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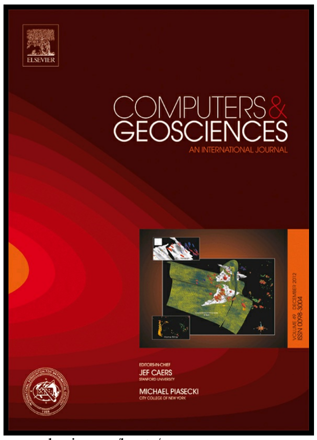

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StackSplit - a plugin for multi-event shear wave splitting analyses in SplitLab

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Abstract

SplitLab is a powerful and widely used tool for analysing seismological shear wave splitting of single event measurements. However, in many cases, especially temporary station deployments close to the noisy seaside, ocean bottom or for recordings affected by strong anthropogenic noise, only multi-event approaches provide stable and reliable splitting results. In order to extend the original SplitLab environment for such analyses, I present the StackSplit plugin that can easily be implemented within the well accepted main program. StackSplit grants easy access to several different analysis approaches within SplitLab, including a new multiple waveform based inversion method as well as the most established standard stacking procedures. The possibility to switch between different analysis approaches at any time allows the user for the most flexible processing of individual multi-event splitting measurements for a single recording station. Besides the provided functions of the plugin, no other external program is needed for the multi-event analyses since StackSplit performs within the available SplitLab structure which is based on MATLAB. The effectiveness and use of this plugin is demonstrated with data examples of a long running seismological recording station in Finland.

Keywords: MATLAB, shear wave splitting, SplitLab, multi-event, stacking, inversion

1. Introduction

Seismic shear wave splitting analysis has become an important tool to study Earth's anisotropic behavior in the upper mantle as well as the crust and lowermost mantle (D" layer). For this purpose several methods were developed to measure the parameters that best describe the orientation and strength of an anisotropic region in Earth's interior. These parameters are commonly the fast polarisation axis direction ϕ of the split shear wave and the delay time δt, measured between the arrival times of the two split waves. For a detailed overview on applications and interpretations of shear wave splitting measurements I refer to the review papers published by Savage (1999) and Long and Silver (2009).

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Table 1: Names of modified SplitLab functions, new outputs and brief description of main modifications. Abbreviation *ndf* stands for number of degrees of freedom.

function name	new outputs	remark
`splitlab.m`	-	adjustments for implementation of StackSplit
`geterrorbars.m`	ndf	fixed taper and ndf calculation (Walsh et al., 2013)
`geterrorbarsRC.m`	ndf	fixed taper and ndf calculation (Walsh et al., 2013)
`preSplit.m`	-	adjustments to save new outputs temporary
`splitdiagnosticplot.m`	-	adjustments to save new outputs temporary
`saveresult.m`	-	adjustments to save new outputs finally
`database_editResults.m`	-	adjustments to avoid database conflicts
`seisfigbuttons.m`	-	adjustments to avoid database conflicts

One of the mostly used and widely accepted analysis programs in the world-wide seismological community is the SplitLab environment (Wüstefeld et al., 2008) written in MATLAB (> 150 citations until end of 2016[1]). This software package contains all functionality for shear wave splitting analysis starting with requesting data for a selected recording station from different data centers, measuring the splitting parameters ϕ and δt simultaneously with three different methods and finally visualize and save the measured results for further analyses and modelling. In summary, SplitLab allows to perform shear wave splitting measurements in a comfortable and user-friendly way and without any need for advanced programming skills.

However the original SplitLab environment is mainly designed for teleseismic shear wave splitting analysis and only allows to perform single event measurements. Here three different approaches are applied simultaneously: the rotation-correlation method (hereinafter RC, e.g. Bowman and Ando, 1987), the energy minimization method (SC, Silver and Chan, 1991) and the eigenvalue method (EV, e.g. Silver and Chan, 1991). Each of these methods performs a grid search to find the pair of parameters (ϕ, δt) that best removes the effect of splitting from the recorded waveforms (see Wüstefeld et al., 2008). A comparison of the individual results of the three methods can be used to classify the quality of the measurement automatically (Wüstefeld and Bokelmann, 2007).

The observation of suitable S-wave phases for splitting analyses is limited by the specific global epicenter distribution around a station location (distance and backazimuth of events). The typically uneven source distribution leads to large backazimuthal gaps which then limit the estimation of anisotropy models. Furthermore, in many cases the recordings only have low signal amplitudes on the transverse component which can lead to unstable results (e.g. Restivo and Helffrich, 1999; Vecsey et al., 2008; Monteiller and Chevrot, 2010). Thus in the past several stacking techniques were outlined to determine an overall result for ϕ and δt

[1]after Google Scholar, https://scholar.google.com/

by stacking the individual error surfaces of the single event measurements obtained from the grid search procedure (Wolfe and Silver, 1998; Restivo and Helffrich, 1999). Recently a waveform based inversion technique was published by Roy et al. (2017) that utilizes the similarity of waveforms from a limited source region and concacenates the individual recordings. Especially temporary recording networks as well as stations located in noisy environments like close to the sea or even on the sea floor can benefit from such stacking techniques (e.g. Restivo and Helffrich, 1999).

A look on published studies, which used SplitLab for analysis in recent years, shows that multi-event methods for stacking are widely applied by the community (e.g. Eakin et al., 2010; Zietlow et al., 2013; Martin-Short et al., 2015; Bodmer et al., 2015). Nevertheless, the outputs of SplitLab often are processed with unpublished and poorly documented code snippets and scripts. Their usage makes efficient postprocessing quite difficult for users without advanced programming skills.

Here I present the StackSplit plugin that can be implemented easily into the existing and familiar SplitLab environment without big efforts on the one hand but maximum efficiency for multi-event analyses on the other one. Additionally, users can henceforth apply the same analysis program to their data but now also have the opportunity to directly use their single event measurements for multi-event processing. In order to perform different measurements with individual splitting methods, I provide a graphical user interface (GUI) that allows to easily switch between the single approaches at any time. Thus, the main aim of StackSplit is to ease the application of multi-event analysis for the wide audience of users that already use SplitLab or potentially want to apply it in future.

2. Description of the program

2.1. General remarks

Besides the original SplitLab package released by Wüstefeld et al. (2008), a slightly modified version is available from Porritt (2014) for which several improvements and extensions were introduced. In the latter one also a new output variable was implemented which stores and saves the complete content of a calculated error surface for the selected event for further analysis outside of SplitLab. At this point I extended the parameters and values which are saved in that output variable by saving also the individually cut seismogram traces (raw or optionally filtered) used for the inversion, the estimated degrees of freedom used for error calculation and several other parameters. These different variables are essential to ensure full functionality of StackSplit. Hence the application of multi-event measurements only is possible for new SplitLab projects created after the installation of StackSplit. The original SplitLab functions, that were slightly modified to successfully implement StackSplit, are listed in Table 1.

However, in the StackSplit package provided for download, the installer file checks which of both versions is currently stored on your system. Thus it is not required to change a running SplitLab version if one only

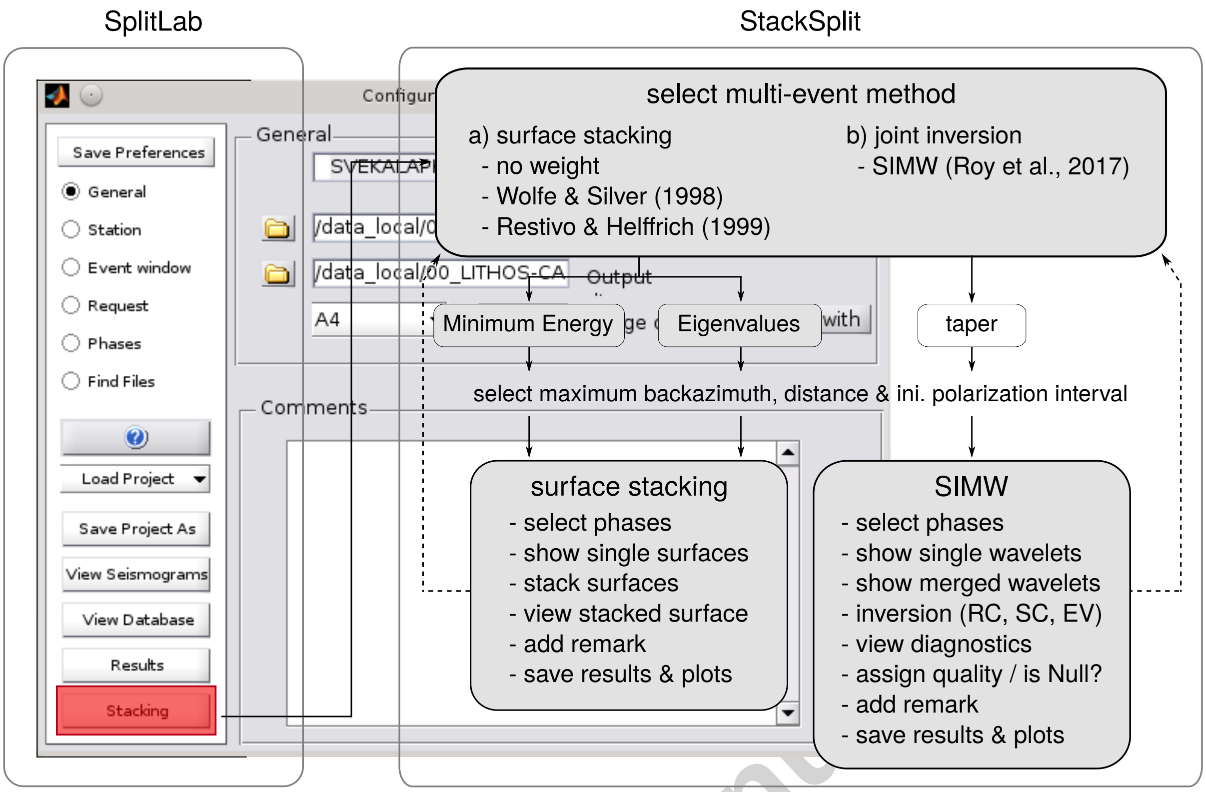

Figure 1: StackSplit workflow with main features/processing steps. Boxes colored in gray are essential, white ones indicate optional settings. For details see text.

wants to run StackSplit without changing the settings of the main program. For details see the user guide in the supplementary material that comes with this paper.

Independently of the used SplitLab version, after installing the plugin, a new button called "Stacking" is available for selection at the lowermost position on the sidebar of the main SplitLab window (Fig. 1). Furthermore, StackSplit makes use of SplitLab's global variable `config` to store adjusted settings for a future call of the current project. Since all StackSplit function names begin with `SS_` interested users easily can take a look into the source code of the corresponding routine.

For the sake of completeness, I also implemented the modified equations by Walsh et al. (2013) to correctly calculate the degrees of freedom needed for error estimation (see Table 1). It was found that the original equations published by Silver and Chan (1991) will overestimate the degrees of freedom by a factor of 4/3 and thus the calculated standard errors are too small (Walsh et al., 2013).

2.2. StackSplit main module

The StackSplit workflow (Fig. 1) is organised in a GUI (Fig. 2) from which the user easily can apply and test different methods for multi-event processing based on previously carried out single event measurements.

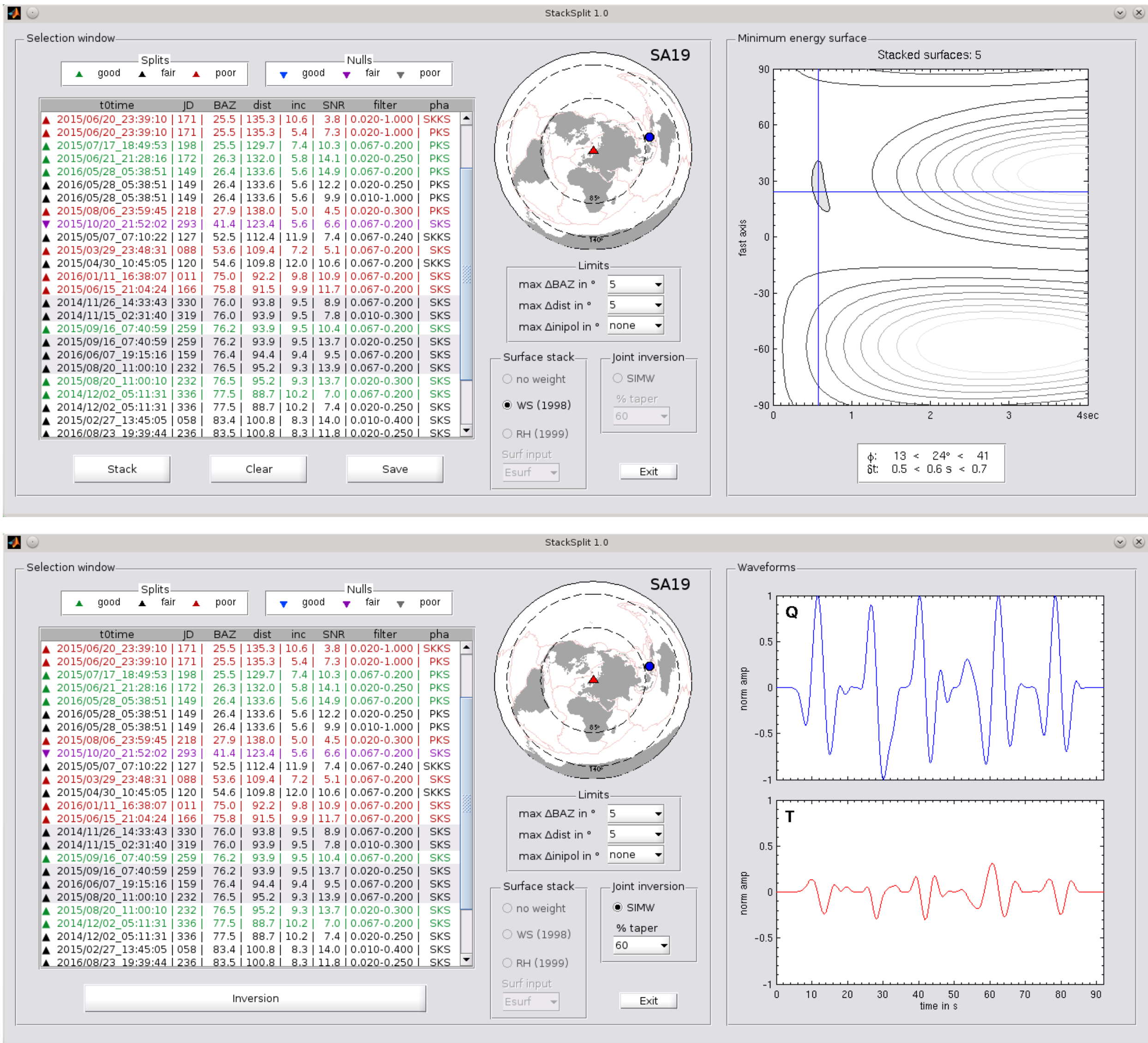

Figure 2: Graphical user interface of StackSplit for two different approaches. Top panel shows an example of five stacked minimum energy surfaces using the WS method. The result corresponds to the diagnostic plot displayed in Fig. 3a. Bottom panel shows the concatenated waveforms for the same five events when SIMW is selected. The corresponding inversion result is displayed in the exemplary diagnostic plot in Fig. 4 . The listbox on the left side in both panels lists the individual entries of seismic phases for which a single event measurement was done and saved in SplitLab, the equidistant azimuth plot displays the distribution of the used events.

To run StackSplit at least two saved single event measurements are necessary for a SplitLab project. Within the GUI the user has different choices how the data should be processed. Optionally, independent of the selected method, the user can define limits for the multi-event application regarding the selection ranges of event backazimuths, epicentral distances and initial polarizations. The latter one can find application especially when the initial polarization direction does not equate with the backazimuth like for direct S waves from local events (e.g. Gerst and Savage, 2004; Eakin et al., 2016) or source-side splitting measurements (e.g. Wookey and Kendall, 2004; Eakin and Long, 2013). By default a limit of 5° is set for all three parameters when StackSplit is run the first time for a project. Overall the StackSplit features can roughly be divided into two different multi-event approaches that are briefly described in the following.

2.3. Surface stacking

To calculate robust shear wave splitting parameters, firstly the user can select one of the standard stacking approaches that are applied on the output error surfaces of the single event measurements (Fig. 2).

In StackSplit I implemented the most common three surface stacking approaches which in general only differ in their relation to the used weight and normalization (see below). At this point the user can also choose between two different surface inputs that were saved within the framework of the single event measurements. The first is the minimum energy surface that is generated using the SC method (Silver and Chan, 1991). In this context the error surface represents the energy on the corrected transverse component calculated by grid-searching in the ϕ-δt parameter space. As second input the user can select the eigenvalue surface (e.g. Silver and Chan, 1991) whose computation depends on the previously selected eigenvalue-based option for the grid-search (maximizing λ_1 or λ_1/λ_2, minimizing λ_2 or $\lambda_1\lambda_2$, see Silver and Chan, 1991; Wüstefeld et al., 2008). Both methods lead to very similar results but can be applied to different input data depending on the knowledge about the initial polarization (see e.g. descriptions in Long and Silver, 2009).

If several seismic phases (e.g. SKS, SKKS or PKS) were analysed for an event, the user can also stack these phase results separately. This could help to stabilize the overall result especially when disrepant splitting parameters are observed for different phases of an event. Such characteristics were found for SKS and SKKS phases which often are interpreted as indicator for an anisotropic source in the lower mantle (e.g. Wang and Wen, 2007; Lynner and Long, 2014).

For an overview the user can browse through the individually saved single event measurements made with SplitLab that are listed in the listbox on the left hand side of the GUI (Fig. 2). Additionally, the error surface of the corresponding single event measurement is displayed in the right side panel. This setting allows the user to easily go through the whole available event list entries and check the error surfaces, especially for varying splitting parameters ϕ and δt regarding the different available backazimuth regions. The selection of more than one event list entry enables the user to compute a stacked surface with the currently selected method. The individual stacking approaches can easily be accessed by the different radio buttons in the "Surface stack" panel (Fig. 2). Furthermore, at any time the analyst is able to switch between the different methods, check the results, save them or restart the analysis with adjusted settings.

2.3.1. Stacking raw surfaces

This option (no weight) applies the stacking on the raw surfaces without any further consideration of the quality in terms of a weight or normalization. However, the true topography of each single error surface and thus the signal-to-noise ratio (SNR) directly influences the overall stacking result. This option is a good selection if, for example, one would like to calculate a total event surface using single measurements of the same event but different frequency filters (e.g. Wüstefeld, 2007). By this, the analyst can test the robustness of a measurement or detect possible frequency dependencies. As for the two following options, the standard errors for the stacked surface are calculated by assuming a χ^2 distribution for an underlying Gaussian noise process (e.g. Wolfe and Silver, 1998). Finally for each single error surface the estimated degrees of freedom are summed to get an overall value.

It has been noted that, if a clear backazimuthal dependency of the splitting parameters is observed, the stacking will not provide reliable results anymore. Instead of a single layer with horizontal anisotropy such characteristics point towards more complex anisotropic structures (Silver and Savage, 1994; Rümpker and Silver, 1998). Thus stacking would generate a smoothed error surface that erroneously indicates a single horizontal anisotropic layer beneath the station.

2.3.2. Method after Wolfe & Silver

As another option the user can select the widely applied method proposed by Wolfe and Silver (1998) referred to as WS in the following. Depending on the used input each single error surface is normalized before stacking, either to its absolute minimum (for λ_2, $\lambda_1\lambda_2$ and minimum energy) or maximum (λ_1 and λ_1/λ_2).

2.3.3. Method after Restivo & Helffrich

The final option of the surface stacking approach is the procedure initially introduced by Restivo and Helffrich (1999), in the following RH, that is a slight extension of the WS approach. Here each surface firstly undergoes a weighting depending on the measured SNR and secondly a normalization which reduces a high impact of overrepresented backazimuth directions (see Restivo and Helffrich, 1999).

2.4. Simultaneous Inversion of Multiple Waveforms (SIMW)

The second stacking approach is a waveform based multi-event inversion recently published by Roy et al. (2017) called SIMW (Simultaneous Inversion of Multiple Waveforms). In contrast to the surface stacking methods outlined in the previous section, SIMW directly works on the time series and not on the already calculated error surfaces. First all events of a preferred region with similar backazimuth and epicentral distance are selected and the corresponding waveforms of the radial Q and transverse T components are concatenated in the time domain. Within StackSplit all single waveforms are normalized to the maximum

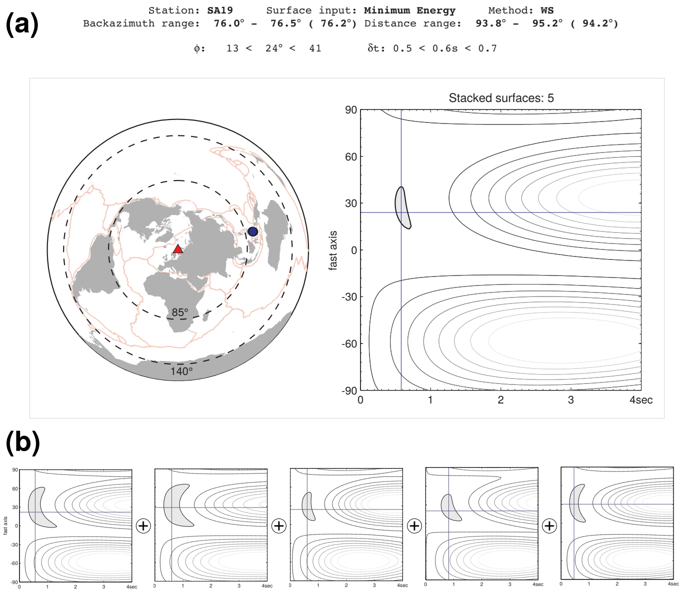

Figure 3: **(a)** Exemplary diagnostic plot for the WS surface stacking approach with five used single minimum energy (SC) surfaces. The corresponding single event surfaces are displayed in **(b)**. Please note that, for the sake of clarity, for each measurement the single surfaces are not included in the saved diagnostic plot. The 95 % confidence region in each surface is indicated by the gray shaded area.

of their corresponding Q components before concatenation to avoid a bias due to large amplitude recording. Optionally a taper can be applied on each single wavelet before merging them together to reduce influences of potential noise sequences included in the time window used for the single event mesasurement. The default taper in total influences 20 % of the corresponding Q and T waveforms, so 10 % at both the beginning and end. Then the whole generated waveform is inverted simultaneously using the three different methods implemented in SplitLab (RC, SC and EV) to remove the effect of splitting by performing a grid search (see section 1). The corresponding backazimuth for the concatenated waveform is calculated as a simple mean out of all used single event backazimuths. This is the only limitation of SIMW and thus the window limits for considered backazimuths and epicentral distances should be selected with care (Fig. 2). On the other hand the application of SIMW, equally to the single event measurements, enables the user to assign a quality rank to the calculated multi-event result as proposed by Wüstefeld and Bokelmann (2007). The resulting splitting parameters are the best joint solution for all used waveforms. For a detailed description of SIMW including the application to two long running seismic networks, see Roy et al. (2017).

Within the "Waveforms window" (Fig. 2), the corresponding waveforms for the radial and transverse components of the currently selected single measurement are displayed. If more than one entry is selected, the corresponding concatenated waveform appears in that window (see example in Fig. 2).

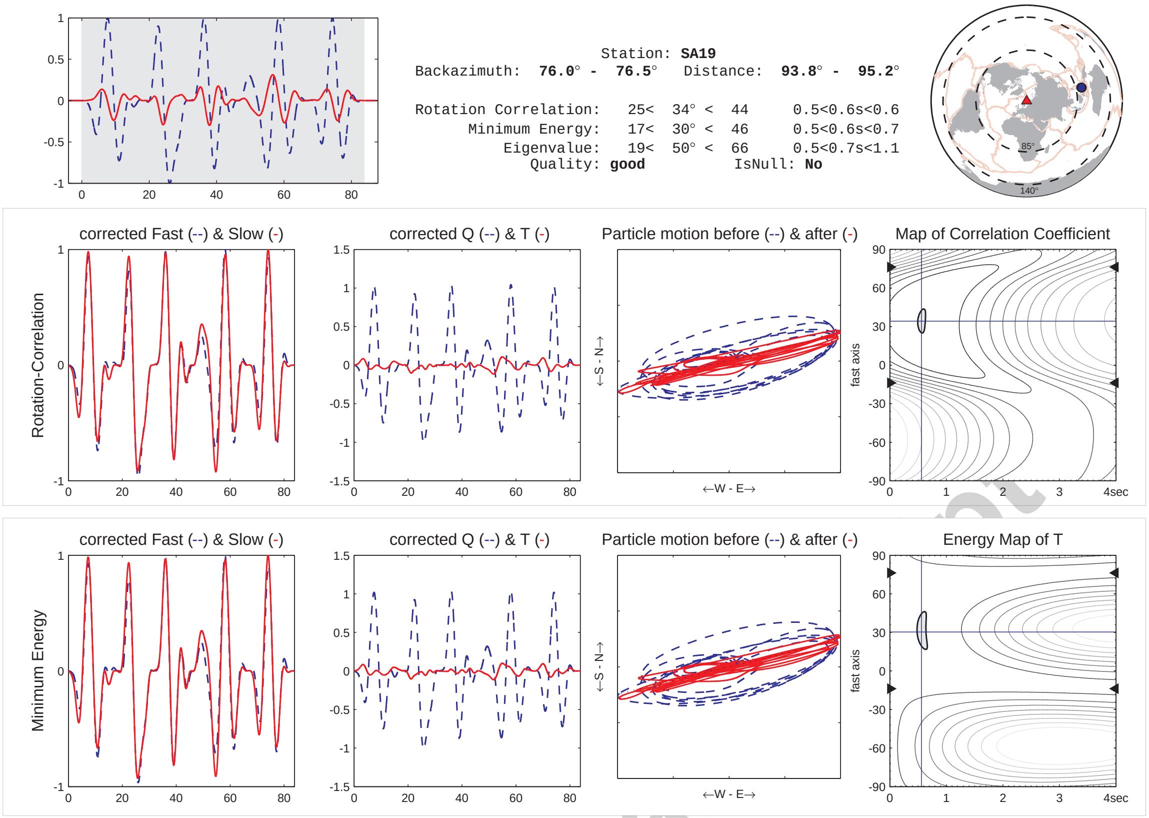

Figure 4: SIMW diagnostic plot for five exemplary phase records from earthquakes (top left panel) that occured in the South East Asia region between fall 2014 and fall 2016. Displayed are the standard SplitLab panels for the RC and SC methods (see Wüstefeld et al., 2008) except the worldmap in the upper right corner that displays all the used events. The header gives additional information about the measurement and the input data.

2.5. StackSplit outputs

Depending on the used multi-event method, StackSplit generates different output files which can be used for further analysis and modelling outside of SplitLab (e.g. using the MSAT toolkit by Walker and Wookey, 2012) or to visualize the results (e.g. using the Generic Mapping Tools by Wessel et al., 2013). Firstly, independent of the method, each saved measurement (surface stack or SIMW) is stored in the global MATLAB structure variable `eqstack` that is automatically generated when StackSplit is run the first time for a project. Similar to SplitLab's `eq` variable this structure contains information about each conducted multi-event measurement including the computed values for ϕ and δt as well as the whole content of the used input events/phases.

Besides this main storing variable, each saved result will appear in a plain text file that contains the whole information about the measurement like station name, considered backazimuth and distance ranges as well

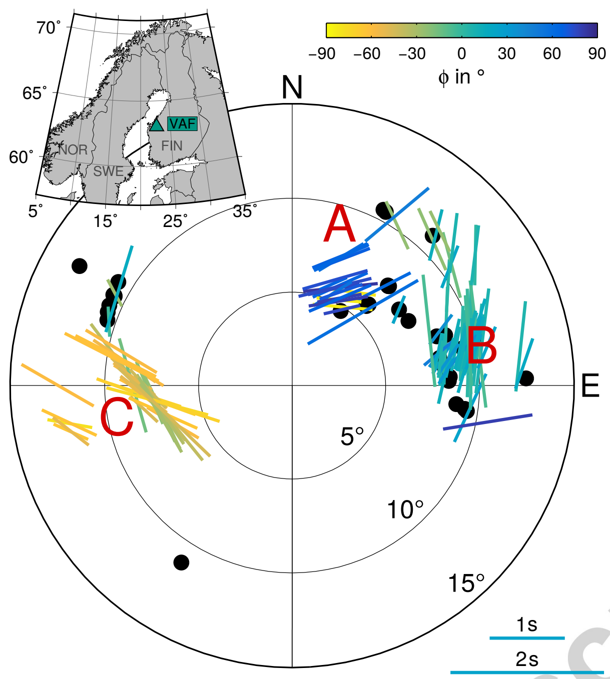

Figure 5: Location and determined single-event splitting parameters of all qualities (good, fair and poor) at permanent station VAF as a function of backazimuth and incidence angle (radial axis from center to outside). To highlight the observed variation of the fast polarisation axis with backazimuth the single bars additionally are color coded. Black filled circles respresent null measurements.

as the results of the multi-event measurement. Separately for both approaches, surface stack and SIMW, a text file is compiled in the folder of the set result path. Additionally diagnostic plots are automatically saved in the preferred file format for each measurement. For the surface stack the diagnostics show the final stacked surface (same like in the GUI panel) as well as the event distribution of the selected events used for the current stacking (Fig. 3). On top, information about the settings as well as the final result is given. A diagnostic plot for measurements conducted with SIMW looks similar to the original SplitLab diagnostics (Fig. 4). Besides the corresponding information about the multi-event measurement, in addition the distribution of the used events/phases is displayed in the upper right corner.

3. Application example

To demonstrate the performance of StackSplit with a real data example, I present measurements of the seismic permanent station VAF of the Finnish National Seismic Network for which recordings of around ten years (2007-2016) are freely available (Fig. 5). In the past shear wave splitting was also partly studied within the SVEKALAPKO project at this station (Vecsey et al., 2007).

First, the data was analysed with the standard single event analysis in SplitLab which yielded in total

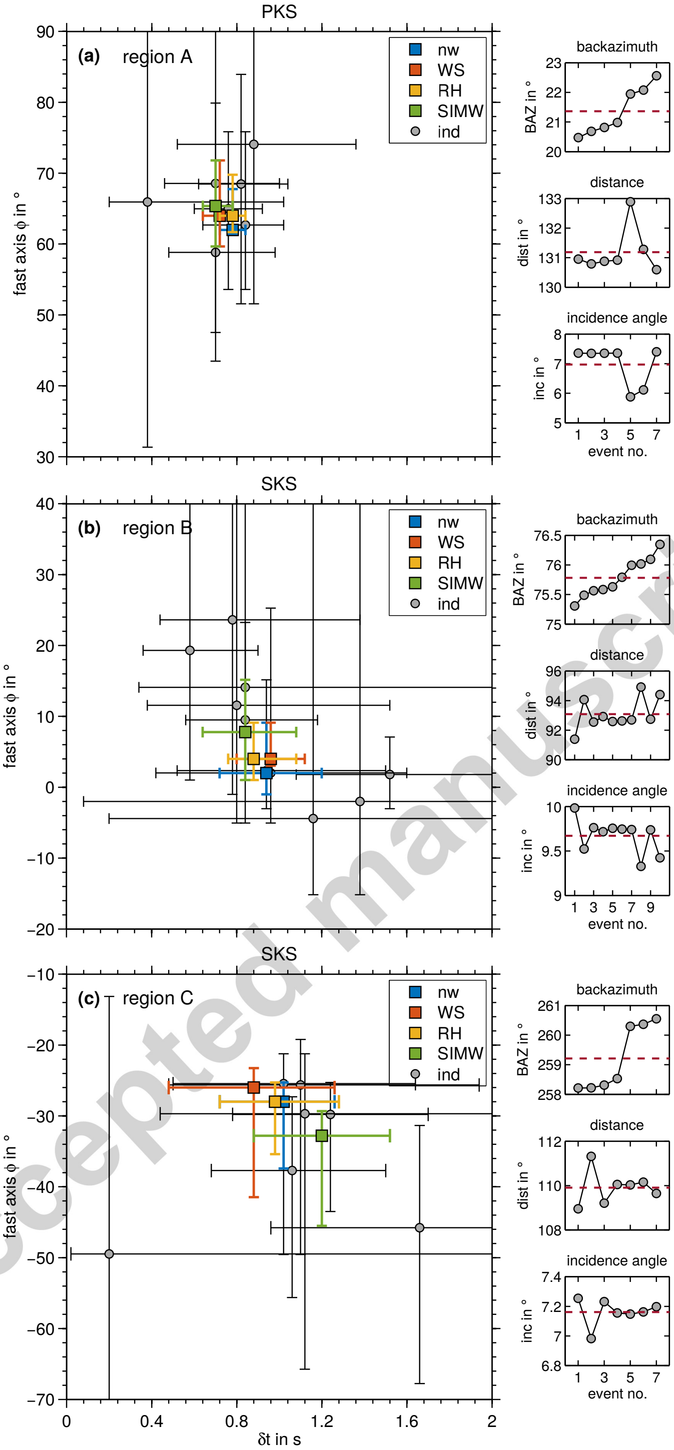

Figure 6: Distribution of determined splitting parameters for the individual single (gray circles, *ind*) and multi-event (colored, *nw*: no weight; *WS*: Wolfe & Silver, 1998; *RH*: Restivo & Helffrich, 1999; *SIMW*: Roy et al., 2017) measurements at permanent station VAF. For all methods only the SC results are shown. The small panels on the right hand side give information about the backazimuth, epicentral distance and incidence angle (from top to bottom) of the used event/phase. The horizonal dashed red line indicates the calculated mean for each parameter. The shown error bounds represent the minimum and maximum range of the calculated confidence regions (see Wüstefeld et al., 2008). Please note the different axis scales for the fast axis ϕ.

163 measurements that include non-null and null measurements of all qualities (ranked as good, fair and poor following Barruol et al., 1997; Wüstefeld and Bokelmann, 2007). All waveforms were processed using a bandpass filter with mainly corner periods between 5 s and 15 s. In order to improve the SNR of the single phase arrivals, partly the corner periods were slightly adjusted as done in other studies (e.g. Eakin et al., 2016).

In Fig. 5 the results of the single event measurements are presented that indicate complex anisotropy beneath the station due to strong variations of the splitting parameters with backazimuth. Thus for this station multi-event procedures without a preselection of backazimuths and incidence angles are not suitable to generate a single set of averaged splitting parameters; otherwise the backazimuthal characteristics would be smoothed out in the overall result. However, this station is a good example to compare the different approaches implemented in StackSplit for a multi-event analysis within limited backazimuth regions. Please note, that for the RH method in this case the backazimuthal normalization has minor influence on the stacked result.

The single event results can roughly be divided into three regions with average backazimuths (BAZ) of 21°, 75° and 259° (regions A-C, Fig. 5). For each group I selected a set of 7-10 representive low quality measurements that were mostly ranked as poor with SNRs between 4 to 10 to test the stacking procedures. However, some results which were ranked as fair but with similar SNR, were also included. The backazimuth and epicentral distance range for these used events within each group is less than 4 ° (Fig. 6).

Subsequently, for each of the four methods implemented in StackSplit, splitting parameters were computed for the three selected backazimuth regions (Fig. 6). Since for the surface stacking procedures the selectable inputs are the minimum energy (SC) and eigenvalue surfaces (EV), a direct comparison with SIMW is only possible for these two methods. For the sake of clarity, in Fig. 6 only results based on the SC method are presented. However, the results based on the EV method reveal a very similar behavior.

In general the determined multi-event results show similar values for the fast axis ϕ and delay times δt separately for each of the selected backazimuth regions. For region A (BAZ $\sim$ 21°, 7 PKS phases) the observed difference of the absolute values is 3° for the fast axis and 0.1 s for the delay time. The results for region B (BAZ $\sim$ 75°, 10 SKS phases) have a wider scatter for ϕ with a maximum difference of around 6 ° between the different methods but also a small variation of 0.1 s for δt. The splitting parameters obtained for region C (BAZ $\sim$ 259°, 7 SKS phases) show similar characteristics with maximum differences of around 6° for the fast axis and slightly larger variations of 0.3 s for δt.

As expected, the errorbounds (that represent the confidence level for each measurement) of the results from stacking, overall are essentially smaller compared to the single event measurements whose error bars partly span across the whole parameter space (Fig. 6). Thus, independently of the applied method, the confidence into the obtained multi-event splitting parameters has been raised for all three backazimuth regions A-C.

4. Conclusions

I have introduced StackSplit, which is a flexible and easy to use plugin for the widely applied shear wave splitting environment SplitLab. StackSplit was mainly designed to allow performing multi-event analysis without big efforts for all seismologists that already use SplitLab for single event measurements or plan to use it in future. Besides the commonly already used standard stacking techniques, this package provides also a new waveform based inversion approach (Roy et al., 2017) that delivers similar results for limited backazimuth regions. The flexible graphical user interface allows to switch between the different methods and to compare the corresponding outputs to receive high quality measurements for ongoing interpretations. However, the standard analysis can be done as in the past with the exception that now directly a multi-event processing interface is available for efficient analaysis within a familiar program environment.

Code availability

The StackSplit code and a detailed documentation is available at GitHub (https://github.com/michaelgrund/stacksplit) and MathWorks File Exchange platform. The code was tested with MATLAB versions between 2012a and 2014a operating on Linux and Windows systems. However, in general no issues are expected for other versions. If your version is MATLAB 2014b or newer I recommend to use the SplitLab version provided by Porritt (2014). StackSplit automatically checks for the available version on your system.

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Data for station VAF was requested from GEOFON at GFZ Potsdam where it is freely available for download. The examples in section 2 were generated with data of a temporary station (SA19) that is part of the ScanArray network (see Grund et al., 2017).

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