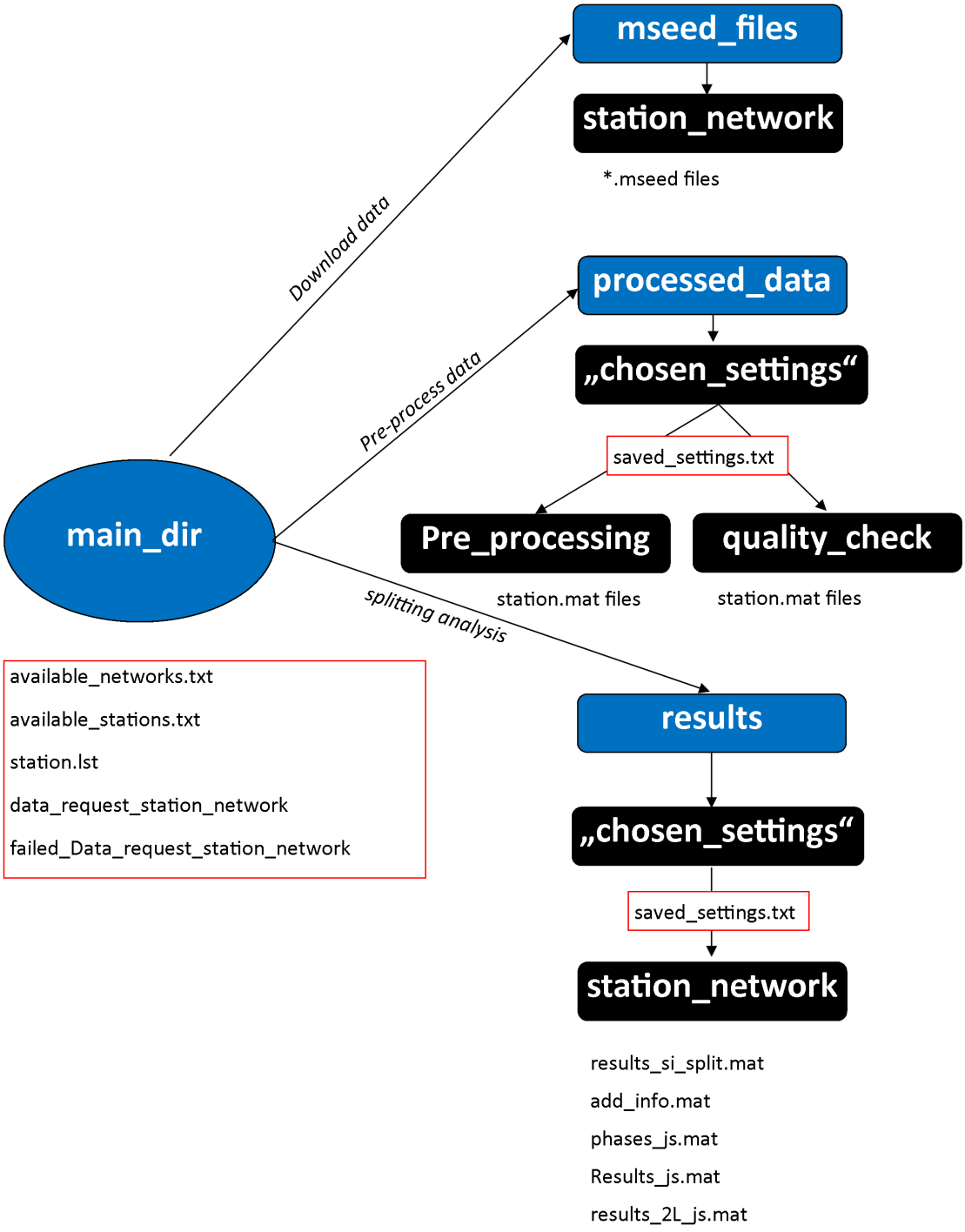



Figure 2 Libary Structure

# 5. Main Menu

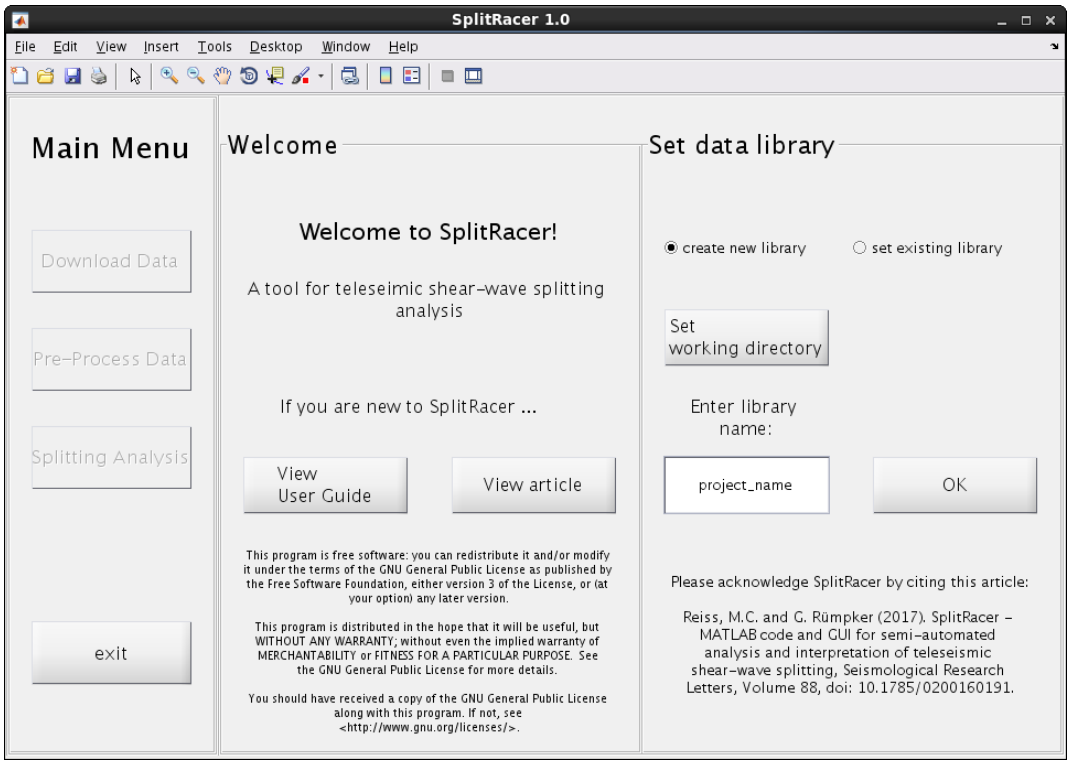



Figure 3 Main Menu

Once you executed the start_SplitRacer.m script, you must first decide whether you already have data which you wish to analyze or down load new data.

If you wish to start a new project, simply set a working directory and enter a name. Click 'OK' to continue.

If you wish to use existing data, please note that you need the following:

- A folder called ~/{projectname}/
- In this folder:
  - a **data request file** per station including all necessary information of the .mseed files regarding the event it should be attributed. These files should be named 'data_request_station_networkcode' e.g. *data_request_AIGLE_CH* for the station AIGLE of the Swiss permanent network CH
    The format of the text file must be

| YYYY | MM | DD | HH | MM | SS.SS | lat | lon | dist | baz | depth | m | files |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2012 | 01 | 01 | 05 | 27 | 55.98 | 31.46 | 138.1 | 90.85 | 40.1 | 365.3 | 6.8 | /mseed_files/AIGLE_CH/ file1.mseed |

in single columns

- A file called station.lst which lists the used stations
  The format of the text file must be:

| Station | networkcode | latitude | lon |
|---|---|---|---|
| AIGLE | CH | 46.341610 | 6.953360 |

- *.mseed files must be stored
  ~/{projectname}/mseed_files/station_networkcode/*.mseed
- Only those events in the data request file are used
- SplitRacer depends on a set structure of folders, if you do not set up your data as described above, the program will not find the data
- *.mseed files must consist of 3 components and one hour starting with event origin time, either as BH or HH channels

## 6. Download Data

If you want to download new data, simply click ‘Download Data’ in the main menu.

There two sections, ‘Station Parameters’ and ‘Event Parameters’. This GUI works with FDSNWS and data is downloaded and directly stored without any additional programs.

Station Parameters:

- Data center: choose appropriate data center
- Network code of seismic stations: choose available network code
- Channel name: Choose appropriate channel name
- Stations: choose available seismic station or *all*

These parameters must be set to download data.

Available data centers are stored in the file ‘data_centers.dat’ located in program’s folder **defaults**. If you want to change/add data centers, go to this file and add the necessary information. However, you have to make sure that the data center supports FDSNWS and the data is readily available.

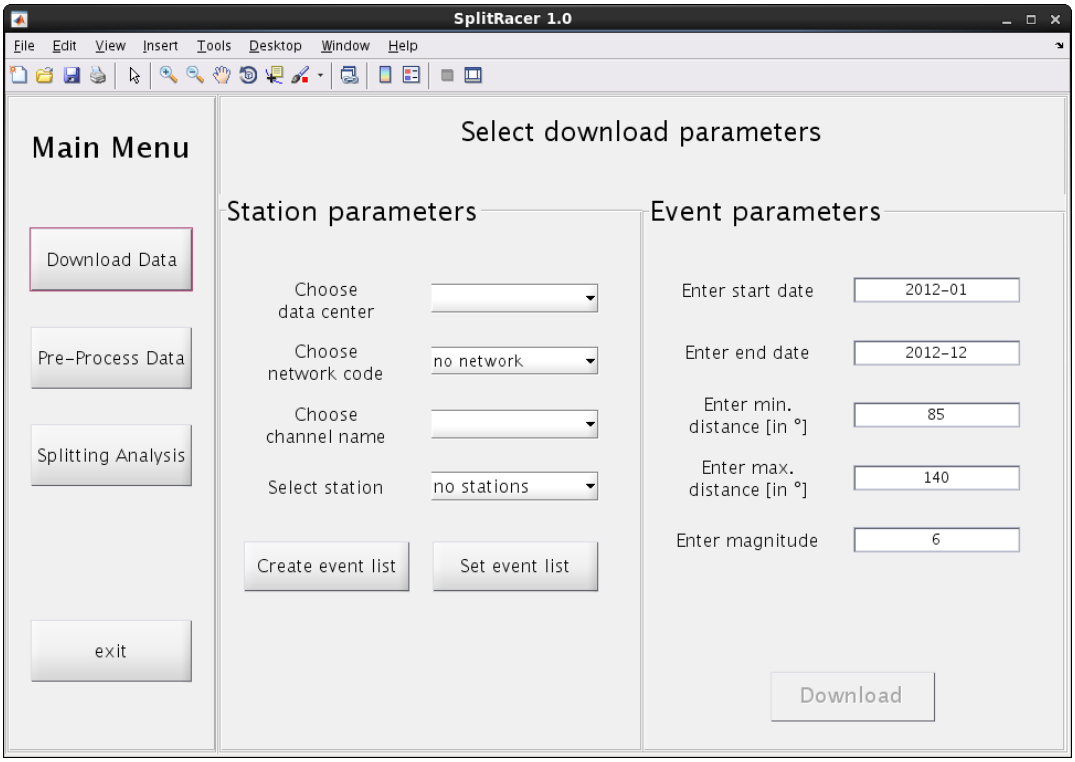



Figure 4 Download Data Menu

Once you choose a data center, a FDSNWS request is sent and the available networks retrieved. This information is stored in your selected working directory (~/{projectname}/available_networks.txt). For the analysis, we rely on HH and BH channels. Again, a FDSNWS request is sent and available stations retrieved. Also, this information is stored in your selected working directory (~/{projectname}/available_stations.txt).

Once you have set the stations parameters, you can set the event parameters.

Event parameters:

- event list: this list is located in the program's folder **defaults** and is a text file. Its format is

| Date \| | Lat \| | Lon \| | Depth \| | m |
|---|---|---|---|---|
| 2010-01-02T08:45:33.020Z | 12.424 | 141.949 | 8 | 6.1 mwb |

  Please note the header line, in which single headers are divided by |. A default list is provided, starting 01.01.1990 until 10.12.2016. The default event list includes all earthquakes above magnitude 6 in the specified time range. If you wish to change this list, please click on 'Create event list', which redirects to the earthquake archive of the USGS. You do not need to specify distance ranges when downloading an event list from USGS, the program automatically checks which events lie within the specified parameter range. Please download the list as CSV file and prepare it to match the default event list. Please store it in the same folder .

- Start date: choose desired start date
- End date: choose desired end date
- Minimum distance: set an appropriate distance. Please consider that for teleseismic shear-wave splitting, a minimum distance of 85° is necessary.
- Maximum distance: set an appropriate distance. Please consider that for teleseismic shear-wave splitting, a maximum distance of 180° is necessary.
- Magnitude: Please set an appropriate minimum magnitude and note that the default event list only lists events above magnitude 6.

**When setting these parameters, please make sure your specified event parameters are in agreement with the used event list!**

Once all parameters have been set, click the 'Download' button. Downloading data may take a while!

## 7. Pre-Processing Data

Once you have down loaded data or given the appropriate input format for existing data, pre-processing is necessary. Simply click on the 'Pre-Process Data' button.

SplitRacer aims to automatize those processing steps which can be objectively quantified. This is why there are a number of things to consider before shear-wave splitting analysis is used.

- Events need to be imported and checked for completeness
- To avoid lengthy computing time, minimizing the amount of data samples is necessary
- Not all events can be used for the analysis, as they might be contaminated with noise or other phases
- Filters can be applied to enhance the signal

These processing steps can be divided into those running in the background and do not require your input, others depend heavily on the data set itself.

For the analysis, you need to specify a filter range and SNR cut-off. The latter is used to discard phases from events below the threshold and significantly reduces the data set. As shear-wave splitting measurements might also depend on the frequency, the appropriate filter for the analysis is also important. Before the analysis, it is best to check your data in advance.

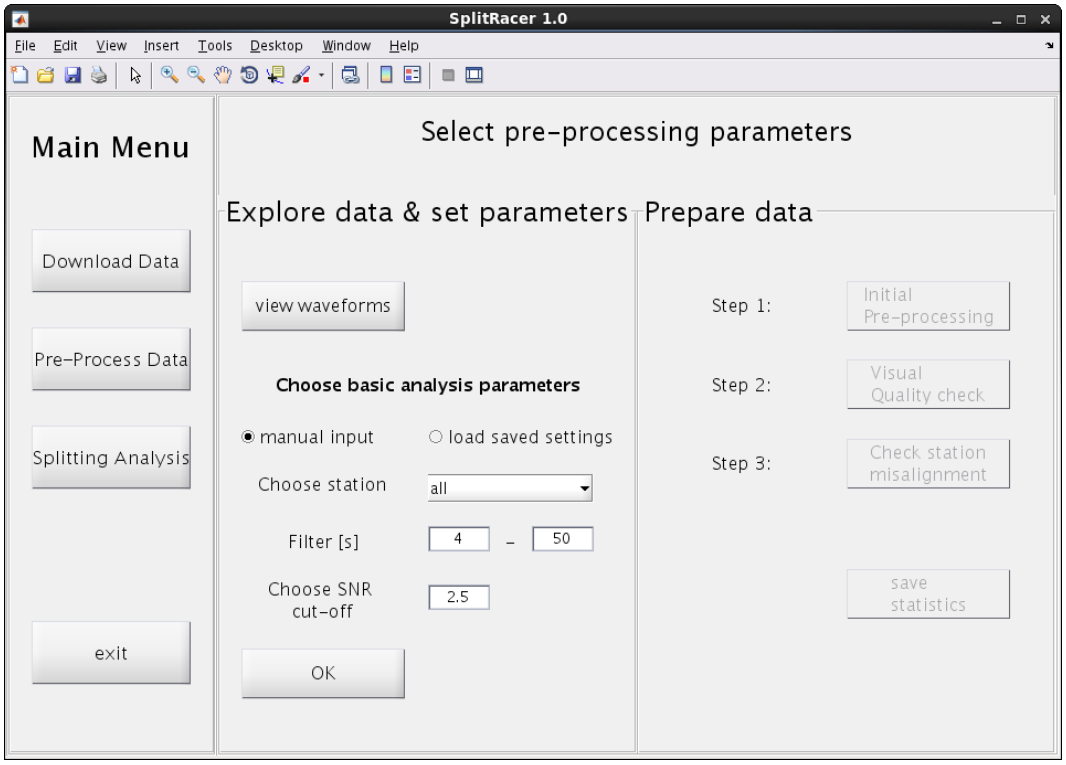



Figure 5 Pre-Process Data Menu

To view seismograms before analyzing, click on the 'view waveforms' button. A new window opens with a menu.

Parameters:

- Station: choose desired station
- Event: choose any event

Once an event is selected, the corresponding *.mseed file is read, an anti-aliasing filter (low pass 1 s) and a re-sampling with 20 Hz is applied.

The first plot ('Entire trace') shows the ZNE components of the entire trace of the chosen event, unfiltered. To the right, the second plot window shows the spectrogram of each trace, also unfiltered. This should be used as a guide to filtering processes.

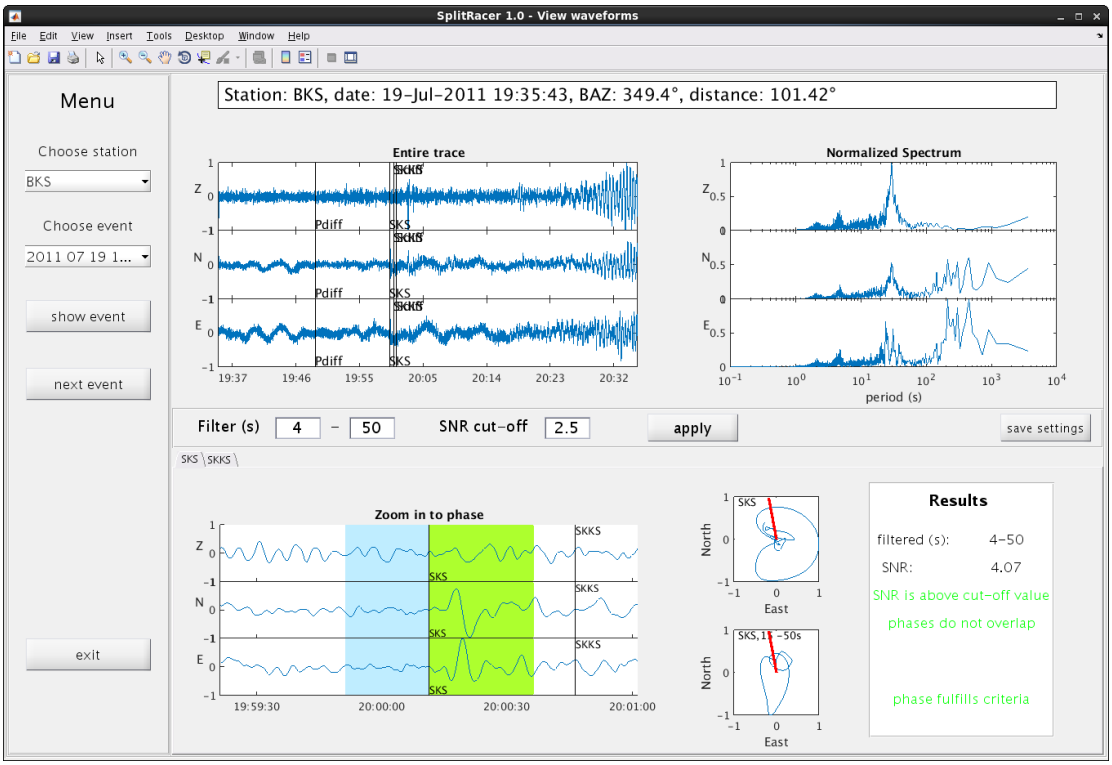



Figure 6 View Waveforms GUI

To the bottom, a zoom into all phases which could possibly be used for teleseismic shear-wave splitting analysis is shown. Each phase is plotted in its own tab, showing 100 s cut out around the phase to the left, as well as the particle motion of the signal time window (highlighted in green) and its long period particle motion. To the right, an information window is shown, consisting of the filter range used, as well as calculated SNR. The noise window used for the analysis is highlighted in blue in the 'Zoom in to phases' plot.

The top and bottom plots are divided by a small GUI. Its parameters are:

- Filter range: a standard filter of 4-50 s has proven to be practical
- SNR cut-off: this depends on the quality of the data

Using the 'apply' button, the specified parameters are applied to the single phases. You can try out different values and see how it affects your data. Here, the SNR cut-off value is not used to discard data but simply compare it to the calculated SNR of the phase: The results are always shown in the tabs for single phases. After applying a filter and SNR cut-off, the information window displays whether the calculated SNR fulfills the specified cut-off range and if a phases is preceded by another phase by less than ten seconds. In the following pre-processing steps, these phases will be discarded.

To find out which parameters should be used for the entire pre-processing, it is best to search for an event with a clear phase. Once you are satisfied with the specified parameters, you can click the 'save settings' button to save the set parameters for further analysis. These settings are stored in

~/{projectname}/processed_data/Filter_{filter values}_SNR_{snr value}/saved_settings.txt.

Each time you specify new settings, a new folder is generated and a file specifying the settings is stored as well.

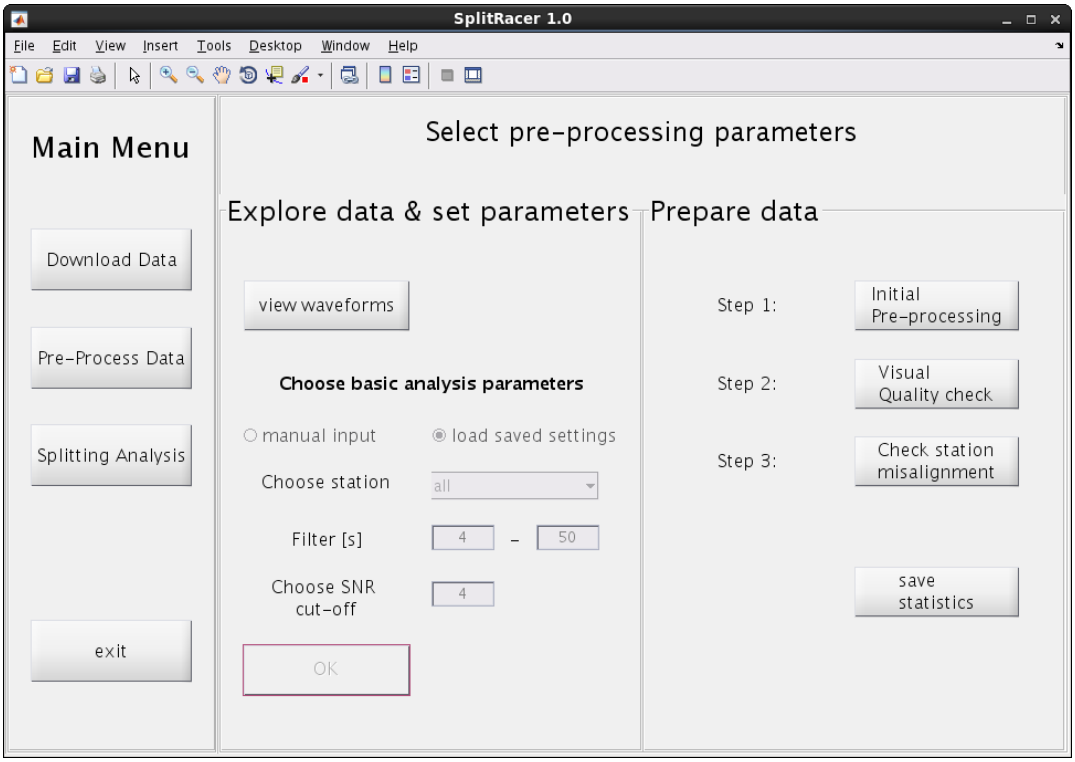



Figure 7 Pre-Process Data Menu after chosing settings

Back in the main program, you can decide if you want to use the settings you saved or put in different settings. Once you click 'OK', the 'Prepare data' buttons are enabled and the pre-processing starts.

Please note that you have to do all three steps in order.

**Step 1: *Initial Pre-processing***

Data is read, checked for completeness and gaps. An anti-aliasing filter (1s low pass) and re-sampling to 20 Hz is applied. Then, SplitRacers calculates travel times for all interesting phases for each event. The program then checks whether the phase is not preceded by another phase by less than 10 s (this ensures an appropriate signal window later) and whether it fulfills the SNR cut-off value. If so, it is saved. For each station, a station_networkcode.mat file is stored in ~/{projectname}/processed_data/ Filter_{filter values}_SNR_{snr value}/pre-processing/.

This may take a while. If you specify new settings, a new folder will be created.

**Step 2: *Visual Quality check***

Here, you can check which phases are saved for the following analysis. The first plot to the left ('entire trace') shows ZNE components of the entire event. Below is a 100s zoom in to the phase which fulfilled all criteria, marked in green. To the top right, the GUI shows ZRT components of the same 100 s zoom in.

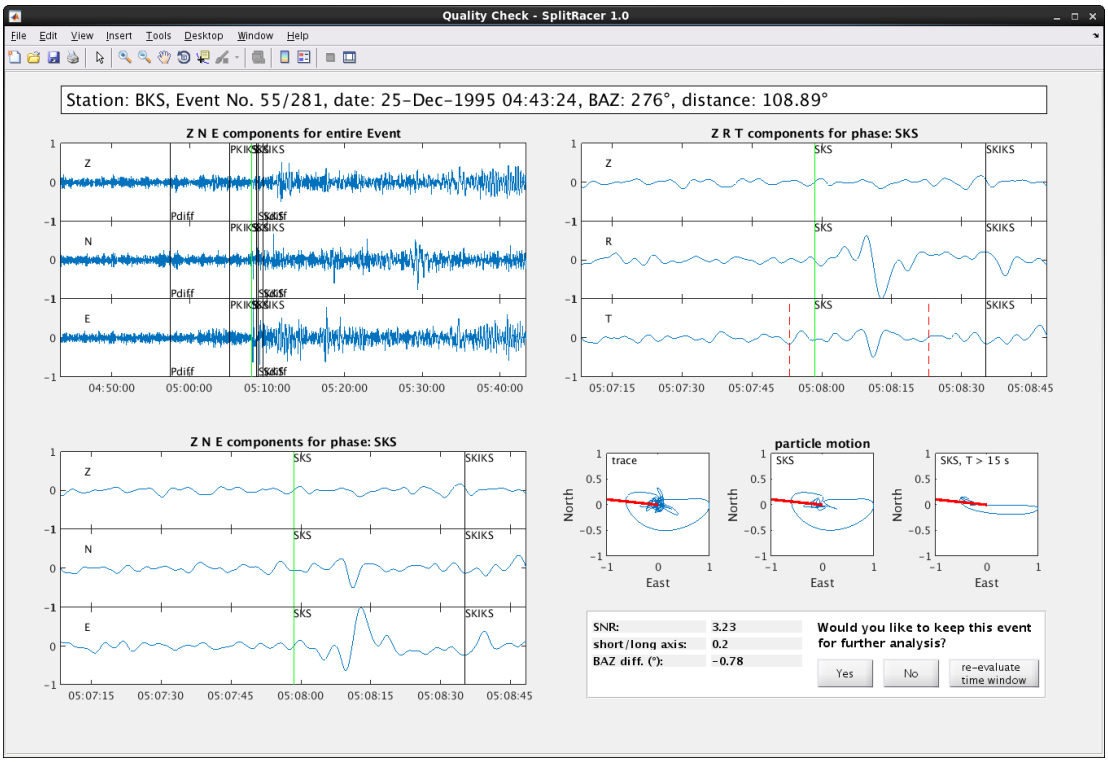



Figure 8 Visual Quality check GUI

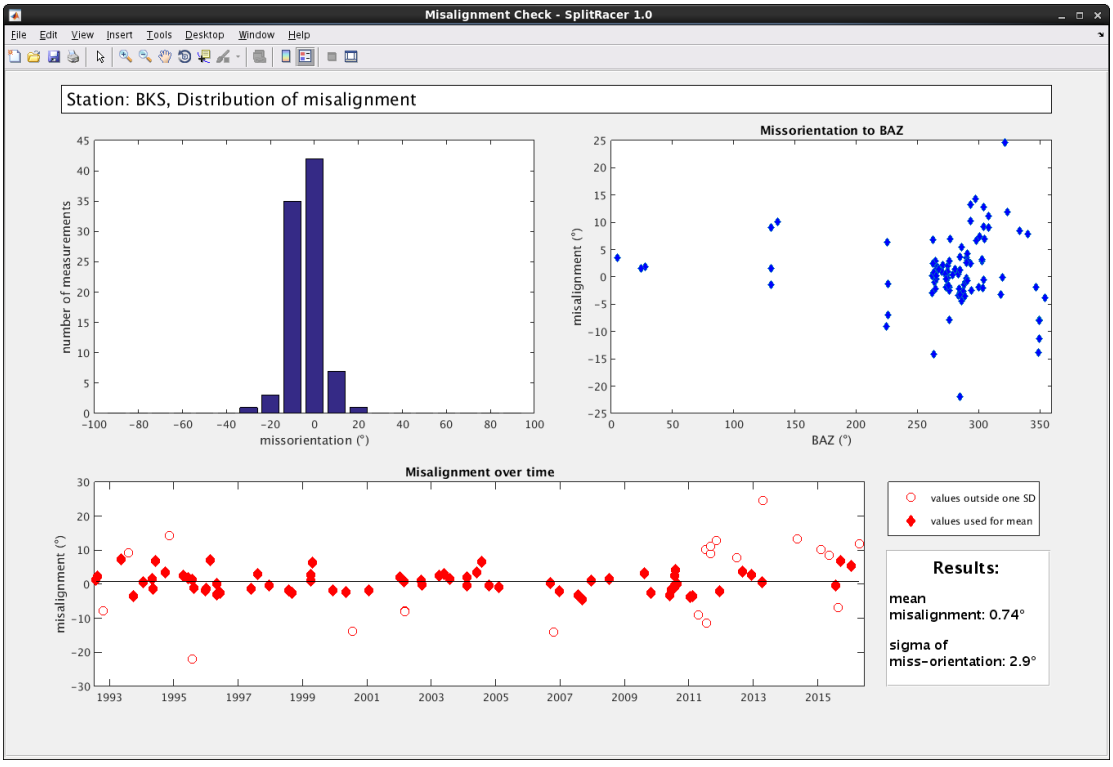
Below, the particle motion of the north and east components are shown. The first sub plot shows the particle motion of 100s zoom in. The second plot shows the particle motion of the signal time window (denoted by red bars above). The third plot shows the long-period particle motion of the signal time window. This is used to calculate a possible misalignment of the sensor, as the long axis of the long period particle motion should be parallel to the backazimuth of the event. This value is also stored for the following analysis. Please see the accompanying paper for further information.

At the bottom of the window, a small information box and GUI are placed. Here, all necessary information is given. You can decide if you want to save the event, discard it or change the signal time window. Once 'yes' or 'no' is clicked, the window shows the next phase. Please note you can use keyaboard short cuts for this subroutine. User 'y' for yes, 'n' for no and 't' for re-evaluate time window.

For each station, a station_networkcode.mat file is stored in

~/{projectname}/processed_data/ Filter_{filter values}_SNR_{snr value}/quality_check/.

**Step 3: *Check station misalignment***




The output of the previous step is used to show if any characteristic misalignment of the sensor exists. Once you click 'check station misalignment' a figure opens. In the first plot to the left, the overall distribution of misalignment is shown as bar plot. To the right, misalignment with backazimuth is shown. Below, the misalignment is shown depending on time. A mean value is

calculated and can be used to correct a station's misalignment. However, if any of the three plots suggest characteristic misalignment with backazimuth or time, this is not advised.

For each station, a mean correction value is saved in its * .mat file in ~/{projectname}/processed_data/ Filter_{filter values}_SNR_{snr value}/quality_check/.

After you have worked through all processing steps, statistics of the entire pre-processing analysis can exported to the graphics_output folder. A station_baz_stat.png files is also saved for your convenience.

# 8. Splitting Analysis

Once all pre-processing steps are done, you can start the shear-wave splitting analysis.

SplitRacer uses the energy minimization method to calculate shear-wave splitting. This is implemented as a grid search for the parameters phi and dt, which when used on the original transverse component, minimizes the energy best. For further information and reference, please see the accompanying paper.

First, just can load the filter settings from the pre-processing or, if you have analyzed e.g. a station of the same network before and you want to use the same settings, load these settings. If you choose to load settings from pre-processing, you can still change all the parameters:

- Station: choose desired station or ALL
- Filter: choose appropriate filter
- Number of time windows: choose number of time windows
- Phi range: the grid search is either facilitated from -90° to 90° or 0°-180°

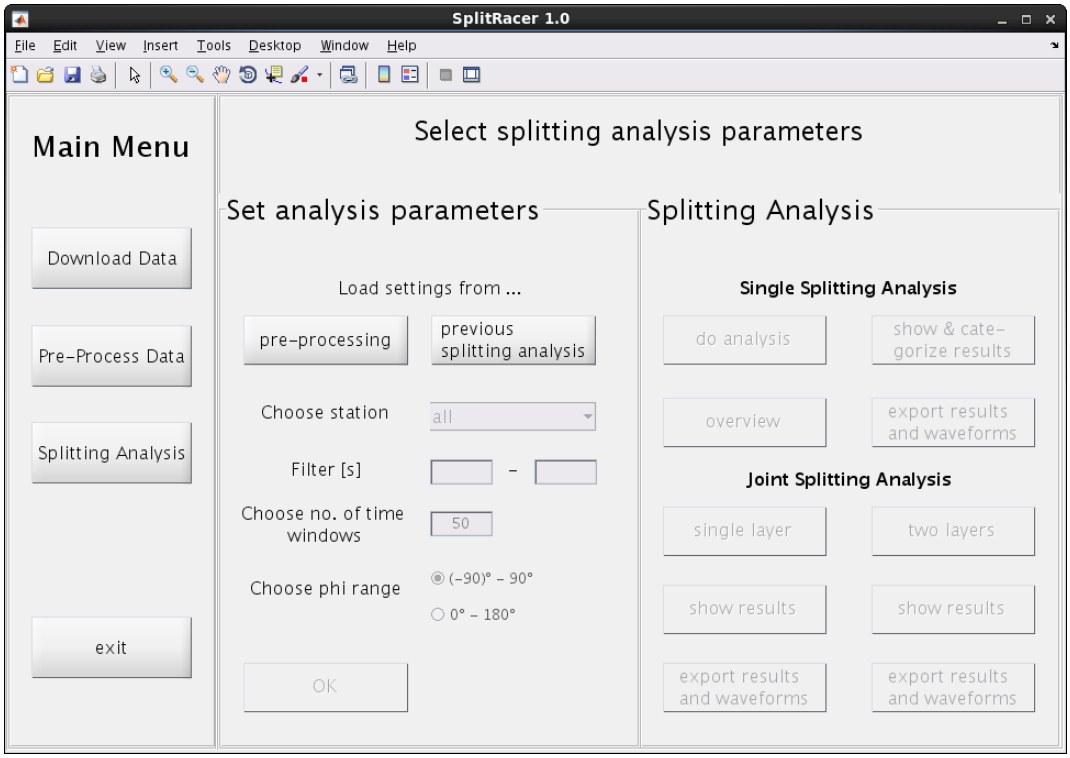



Figure 9 Splitting Analysis Menu

A new folder

~/{projectname}/results/ Filter_{filter values}_SNR_{snr value}_tw_{number timewindows}/

will be created, storing the settings as ‘saved_settings.txt’ file. Each time you specify new settings, a new folder is generated and a file specifying the settings is stored as well. This file also contains information on which settings folder was used for the pre-processing.

## 1. Single Splitting analysis

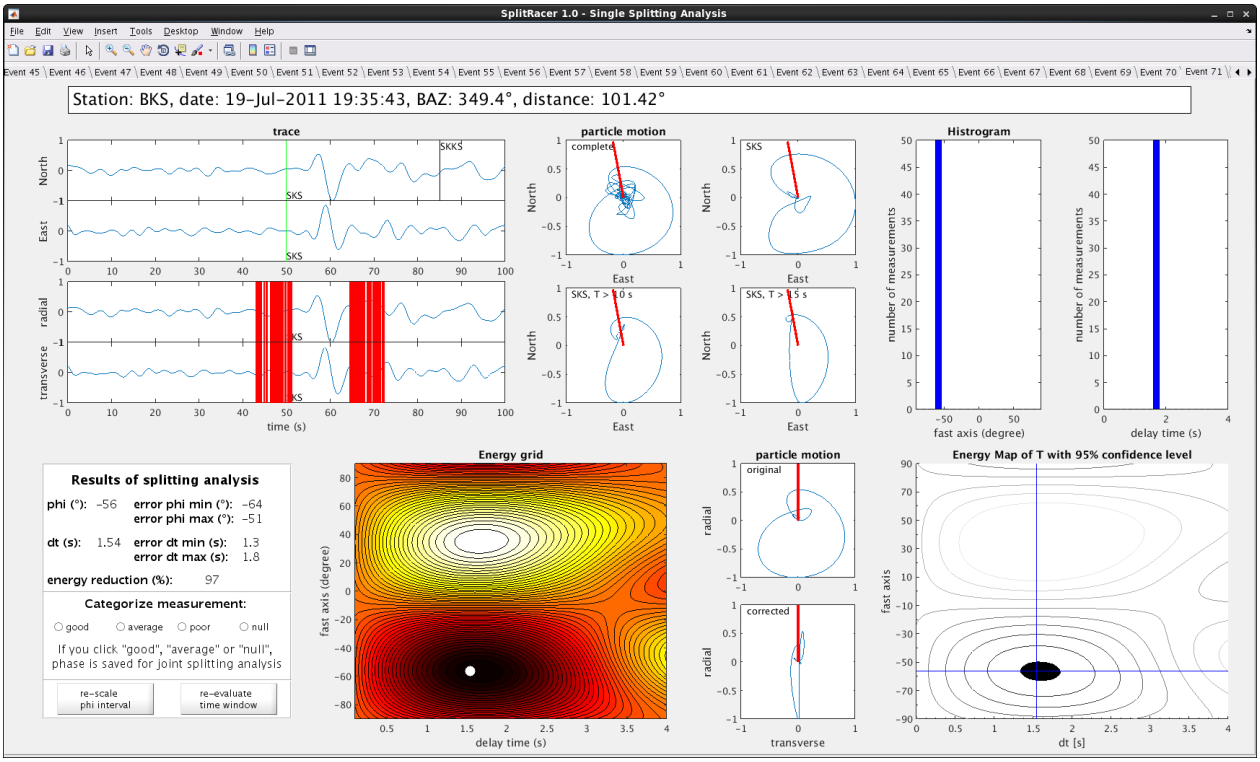



Figure 10 Single Splitting Analysis GUI

To start the single splitting analysis, simply click the *do analysis* button in the ‘Single Splitting Analysis’ panel. Depending on the number of events which you saved during the quality check, and the number of time windows, this may take a while. After calculation, click the *show and categorize results* button. Here, you need to choose between viewing all events are the same time separated by tabs or viewing events consecutively. If you have many events, the second option will be much faster.

Each tab has a header with information on the station and event. In the top panel to the left, a 100s zoom in to the phase is shown in NE and RT components. In the center, four particle motions are shown for NE components. First, for the entire 100s NE components, second, for the particle motion of NE components of the original signal time window as defined in the quality check. The third and fourth show long-period particle motions filtered with a bandpass

of 10-50s and 15-50s, respectively. The top right plot shows a histogram of the results of the splitting analysis per single time window.

In the bottom panel, an information box with GUI is placed, which states the result of the splitting analysis, error bars and energy reduction. The lower part of the information box where the GUI is placed only appears after the analysis has been calculated for all events. In the center, a mean energy grid is shown, followed by the original and corrected particle motions of RT components. To the right, the 95% confidence level is shown.

You can go through all tabs and compare the outcome of the analysis. You will notice that the GUI appears only in the first tab. Once you are finished with comparing the results, you can start categorizing the results in the first tab. Please consult the accompanying paper or other literature on how to categorize measurements. If you are dissatisfied with the chosen time windows or the phi range, you can re-calculate single phases by clicking the corresponding button. For each station, results are stored in several ways:

For further analysis:

- As .mat file containing all necessary data and splitting results
  ~/{projectname}/results/ Filter_{filter values}_SNR_{snr value}_tw_{number timewindows}/ /station_networkcode/results_si_split.mat

In the graphics_output folder for other uses

- As .txt file containing the results of the splitting analysis per phase and your categorization
  Format:

| Date | Time | Phase | BAZ | Sensor correction | phi | dt | phi Err min | phi err max | dt Err min | dt Err max | categeory | Confidence level |
|---|---|---|---|---|---|---|---|---|---|---|---|---|

- As .png file per event

For the joint splitting analysis, an additional file is saved as

~/{projectname}/results/ Filter_{filter values}_SNR_{snr value}_tw_{number timewindows} /station_networkcode/phases_js.mat.

It includes all events which the user chose to be ‘good’, ‘average’, or ‘null’ in the single splitting analysis.

Back in the main splitting program, you can show an ‘overview’. In the opening figure, the top panel shows the splitting parameter distribution and pie wedges. These demonstrate the distribution of used phases and their quality. The bottom panel shows the polarization and delay time plotted over backazimuth. Azimuthal dependence of the splitting parameters can be

used to infer spatially varying anisotropic layers. The GUI placed in the left hand side can help to explore whether a possible dependence is characteristic.

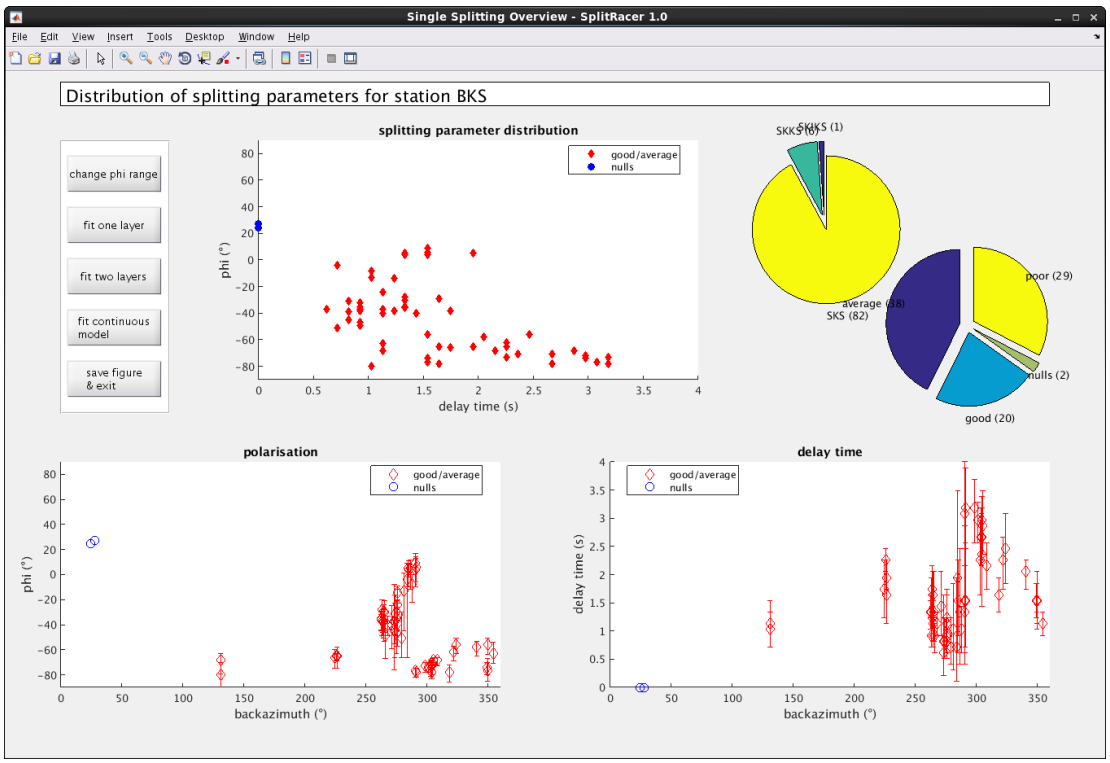



Figure 11 Overview GUI

Options:

- Fit one layer: calculates an average layer from splitting parameters
- Fit two layers: calculates apparent splitting parameters from different two-layer models. The best ten models are then shown in top left plot
- Fit three parameters: calculates apparent splitting parameters from different models with ten layers, where the delay time is fixed. The best ten models (uppermost and lowermost layer) are then shown in top left plot

Please note that for calculating these models, an average period of 10s is assumed for the phases with standard deviations for the splitting parameters of 20° and 1s. If you want to alter these parameters, go to the subroutine *overview.m* in the **Single_Splitting** folder, line 373 ff. If you want to alter the sample intervals of the models, go to *search_layer_para.m* in the same folder.

This routine also uses the previously saved splitting_results.txt file per station to write files in a readable format for GMT. Splitting results are saved in the output_graphics folder.

## 2. Joint Splitting analysis

The joint splitting analysis uses all phases at a given station while employing a grid search to find the parameters phi and dt which best minimize the energy on the transversal component. Please see the accompanying paper for an in depth discussion of the method itself.

There are two options, whose applicability depends on the outcome of the single splitting analysis. If the 'overview' figure does not show azimuthal dependence, a single anisotropic layer beneath the station can be inferred. If azimuthal dependence was evident, then a two layer joint splitting approach might be better suited.

### i. One layer

Depending on the number of events and time windows chosen, it may take a while to calculate joint splitting for one layer. When the calculation is finished, you can click on *show results* to visualize the outcome. This figure is divided into two parts: the left half is static and displays a header with the given station, an information box with the result of the analysis and the 95% confidence level. The right half is divided into tabs. Each tab displays a maximum of two phases used in the joint splitting analysis. In the center, NE and RT components are shown. Red bars indicate the used time windows. To the right, the original and corrected particle motions are shown, as well as the amount of energy reduction. The last tab includes the option to remove events from the analysis by simply typing the appropriate event number in the editable field. For correct statistics, remember to change the category of the removed event to 'poor' in the single splitting results text file (a button will guide you directly to this file).

You can view the results again after calculation by clicking on the *show results* button. Results are saved as .mat file as

~/{projectname}/results/ Filter_{filter values}_SNR_{snr value}_tw_{number timewindows}/station_networkcode/results_js.mat.

If you click on 'export waveforms', results and waveforms are stored in the graphics_output folder. Several files usable in GMT are also written: i) using the –SVb option, js_gmt.tab plots the found pair of splitting parameters, ii) using the –SW option, js_errbar1.tab plots the maximum error and js_errbar2.tab the smaller error of the 95% confidence levels.

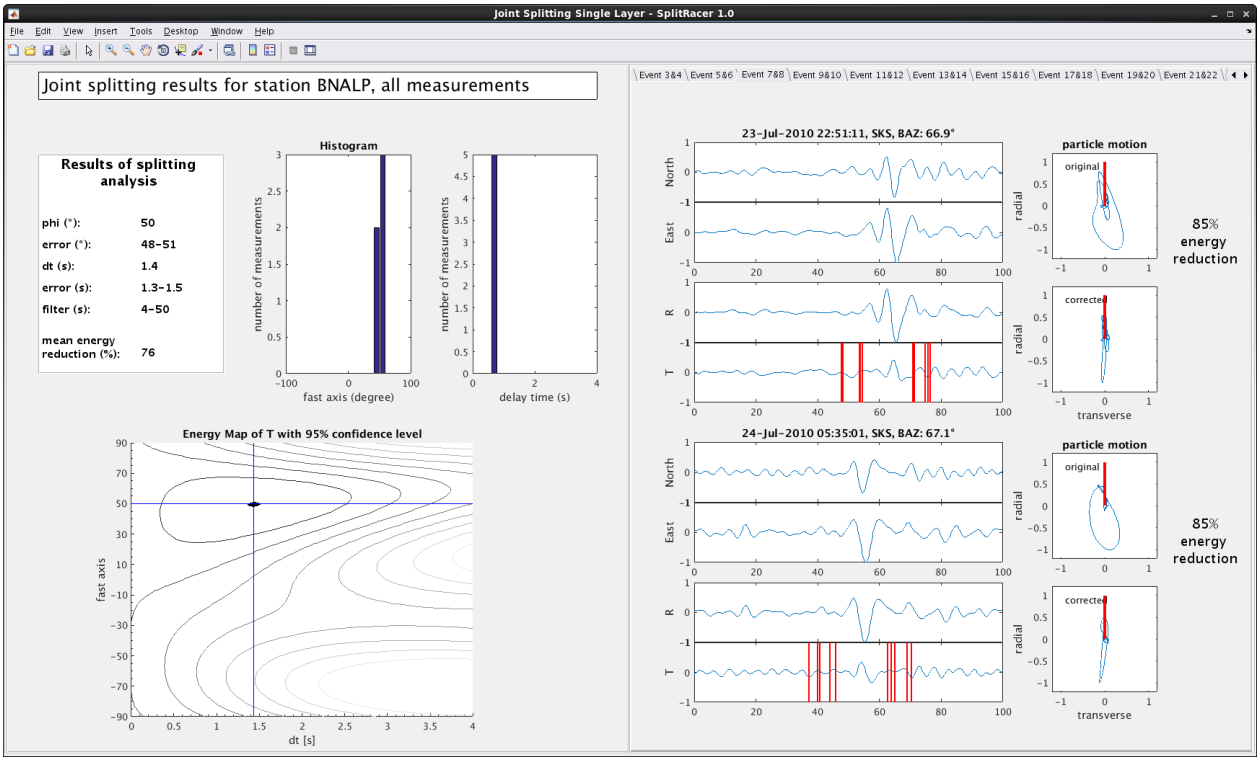



Figure 12 Joint Splitting Analysis One Layer

## ii. Two layers

Depending on the number of events and time windows chosen, it may take a while to calculate joint splitting for two layers. After each iteration, the MATLAB Command Window displays the elapsed time. We cannot advise attempting a calculation without the Parallel Computing Toolbox. Also, you should start with one time window only.

When the calculation is finished, you can click on 'show results'. The GUI (see Fig. 13) is divided into two parts: the left half is static and displays a header with the given station, an information box with the result of the analysis and the 95% confidence level for both layers. The right half is divided into tabs. Each tab displays a maximum of two phases used in the joint splitting analysis. In the center, NE and RT components are shown. Red bars indicate the used time windows. To the right, the original and corrected particle motions are shown, as well as the amount of energy reduction.

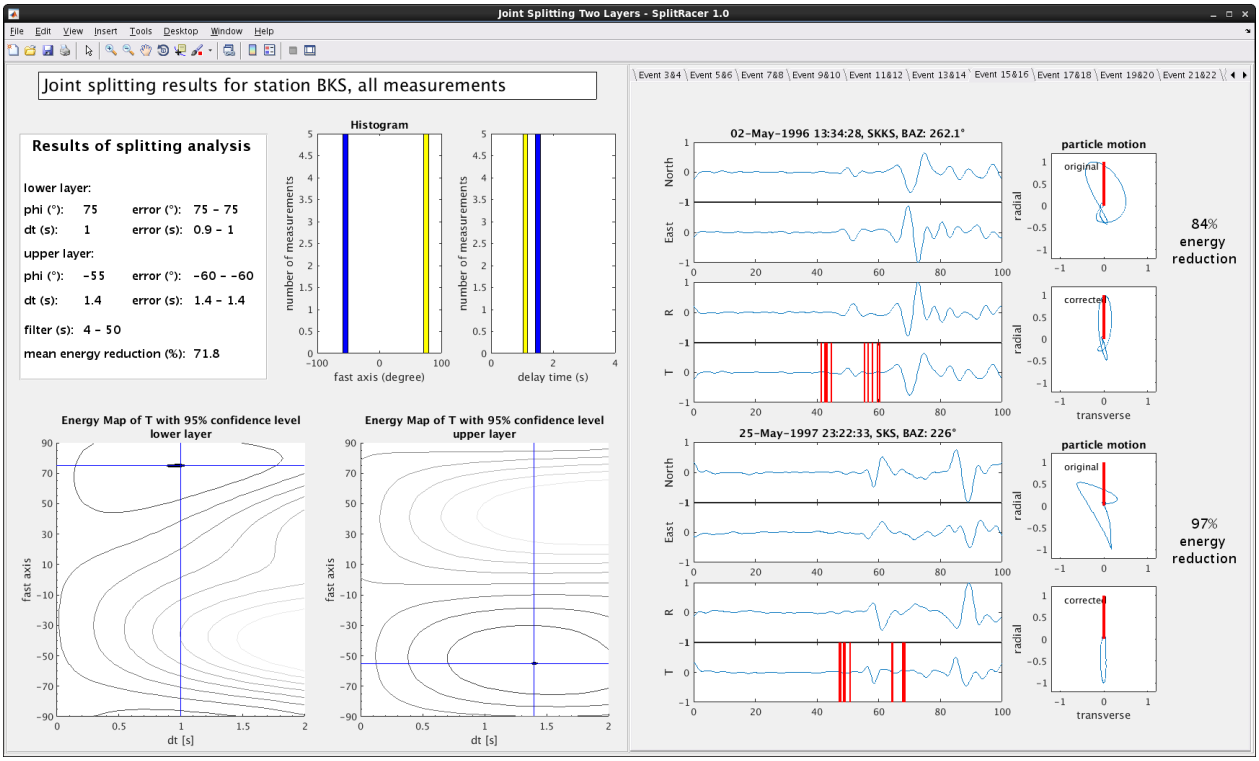



Figure 13 Two Layer Joint Splitting

The last tab includes the option to remove events from the analysis by simply typing the appropriate event number in the editable field. For correct statistics, remember to change the category of the removed event to 'poor' in the single splitting results text file (a button will guide you directly to this file).

Results are saved as .mat file as

~/{projectname}/results/ Filter_{filter values}_SNR_{snr value}_tw_{number timewindows}/station_networkcode/JointSplit/results_js_2L.mat.

If you click on 'export waveforms', results and waveforms are stored in the graphics_output folder. Several files usable in GMT are also written: i) using the –SVb option, js_gmt.tab plots the found pairs of splitting parameters, ii) using the –SW option, js_errbar1.tab plots the two maximum error and js_errbar2.tab the smaller errors of the 95% confidence levels.

## 9. Output Formats

Waveform data is always exported as .txt, while graphics are genereally stored as .png. Some files are formatted to be readily used in gmt. Please see the sketch below for an overview of the given outputs. For each setting during pre-processing and splitting analysis, a new folder will be generated. Please see the list below for a complete description of available output contents.

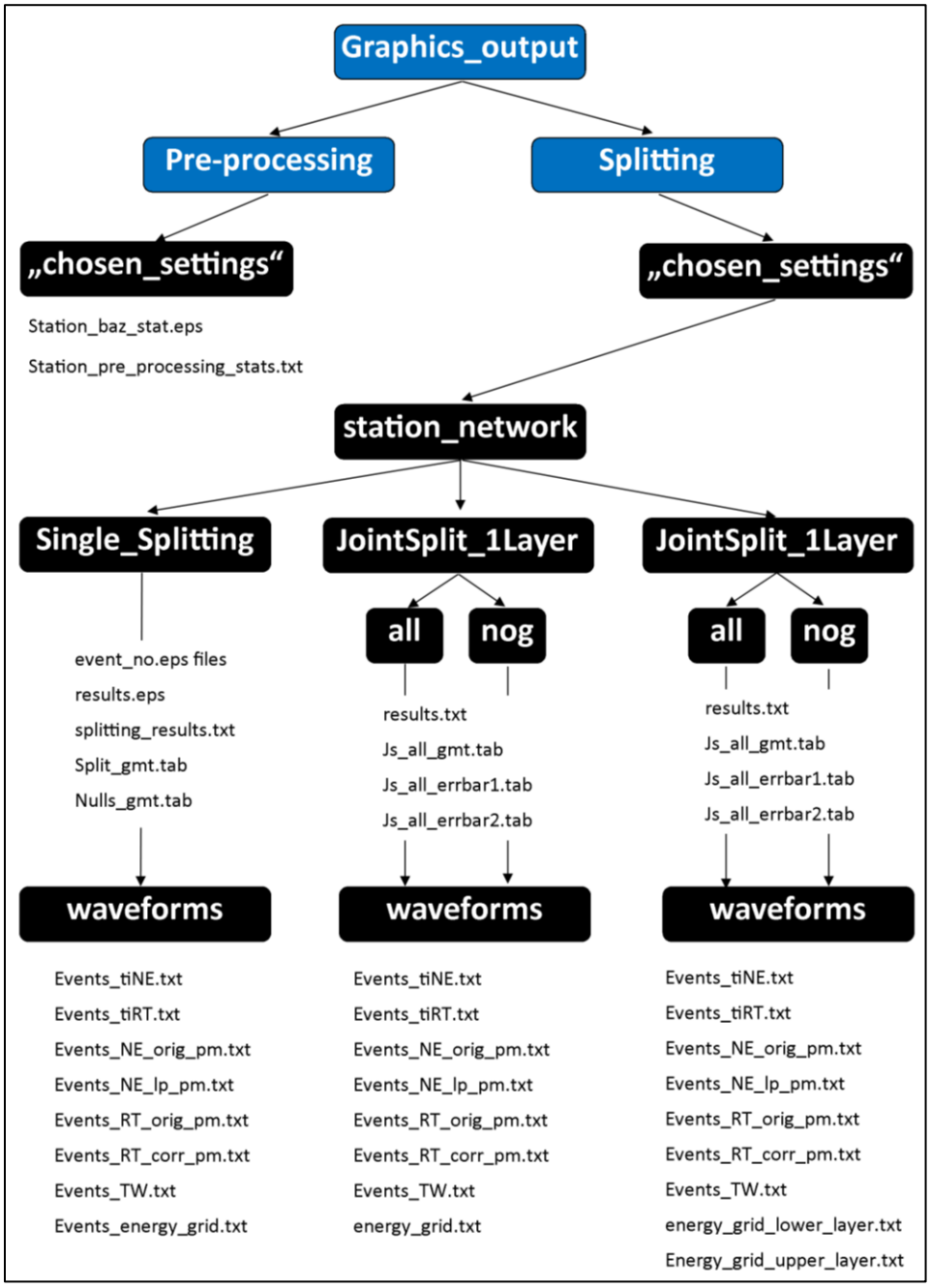



Figure 14 Overview of the graphics_output folder

File Contents:

| File name | content |
|---|---|
| **Pre-Processing** | |
| Station_baz_stat.png | Screenshot of *Check Station Misalignment* |
| Station_pre_processing_stats.txt | Summary of pre-processing |
| **Single_Splitting** | |
| event_no.png files | Screenshot per phase of single splitting measurement |
| results.png | Screenshot of single splitting *overview* |
| splitting_results.txt | Summary of results of all phases used in single splitting<br>Format:<br>date - time - phase - BAZ - sensor correction - phi - dt - phi err min - phi err max - dt err min - dt err max - category - confidence level |
| Split_gmt.tab | Average and good splitting results are saved as<br>lon – lat – phi – dt<br>To be plotted with gmt psxy -SVb |
| Nulls_gmt.tab | Nulls are saved as<br>lon – lat – BAZ – 0.8<br>lon – lat – BAZ – 0.4<br>To be plotted with gmt psxy -SVb |
| **JointSplit_1Layer & JointSplit_2Layer** | |
| results.txt | Summary of results |
| js_gmt.tab | joint jplitting results are saved as<br>lon – lat – phi – dt<br>To be plotted with gmt psxy -SVb |
| js_errbar1.tab | joint splitting results are saved as<br>lon – lat – phi – dt<br>To be plotted with gmt psxy -SW |
| js_errbar2.tab | joint splitting results are saved as<br>lon – lat – phi – dt<br>To be plotted with gmt psxy -SW |
| Waveforms – Single_Splitting | |
| Events_tiNE.txt | North/East components per event<br>100 s zoom in around phase<br>Format:<br>time vector, North, East |
| Events_tiRT.txt | radial/transversal components per event<br>100 s zoom in around phase<br>Format:<br>time vector, radial, transversal |
| Events_NE_orig_pm.txt | North/east components for particle motion per event for the chosen signal time window<br>Format:<br>North, East |
| Events_NE_lp_pm.txt | North/East components for long period-particle |

| | |
|---|---|
| | motion per event for the chosen signal time window<br>Format:<br>North, East |
| Events_RT_orig_pm.txt | radial/transversal components for particle motion per event for the chosen signal time window<br>Format:<br>radial, transversal |
| Events_RT_corr_pm.txt | radial/transversal components for corrected particle motion per event for the chosen signal time window<br>Format:<br>radial, transversal |
| Events_TW.txt | used time windows per event<br>Format:<br>start time, end time |
| Events_energy_grid.txt | energy grid per event<br>Format:<br>delay time, polarization, energy<br>To black the 95% confidence level, please use the value for the confidence level in the splitting_results.txt file |
| Waveforms – JointSplit_1Layer | |
| Same as single splitting except | |
| energy_grid.txt | joint splitting energy grid<br>Format:<br>delay time, polarization, energy<br>To black the 95% confidence level, please use the value for the confidence level in the results.txt file |
| Waveforms – JointSplit_2Layer | |
| Same as single splitting except | |
| energy_grid_lower_layer.txt | joint splitting energy grid for lower layer<br>Format:<br>delay time, polarization, energy<br>To black the 95% confidence level, please use the value for the confidence level in the results.txt file |
| energy_grid_upper_layer.txt | joint splitting energy grid for upper layer<br>Format:<br>delay time, polarization, energy<br>To black the 95% confidence level, please use the value for the confidence level in the results.txt file |

## 10. Alterations

It is possible to adapt SplitRacer to local or teleseismic S phases. Per default, teleseismic S phases are plotted and thus you only need to change which phases should be analyzed. This can be found in the function rc_phases.m in the folder pre-porcessing.

SplitRacer can also be altered for local events. First, you need to feed existing data to SplitRacer as described in *Download Data*. In the **defaults** folder of SplitRacer, you need to add appropriate travel time tables. Existing travel time tables are labelled according to their phase name, sampling a distance between 85-180° with a spacing of 0.1° and depth range of 0-700 km with a 10 km spacing. This results in a matrix of 951x71 travel times. Once you add travel time tables, you need to change the distance and depth range in the function interp_tt.m.

As the length of miniseed files of local events will be different to teleseismic events, a line in the code checking this length and even interpolating the full-hour files should be changed. Please see prep_data.m line 77 and re_sample.m line 16. You should also alter the length of the time windows for the pre-processing and analysis, see rc_phases.m line 64 and following, qc_phases.m line 151 and following.

As the main purpose of SplitRacer is the analysis of teleseismic events, please note that this description to incorporate local S phases may not be complete.

## 11. Trouble shooting

If you find any errors, do not hestitate to contact us at splitracer@geophysik.uni-frankfurt.de.

Known problems:

- Do not click twice on the buttons in the GUI when choosing paths, as the program will then create wrong links.
- If a station in the station.lst appears more than once, the subroutines will return an error.
- The tab view mode for viewing single splitting results might crash depending on your java heap space as well as your systems memory. View events once at a time instead.

To be continued …