SWAS: A shear-wave analysis system for semi-automatic measurement of shear-wave splitting above small earthquakes

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Abstract

The complexity of shear wave-arrivals above small earthquakes makes the polarisations and time-delays of shear-wave splitting above small earthquakes difficult to measure. We report a semi-automatic shear-wave analysis system, SWAS, that appears to combine the benefits of both visual and automatic techniques. Initially, SWAS automatically estimates shear-wave polarisations and picks shear-wave arrivals by an expert system, which provides sufficiently accurate initial measurements for visual adjustment. SWAS then allows easy comparison and adjustment of picks between screen images of original seismograms, seismograms rotated into anisotropic polarisations, and polarisation diagrams (hodograms), with immediate plotting in various standard or non-standard configurations. This speeds up visual measurements by well over an order of magnitude, and typically allows records of almost all small earthquakes ($M \geq -1.0$) to be reliably measured for shear-wave splitting polarisations and time-delays. SWAS was developed and tested for data from the SIL seismic network in Iceland.

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1. Introduction

Shear-wave splitting (seismic birefringence) above small earthquakes writes comparatively subtle signatures into three-component seismograms that are unavoidably scattered, and temporally and spatially variable (Crampin et al., 2004; Crampin and Gao, 2006). This makes it difficult to accurately measure shear-wave splitting parameters of polarisations and time-delays on seismograms either visually or automatically, and the complications may lead to misinterpretations and misunderstandings (Crampin, 1994, 2003; Crampin et al., 2003). Accurate measurement is important because recent evidence suggests that changes in shear-wave splitting monitor the low-level pre-fracturing deformation of the fluid-saturated microcracks pervasive in most \textit{in situ} rocks. This new understanding is a new window into \textit{in situ} fluid-rock interaction, a \textit{New Geophysics} (Crampin, 2003), which allows the accumulation of stress before earthquakes to be monitored (Crampin, 1999; Volti and Crampin, 2003a,b), and the calculation, evaluation, and prediction, and possibly even control of certain oil-production operations (Angerer et al., 2002).

Crampin and Gao (2006) review both visual and automatic techniques for measuring the polarisations...
and time-delays of shear-wave splitting. No existing technique is wholly satisfactory. Visual analysis of various displays, although probably the most accurate and certainly the most flexible, tends to be subjective, tedious, and time consuming. Automatic techniques are wholly effective only on impulsive, high signal-to-noise-ratio records displaying near-classic examples of shear-wave splitting, which is typically no more than about 20% of most local earthquake seismograms. Thus in order to get accurate measurements, automated measurements must either be subjected to visual checking, which is again tedious and time-consuming, or the original seismograms, before processing, must pass very rigorous criteria which exclude a significant proportion of the earthquake records. Such heavy selection is undesirable and may seriously bias the results.

Biased results are particularly undesirably when measuring sparse data sets, such as monitoring the accumulation of stress before earthquakes (Crampin, 1999; Volti and Crampin, 2003a,b). There are seldom sufficient source earthquakes to allow severe data reductions, where such reductions would typically restrict shear-waves to particular source regions, ray paths, and earthquake-mechanism geometries. The strong variations with azimuth and incidence angle inherent in all anisotropic measurements, could make such biased geometries seriously misleading.

Crampin and Gao (2006) show that neither visual displays nor automated techniques are wholly successful in measuring shear-wave splitting. Here, we present a shear-wave analysis system, SWAS, developed for semi-automatic measurement of seismic shear-wave splitting which combines the merits of both visual display and automatic techniques. SWAS is developed and tested on 8-months’ data from the SIL seismic network in Iceland (Stefánsson et al., 1993).

An earlier system analysis method, SAM (Gao et al., 2004) for measuring shear-wave splitting was based on cross-correlation of fast and slow shear-waves and visual polarisation checking (Gao and Zheng, 1995). SAM, a direct precursor of the SWAS program, successfully measured shear-wave splitting parameters above swarms of small earthquakes (Gao et al., 1998), but is not generally applicable because of the limitations of all cross-correlation techniques (Crampin and Gao, 2006).

![Fig. 1. Flow chart for measuring shear-wave splitting by expert system analysis.](image)

![Fig. 2. Screen images from SWAS showing shear-wave splitting analysis of M = 0.25 earthquake recorded within the shear-wave window at station SAU in the SIL seismic network in Iceland. The time axis of the 100 samples/s seismogram is in seconds and it is filtered with a butterworth 3.0–50.0 Hz bandpass. Vertical bars spanning the P- and S-wave arrivals (from SIL earthquake catalogue data) mark (0.1 s) time-intervals for PDs in Fig. 2c below. Header information is described in Section 4. (a) Screen image [origin]: original seismograms from top: EW-, NS-, and vertical-seismograms (unprocessed apart from filtering), and horizontal-components rotated into radial- and transverse-polarisations. Note data in the right-hand header is blank before SWAS/ES processing. (b) Screen image [fast/slow]: seismograms showing shear-wave splitting as identified by the SWAS/ES automated picking. Notation as in (a) but lower two seismograms are rotated into the fast and slow polarisations determined by SWAS/ES analysis, with the polarisations, fast and slow arrivals, and time-delays indicated in top-right header. The fast and slow shear-wave arrivals (from start of screen image) are marked by vertical lines. (c) Screen image [polarisation]: PD display for visual examination of polarisation and time-delay. From the top, mutually orthogonal PDs are: sagittal section (up, down, towards, and away from the source); horizontal view from source (up, down, left, and right from the source), and horizontal section (towards, away, left, and right from the source). Each column of PDs shows particle motion in the 0.1 s (10 sampling points) time-intervals marked in the seismograms spanning the P- and S-wave arrivals in (a) and (b). The ‘× N’ marked above each column indicates relative scaling. SWAS/ES fast and slow shear-wave picks are marked by circles in the horizontal PDs in-time interval X. At the bottom is an enlarged horizontal polarisation-diagram spanning the selected fast and slow picks. The template shows current selection of row, column, first point, and last point of the time-delay, and directions for visual adjustment. The green line marks the average polarisation between the two circled points. Small ticks on the PDs mark time-series samples, which are outward facing for clockwise rotation, and inward facing for anti-clockwise rotation. The template shows current selection of row, column, first and last points of the time-delay, and [directions] for visual adjustment. (d) Screen image [polarisation]: same as Fig. 2c but visual adjustment has reduced the fast shear-wave arrival by one sample, and reduced the slow shear-wave by 5 samples. The polarisation has changed from 86 to 87 and the time-delay from 100 to 140 ms. (e) Screen image [fast/slow]: showing the adjusted difference in fast and slow shear-wave picks. Both fast and slow picks now start at the larger signals and there is comparatively little noise before the slow component.
Fig. 2.
Fig. 2. (Continued)
2. An expert system for automatic identification and measurement

The first step with SWAS is to automatically identify and measure shear-wave polarisations and arrivals of fast and slow shear-waves by the expert system (ES) briefly discussed in Appendix A and at greater length by Hao et al. (2006). Due to the complexity of shear-wave splitting (Crampin et al., 2004; Crampin and Gao, 2006), the ES analysis requires the two-stage process indicated in the flow chart in Fig. 1.

Using earthquake location parameters and P- and S-wave arrival-times from the SIL seismic catalogue, the ES determines good first-approximations of the polarisation of the fast shear-wave and the arrival times of the fast and slow split-shear-wave (and hence time-delays) for earthquakes within the shear-wave window (Booth and Crampin, 1985) of each seismic station. The procedure is that an initial set of expert rules determines a set of polarisation and fast and slow phase arrival-times (Fig. 1). This preliminary set of results is then evaluated and optimised by a second set of expert rules and the quality of the final measurement accessed. If the ES calculation is acceptable, SWAS allows measurements to be optimised by user-friendly interaction with screen images as discussed below.

3. Accessing quality of measurements

Accessing the quality of the measurements is crucial in automatically deciding if results are acceptable. In order to determine quality, following Appendix A, we introduce two parameters: where the quality depends principally on the signal-to-noise ratio (see also Hao et al., 2006).

The two qualities are: \( Q_p \), the quality of the polarisation of the fast split shear-wave; \( Q_t \), the quality of the time-delay. There are three grades: \( Q_p, Q_t \), are each equal to 1, 2, or 3, for good, acceptable, or unacceptable, respectively, where unacceptable, \( Q = 3 \), results are rejected.

The basic rules for identifying the quality of shear-wave splitting identifications and measurements are as follows:

1. If the signal-to-noise-ratio, \( r_{sn} \geq c_{rsn1} \), the quality of polarization, \( Q_p \), is set to 1 (\( Q_p = 1 \)), and if \( c_{rsn1} > r_{sn} \geq c_{rsn2} \), then \( Q_p = 2 \), where \( c_{rsn1} \) and \( c_{rsn2} \) are two pre-set noise coefficients. In this study of data from the SIL seismic network, we typically set \( c_{rsn1} = 5.0 \) and \( c_{rsn2} = 3 \). If \( r_{sn} \leq c_{rsn2} \), the polarisations are not acceptable, \( Q_p = 3 \), and the earthquake record is rejected.
We also define two parameters: \( d_{\text{bef}} \) is the difference of maximum and minimum values of amplitudes within a similar time window immediately before the arrival of fast shear-wave: and \( d_{\text{aft}} \) is the difference between the maximum and minimum values of amplitude within a 10 point time window (say) immediately after the arrival of fast shear-wave. We also set similar parameters for the slow shear-wave. We set a signal ratio coefficient \( r_d \). In this study of data from the SIL seismic network, we typically set to \( r_d = 2.8 \). If \( d_{\text{aft}}/d_{\text{bef}} \geq r_d, Q_t = 1 \), and if \( d_{\text{aft}}/d_{\text{bef}} < r_d, Q_t = 2 \). If \( Q_t = 1 \) is for both fast and slow shear-waves, the quality of the time-delay is taken as \( Q_t = 1 \), otherwise \( Q_t = 2 \).

4. Automatic picks and visual adjustments

We illustrate the behaviour of SWAS with screen images of two earthquakes processed by SWAS/ES. The SWAS/ES picks of the first earthquake (Fig. 2) require visual adjustment, and the SWAS/ES picks of the second earthquake (Fig. 3) are satisfactory, and do not require adjustment. Earthquake locations and initial P- and S-wave arrivals are taken from the online SIL seismic catalogue.

Headers in the screen images show, where control buttons (referred to as click buttons) are given in square brackets:

1. Left: earthquake, seismogram, and filtering parameters.
2. Centre: top line – SWAS/ES values of polarisation with click buttons for [visual adjustment] and re-assignable quality \( [Q_p = 1, 2] \); bottom line – click-buttons to change screen images between: [origin] original unprocessed seismograms (as in Fig. 2a); [polarisation] polarisation-diagram display of particle motion (Fig. 2c); [fast, slow] seismograms rotated into fast and slow shear-wave directions (Fig. 2b). Polarisation diagrams are sometimes referred to as PDs, or hodograms.
3. Right: SWAS/ES values of fast and slow arrivals with click-buttons for [visual adjustment], and time-delay in ms and re-assignable quality \( [Q_t = 1, 2] \).

4.1. SWAS/ES processing requiring visual adjustment

Fig. 2 shows SWAS/ES analysis of a \( M = 0.25 \) earthquake recorded within the shear-wave window at station SAU in SW Iceland. A click on the [origin] button displays the original data in Fig. 2a with original EW, NS, and vertical seismograms (unprocessed apart from filtering) and horizontal seismograms rotated into radial and transverse directions. These directions are relative to the earthquake location from the SIL seismic catalogue. The estimated P- and S-wave arrival times are also from the SIL seismic catalogue. Note that in this unprocessed data, the SWAS/ES estimated values for polarisation, shear-wave arrival times, and time-delays in the header are blank.

A click on the [fast, slow] button displays the SWAS/ES arrivals in Fig. 2b. Fig. 2b shows the original EW, NS, and vertical seismograms (as in Fig. 2a), where the lower two horizontal seismograms have now been rotated into fast and slow shear-wave polarisations selected by SWAS/ES analysis. The header now shows: SWAS/ES estimated polarisation of \( 86^\circ \) (clockwise from the radial direction) and quality \( Q_p = 1 \); estimated shear-wave arrival times; 140 ms time-delay which is of also of quality \( Q_t = 1 \).

A click on the [polarisation] button displays SWAS/ES picks in the PDs in Fig. 2c. Fig. 2c shows three rows of mutually orthogonal PDs for the time-intervals in Fig. 2(a) and (b), where the bottom line shows particle-motion in the horizontal plane. The large PD displays horizontal particle motion spanning the fast and slow arrivals in the bottom line of the array of PDs above.

Although the quality of the polarisations and time-delays as assessed by SWAS/ES is good (\( Q_p = 1 \) and \( Q_t = 1 \)), visual examination suggests that the SWAS/ES fast and slow picks in Fig. 2b can be improved. The fast arrival on the fast polarisation is not exactly at the beginning of the large (positive) signal suggesting that the fast pick should be slightly earlier. The slow pick also does not start at the beginning of a comparatively large (again positive) signal. This signal shows a small kink in the waveform, very similar to kink in the larger fast arrival. This suggests that the slow pick should be moved several samples earlier. In addition, the particle motion between the fast and slow picks in the large PD in Fig. 2c is not linear.

The PDs clearly show the necessary adjustment. In the control panel at the bottom of the screen display, adjusting the [first point] button to one point earlier, and the [last point] button five points earlier, we get the PD image in Fig. 2d. The particle motion between the fast and slow shear-waves is now much more linear. This results in a minor change in polarisation values from \( 86^\circ \) to \( 87^\circ \), with a more significant \( \sim 30\% \) decrease in time-delay from 140 ms to 100 s. A click on [fast, slow] shows the seismograms in Fig. 2e, where the picks of the fast and slow waves now start at the beginning of the respective signals.
Fig. 3. Screen images from SWAS showing shear-wave splitting analysis of $M = 0.51$ earthquake recorded within the shear-wave window at station FLA in the SIL seismic network in Iceland. (a) Screen image [fast-slow]: showing clear shear-wave splitting identified by SWAS/ES with a small time-delay of 20 ms. (b) Screen image [polarisation]: showing clear abrupt changes in particle-motion directions in column S 2 with linear motion between the fast and slow shear-wave arrivals.
This comparatively simple user-friendly visual interaction has resulted in more satisfactory picks of fast and slow shear-wave arrivals, and a ~30% reduction in the estimated time-delay between the split shear-waves. The parameters of these images are now preserved, and the screen images can be re-examined and parameters re-adjusted whenever it is thought necessary. This procedure applied to these typical records makes visual examination and adjustment a rapid user-friendly procedure taking from a few seconds to 1 or 2 min to process each station seismogram for reliable repeatable measurements.

4.2. SWAS/ES processing not requiring visual adjustment

Fig. 3 shows SWAS/ES analysis of a $M = 0.51$ earthquake recorded within the shear-wave window at station FLA in North Central Iceland. The notation is as in Fig. 2. Fig. 3a shows [fast_slow] seismograms from

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### Table 1
Comparison of ES and visual picks of polarisations of fast shear-waves

| Station code | Number of events (No.) | Accuracy of polarizations $\leq 5^\circ$ | Accuracy of polarizations $\leq 10^\circ$ | Accuracy of polarizations $\leq 15^\circ$ | Accuracy of polarizations $\leq 20^\circ$ | Accuracy of polarizations $\leq 30^\circ$
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SWAS/ES picks (unprocessed original seismograms are not shown). The fast and slow arrivals begin at the start of two large amplitude (negative) signals with a time-delay of 20 ms. A click on [polarisation] shows the PDs in Fig. 3b which show wholly linear motion between the fast and slow arrivals, suggesting that the SWAS/ES analyses are good and that visual adjustment is not required.

Fig. 3 also demonstrates that SWAS/ES can provide high-quality reliable measurements of shear-wave splitting with very small time-delays (in this case two samples, 20 ms). Such small delay-times would be very difficult to measure by other automatic techniques.

5. Accessing effectiveness of SWAS/ES techniques

In order to access the effectiveness of SWAS/ES evaluations with visual adjustments, we analysed 8-months’

Table 2
Comparison of ES and visual picks of fast and slow shear-waves

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<sup>a</sup> FS and SS refer to arrival times of fast and slow split shear-waves, respectively.
data at stations BJA, KRI, SAN, and SAU in SW Iceland, and BRE, FLA, GRI, and HED in North Central Iceland. Between 01 January and 31 August 2004, there were 855 earthquakes, \( M \geq -1.0 \), recorded within the effective shear-wave windows (incidence angle \( \leq 45^\circ \)) at one or more of these eight stations.

Of these records, 525 (61\%) had SWAS/ES qualities \( Q_p, Q_s = 1, 2 \). These were evaluated by both automated and visual analysis techniques. Assuming visual measurements are the most accurate (see the justification in the next sub-section), we evaluate the relative accuracies of SWAS/ES measurements at each of the eight stations in Tables 1 and 2. The tables show percentages of total number of records of SWAS/ES measurements (qualities \( Q_p, Q_s = 1, 2 \)), which differ from visual measurements by a range of ‘errors’. Fig. 4 shows statistical accuracies at three stations with most data BJA, BRE, FLA, and SAU, and the summation for all eight stations.

The SWAS/ES measurements in Tables 1 and 2 and in Fig. 4 are automatic measurements before visual adjustment. In practice, SWAS/ES measurements are always visually examined for possible visual adjustments. The overall pattern of accuracies as percentages of errors in Fig. 4 is remarkably similar at different stations and for the summation of all stations. This suggests that the comparisons are valid, that effects are consistent between different stations, and that the SWAS/ES com-

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**Fig. 4.** Histograms of % accuracies (% match) of SWAS/ES measurements against visual measurements for a range of errors and a range of qualities. The data are earthquake records within shear-wave window from January to August 2004 for \( Q_p, Q_s = 1 \), at stations: (a) BRE; (b) FLA; (c) SAU; (d) all eight stations. The upper plots are errors of fast shear-wave polarizations as % accuracies for a range of errors (in degrees). The lower plots are errors of fast and shear-wave arrivals as % accuracies for a range of errors (in data points). Histograms are cumulative to the right.
5.1. Justification for assumption of accuracy of visual techniques

The accuracy of many seismic measurements is increased by stacking repeated signals and observing the gradual variations as parameters change both spatially and if appropriate temporally. The accuracy of measurements of shear-wave splitting above small earthquakes cannot usually be improved in this way. This is because one of the characteristic features of observations above small earthquakes is the large seemingly random (±80%) scatter in time-delays. Stacking would merely hide this very dominant feature. The scatter cannot be explained by conventional reading errors, location errors, and/or interpretation-of-structure errors, etc. (Volti and Crampin, 2003a,b). The scatter is observed only in shear-wave splitting above small earthquakes. Controlled-source experiments in seismic exploration operations may show abrupt large changes of polarisations and time-delays, typically at interfaces, but away from fault zones, they do not display the large random uniform scatter always observed above small earthquakes (Li and Crampin, 1991; Yardley and Crampin, 1993). The only viable explanation is that there are critically high pore-fluid pressures on all seismically active fault zones. Such high pore-fluid pressures re-orient micro-crack geometry away from the regional stress directions and cause 90°-flips in shear-wave polarisations (Crampin and Zatsepin, 1997). The behaviour can be modelled and Crampin et al. (2004) show that small differences in the ratio of the lengths of high-pressure ray paths near the fault (with negative time-delays) to the lengths of normally pressured paths to the recorders on the surface (with positive time delays), can easily cause the ±80% scatter in time-delays. These 90°-flips have been confirmed by observations in highly pressurised hydrocarbon reservoirs (Crampin et al., 1996; Angerer et al., 2002), and above major seismically active faults (Section 6.1).

This means that the time-delays of shear-wave splitting above small earthquakes vary significantly from place-to-place and from time-to-time. These rapid variations are confirmed by observations of polarisation diagrams, as in Figs. 2d and 3b, which typically display extremely complicated behaviour. The complicated behaviour, in polarisation diagrams, is the reason why shear-wave splitting is so hard to measure automatically. Whereas, visual observations, particularly the SWAS/ES comparison between radial and transverse seismograms, preferred anisotropic polarisations, and PDs, in Fig. 2, say, can respond to complicated patterns, where the key phenomena are the abrupt, nearly 90°, changes in particle-motion directions marking the

Fig. 5. Comparison of: equal-area polar diagrams out to the effective shear-wave window of 45° of SWAS/ES automatic measurements of shear-wave polarisations (upper diagrams); visual measurements (lower diagrams). The data are earthquake records within an effective shear-wave window of 45° from January to August 2004 with $Q_p, Q_t = 1$ at stations: (a) BJA; (b) BRE; (c) FLA; (d) SAU. The bars (constant-length) are individual polarisations which are summed in equal-area normalised rose diagrams.
onsets of approximately orthogonally polarised shear-waves. These abrupt changes in direction are typically so distinct (in the SIL data in Iceland, as in the Figs. 2d and 3b), and the rotated seismograms show such clear shear-wave splitting (as in Figs. 2e and 3a), that we suggest that question of subjectivity does not arise. Data from other seismic networks may not be so distinctive.

6. Comparing SWAS/ES and visual measurements

6.1. Comparing polarisations

SWAS/ES and visual measurements of polarisations for the period from January to August 2004 are compared in the polar plots in Fig. 5. Fig. 5 shows indi-

![Fig. 6. Comparison of time-delays of shear-wave splitting between the SWAS/ES automatic measurements (upper diagrams) and visual measurements (lower diagrams). The data are earthquake records from January to August 2004 at stations: (a) BJA. (b) BRE; (c) FLA; (d) SAU. Each diagram shows variations of three quantities for the first 8 months for the year 2004. The lower section shows times and magnitudes (0.0 ≤ M ≤ 4.0) of earthquakes within 20 km of each station. The uppermost two sections show time-delays normalised to ms/km. The middle section is for ray paths within band-1 of the shear-wave window (Crampin, 1999), the range of ray paths sensitive to variations in crack aspect-ratios. The uppermost section is for ray paths within band-2 sensitive principally to crack density. The lines are nine-point moving averages.](image-url)
vidual arrivals, at the four seismic stations with most data (BJA, BRE, FLA, SAU), as bars in equal-area rose-diagrams. As the histograms in Fig. 4 suggest, the match of SWAS/ED and visual measurements of polarisations is very good. As is typical elsewhere (Volti and Crampin, 2003a,b), the polarisations at each station are generally parallel and show comparatively little scatter about an azimuthal direction.

Fig. 5 shows two nearly orthogonal preferred directions. The shear-wave polarisations at almost all stations in Iceland are approximately NE-SW as at stations BJA and SAU (Fig. 5a and d). The only exceptions are at stations BRE, FLA (Fig. 5b and c), and HED, which are immediately above the major Húsavik-Flatey Fault, HFF, a transform fault of the Mid-Atlantic Ridge, that runs onshore in northern Iceland. Major faults such as the San Andreas and San Jacinto Faults in Southern California, and the HFF typically display fault-parallel shear-wave polarisations for seismic stations immediately above the fault (Liu et al., 1997; Peacock et al., 1988; Crampin et al., 2003; respectively). These are caused by 90°-flips in shear-wave polarisations as a result of critically high pore-fluid pressures on all seismically active faults which, for these major faults, persist close to the surface.
so that the 90°-flips are observed on surface recorders (Crampin et al., 2002). On smaller faults, these 90°-flips lead to the widely observed ± 80% scatter in time-delays (Crampin et al., 2004). See discussion in Section 5.1.

6.2. Comparing time-delays

SWAS/ES and visual measurements of time-delays for the period January to August 2004 are compared in Fig. 6 for the seismic stations with most data. The time-delays are divided into two groups by the ray path directions within the shear-wave window. Band-1 is the double-leaved solid angle of ray path directions making angles between 15° and 45° either side of the average crack plane. Band-2 is in ray path directions within the solid angle 15° either side of the average crack plane. Band-1 directions are sensitive to crack aspect-ratio, whereas Band-2 directions are sensitive principally to crack density (Crampin, 1999).

Upper diagrams show SWAS/ES measurements and lower diagrams show visual adjustments. Although individual measurements may differ, the general pattern of individual time-delays of SWAS/ES and visual measurements is very similar.

7. Conclusions

We have developed a semi-automatic shear-wave analysis system, SWAS, using an expert system to derive good, sometimes exact, first approximations to the polarisations and fast and slow shear-wave arrivals, that are good enough to facilitate simple visual adjustments. The visual adjustments are easily made by flipping between: screen images of original seismograms rotated into radial and transverse directions; images of fast and slow shear-wave polarisations; images of particle-motion diagrams or PDs. This speeds up visual examination by factors of one or two orders of magnitude. Although the SWAS/ES analysis was developed for and tested on data from small earthquakes \( M \geq -1.0 \) recorded by the SIL seismic network in Iceland, potentially SWAS/ES could be applied to any seismic network data of small earthquakes.

Figs. 2 and 3 demonstrate the easy visual assessment and adjustment of SWAS/ES measurements. Tables 1 and 2 and Figs. 4–6 suggest reliable measurements of polarisations and time-delays can be obtained from the majority of earthquake records with adequate signal-to-noise ratios, where SWAS/ES qualities of polarisations and time-delays are respectively, \( Q_p \) and \( Q_t = 1, 2 \) (for good, and acceptable, respectively). The summary in Table 3 indicates that 77% of all records at all stations could be processed satisfactory with quality \( Q_p \) and \( Q_t = 1, 2 \). Note that had the two particularly noisy stations FLA (on a small island immediately over the HFF) and GRI (also on a small island) been excluded the success rate would have risen to 85%. Consequently, the combination of SWAS/ES for initial estimates, and visual adjustment for optimisation, means that analysis and measurement of shear-wave splitting is now, in principle, comparatively straightforward and rapid.

Visual analysis of the earthquake in Fig. 2 changed the fast arrival by one data point (−0.01 s) and the slow wave by five points (−0.05 s), and obtained, what are believed to be, very reliable measurements of polarisations and time-delays. Changing arrivals by five points is outside the limit of time-delay errors in Fig. 4, whose limit is changes of three data points to fast and slow arrivals. We find that virtually all earthquake signals, which SWAS/ES initially assesses as of quality \( Q_p \) and \( Q_t = 1, 2 \), can be visually adjusted to provide meaningful measurements of polarisations and time-delays. In Iceland, this is about 80% of all earthquakes within the shear-wave window.

SWAS is a user-friendly analysis system for measuring shear-wave splitting, which combines the benefits of automatic identifications, which are, typically sufficiently close to optimum values so that the visual adjustments are minimal, and easy to make. The complexity of PDs (as in Figs. 2c and 3b), and the unavoidable high-degree of scattering (Crampin et al., 2004) suggest that wholly automatic measurements are never possible (Crampin and Gao, 2006). Consequently, SWAS/ES
measurements, where automatic measurements are easily visually adjusted, is probably the best solution that can be expected for routinely measuring shear-wave splitting above small earthquakes.

Acknowledgements

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Appendix A. An expert system for measuring shear-wave splitting

This Appendix presents an expert system, ES, for picking polarisations, and fast and slow split shear-wave arrivals, and hence time-delays. See Hao et al. (2006) for the details of this application of ES. ES analyses are computer techniques using rule-based algorithms for providing expertise in particular topics (Jackson, 1990). ES have been used for earthquake hazard assessment (Zhu et al., 1996), and for identifying seismic phase arrivals (Tong and Kennett, 1996). However, ES and other artificial intelligence, AI, techniques, although intended to solve problems in particularly complicated phenomena, are usually not wholly successful, and are probably only appropriate when other techniques are ineffective. Such AI techniques for measuring shear-wave splitting are currently only suitable for records with near ‘classic’ examples of orthogonally polarised impulsive shear-wave splitting (Crampin and Gao, 2006). Here we develop a widely applicable ES for identifying and measuring shear-wave splitting.

A three-component record of an earthquake is first processed by the expert rules, given below (for the flow chart in Fig. 1), developed from specific knowledge of shear-wave splitting. Preliminary determination of the two principle parameters, the polarisation of fast split shear-wave and the time-delay between the fast and slow shear-waves, are obtained from the initial ES calculations. The results are again processed by expert rules until the output stabilises. Finally the results are evaluated to decide whether the ES estimations are acceptable.

A.1. Initial identification of shear-wave splitting

A.1.1. Initial expert rules: approximate polarisation of fast shear-wave

To operate the ES analysis scheme, we require both the time of the shear-wave phase and the earthquake hypocentral position. We developed SWAS to operate on data from the SIL seismic network in Iceland (Stefánsson et al., 1993), where shear-wave arrival times and earthquake locations are available from the online earthquake catalogue.

In order to identify the initial shear-wave polarisation, we consider two-dimensional motion of a shear-wave arrival in the horizontal plane. For the vector amplitudes of each earthquake, we define two basic quantities, $n_{\text{max}}$, the maximum value of amplitude of the noise for a time window (BTW) before the shear-wave arrival, and $s_{\text{max}}$, the maximum value of shear-wave amplitude in a time window (ATW) after the initial shear-wave arrival. For each earthquake, we define a threshold parameter, $V_{\text{eq}}$:

$$V_{\text{eq}} = \max(c_{\text{bef}}s_{\text{max}}, s_{\text{max}}/c_{\text{aft}});$$

(A1)

where $c_{\text{bef}}$ and $c_{\text{aft}}$ are two coefficients, $c_{\text{bef}} > 1$ and $c_{\text{aft}} > 1$, chosen by experience for each particular seismic station. The coefficients $c_{\text{bef}}$ and $c_{\text{aft}}$ are usually different for different seismic stations, because of the particular geology and geophysical structure surrounding each station.

The shear-wave has arrived when the amplitude becomes greater than $V_{\text{eq}}$. We take B as the three-component seismogram data point immediately after the signal has exceeded $V_{\text{eq}}$. We define data point A as the point in BTW before B, which is nearest to the average value of data in BTW. The approximate value of the shear-wave polarisation, $\varphi_0$, of fast shear-wave is the direction $A \rightarrow B$.

A.1.2. Initial expert system rules: approximate arrivals of fast and slow shear-waves

The horizontal-components of seismogram are rotated parallel and orthogonal to $\varphi_0$, to separate the waveforms of the fast and slow split shear-waves. The fast component within BTW contains a number of cycles of motion where each half-cycle we number sequential $j = 1$ to $k_{\text{bef}}$, say, for each peak-to-trough each with amplitude $a$. Similarly the cycles of motion in ATW are numbered $j = 1$ to $k_{\text{aft}}$. The value of $a$ before the shear-wave arrival is defined as $a_{\text{bef}}$ and the value of $a$ after shear-wave arrival as $a_{\text{aft}}$. The maximum of $a_{\text{bef}}$ within time window BTW and the maximum of $a_{\text{aft}}$ within time window ATW can be written as:

$$A_w = \max(a_w1, a_w2, \ldots, a_wj, \ldots, a_wk),$$

$$A_w = \text{bef and aft, } j = 1, \ldots, k_w;$$

(A2)

where $k_{\text{bef}}$ and $k_{\text{aft}}$ are the number of peaks and troughs the windows BTW and ATW, respectively.
A.1.2.1. ES rules for approximate arrivals of fast and slow shear-waves. The fast shear-wave arrives only when $a$ is larger than the appropriate threshold, $H$. The initial threshold is defined as $H_0$:

$$H_0 = c_i A_{aft}, \quad (0 < c_i < 1; \ i = 1 \text{ or } i = 2); \quad (A3)$$

where $c_i$, chosen by experience, are coefficients for $i = 1$ or $i = 2$, for fast and slow split shear-wave, respectively. The coefficients $c_1$ and $c_2$ may be different for different seismic station records. For the initial calculation or evaluation, let $H = H_0$.

A.1.2.2. ES rules for evaluation of fast and slow shear-wave arrivals. In order to improve arrival times we update the threshold values for the fast and slow shear-waves by the next three rules. We define two constant coefficients, $\gamma_1$ and $\gamma_2$ and $(0 < \gamma_1 < \gamma_2)$ in rule 1, two further constant coefficients, $\gamma_m$ and $\gamma_t$ in rules 2 and 3, and:

$$\gamma = H_t / A_{bef}; \quad (A4)$$

where $H_t$ is the current $H$ value; $H_{t+1}$ is the next calculated of $H$.

The three rules are:

(1) If $\gamma < \gamma_1$, let

$$H_{t+1} = \gamma_1 A_{bef}; \quad (A5)$$

and if $\gamma > \gamma_2$, let:

$$H_{t+1} = \gamma_2 (A_{bef} + \eta H_t); \quad (A6)$$

where the constant coefficient $\eta$, chosen by experience, that meets the condition, $0 < \eta < 1$.

(2) If $H_t > A_{aft}$, let:

$$H_t = \gamma_m A_{aft}, \quad (0 < \gamma_m < 1); \quad (A7)$$

(3) If $a_{wj} > H_t$, $(w = bef \text{ or } w = aft; j = 1, 2, k)$, and

$$a_{w(j-1)} > \gamma_t H_t, \quad (0 < \gamma_t < 1); \quad (A8)$$

and the threshold has been up-dated. The initial arrival of the fast shear-wave is within the half-cycle $j - 1$. A similar rule also applies for the slow shear-wave.

The next two rules chose the best estimates of the shear-wave arrivals relative to these new thresholds.

(4) In order to up-date arrivals of the fast and slow shear-waves, we define the absolute value of some data point, $i$, within the $j$th half-cycle as $x_{j,i}$. If $a_{wi} > H_t$, and:

$$x_{j,1} > c_{spe} n_{\max}, \ (c_{spe} > 1); \quad (A9)$$

where $c_{spe}$ is a coefficient which may be different at different seismic stations, then the arrival of fast shear-wave is within the last vibration, that is the vibration $(j-1)$. A similar rule applies to the slow split shear-wave.

(5) If $x_{j,1} \leq n_{\max}$, move the sample point forward sequentially to the point $i$ where $x_{j,i} \leq n_{\max}$, but $x_{j,i+1} > n_{\max}$. We define this point $i$ as point $C$, and use a new time window NBTW, with the same length as BTW but ending at $C$.

We analyse the polarisation directions of every point from the start of the window NBTW to point $C$ and decide which point is the arrival of the fast shear-wave. In order to objectively obtain the fast split shear-wave arrival, we define a new parameter $p$:

$$p = \sum_{i = \text{start}}^{\text{end}} Z_{\text{amp}}(i) \{\beta - \text{abs}[\varphi(i) - \varphi_0]\}; \quad (A10)$$

where start advances sequentially until reaching the point before $C$ and end is point $C$; $Z_{\text{amp}}(i)$ is the absolute value of the amplitude difference between point, $i$, and point $i-1$; $\beta$ is an acceptable range of angle errors; $\varphi(i)$ is the vibration direction of every point, and $\varphi_0$ is the initial value of the polarisation of the fast shear-wave. The point with the largest value of $p$, named $D$, is taken as the arrival of the fast split shear-wave.

Eq. (A10) is also suitable for the slow split shear-wave, where $\varphi_0$ is now the initial value of the polarisation of slow shear-wave. In Eq. (A10), start is the first data point in time window NBTW, the value of end advances sequentially from the second data point in NBTW to the end point $C$. With same rule as Eq. (A10), the largest value of $p$ is immediately before the arrival of the slow shear-wave at point $D$.

Following these five measurement rules, we obtain preliminary approximate arrivals of fast and slow shear-waves.

A.2. Accurate identification of shear-wave splitting

Having obtained approximate arrivals of the fast and slow split shear-waves from expert rules – 1 in the ES evaluation scheme, Fig. 1, we proceed to the second stage of evaluation and repeat the Expert Rules for improving the estimations of the polarisation of fast shear-wave, and the arrival times of the fast and slow split shear-waves. The ES scheme repeats this process until the values stabilise. These values usually lead to a good automatic evaluations of the polarisation of the fast split shear-wave and the time-delay between the split shear-wave arrivals.
Some additional rules are applied in this second application of ES rules.

(1) If the arrival of slow shear-wave is later than that of fast shear-wave, the result is acceptable, and ES then continues with the rule 2, below. However, application of the ES rules in Section 2, above, may disturb the order of fast and slow shear-waves. If the arrival of the selected ‘slow’ shear-wave is earlier than the ‘fast’ shear-wave, the program rotates the two horizontal components by 90°. Using the new polarisation, the arrivals of fast and slow shear-waves are re-calculated. If new rotated arrival of slow shear-wave is still earlier than new arrival of fast shear-wave, the data is considered to be unacceptable and will be rejected for further analysis.

(2) If the ratio of signal-to-noise $r_{sn}$ is smaller, at any evaluation step, than some specific reference value $c_{rsn2} = 3.0$, say, chosen by experience, the data is considered to be unacceptable and will be rejected for further analysis.

(3) If the arrival of the slow shear-wave is earlier than the fast shear-wave at the conclusion of the second application of ES rules, the data is considered to be unacceptable and will be rejected for further analysis. (This an escape clause for the occasional perverse data set.) Sometimes, more complicated waveforms will result in incorrect identification, and a further rule is required.

(4) Define a new coefficient, $c_k$:

$$k_1(i) = [x(i) - x(m + 1)]/(i - m - 1);$$
$$k_2(i) = [x(n - 1) - x(i)]/(n - 1 - i);$$
$$c_k(i) = \text{abs}\{k_1(i)/k_2(i)\};$$

for $(i = m + 2, \; m = 3, \ldots, n - 3, n - 2);$ 

(A11)

where $x(i)$ is the amplitude of point $i$. If the maximum of $c_k(i)$ is greater than some specific value, $c_H$, that is:

$$\max[c_k(m + 2), c_k(m + 3), \ldots, c_k(n - 2)] > c_H.$$ 

(A12)

After using the rules in Section 2, ES may obtain, say, a shear-wave arrival at the point $m$ in Fig. A1a. However, the preferred true shear-wave arrival should be at point $k$ as in Fig. A1b.

The sample point with the maximum $c_k(i)$ is the arrival of fast (or slow) split shear-wave. Otherwise, the arrival of fast (or slow) split shear-wave is point $m$ (Fig. A1a).

After second stage of calculation and evaluation, the ES produces the best estimates of the polarisations of fast shear-wave and the shear-wave splitting time delays and we need to judge the quality of the estimates.

A.3. Identifying quality of shear-wave splitting

In order to discriminate between different qualities of ES measurements of shear-wave splitting, we introduce two parameters $Q_p$ and $Q_t$ specifying the quality of the measurements of shear-wave splitting. We assume three grades of quality: $Q_p, Q_t = 1, 2, 3$ for good, acceptable, or unacceptable, respectively. The $Q_p$ is related to the ES identification on polarization of fast shear-wave, and $Q_t$ is related to ES identification on arrival of fast shear-wave and arrival of slow shear-wave, and hence the quality of the time-delay.

We define two values specifying, $c_{rsn1}$ and $c_{rsn2}$, good and acceptable signal-to-noise ratios, $r_{sn}$, respectively.

(1) If the ratio of signal-to-noise, $r_{sn}$, is larger or equal than the reference value, $c_{rsn1}$, $(r_{sn} \geq c_{rsn1})$, the quality of the polarization is set equal to 1 $(Q_p = 1)$. If $c_{rsn2} \leq r_{sn} \leq c_{rsn1}$, then $Q_p = 2$. Note, we typically select $c_{rsn2} = 3.0$ and $c_{rsn1} = 5.0$ in this study of seismic records in Iceland.

(2) We define two parameters $d_{\text{after}}$ and $d_{\text{before}}$. The difference of maximum value and minimum value of

![Fig. A1.](attachment:fig_a1.png)
amplitudes within a time window, 10 points, say, immediately after arrival of fast shear-wave is taken as \( d_{\text{fast}} \), and the difference of maximum and minimum values of amplitudes within same time window immediately before arrival of fast shear-wave is \( d_{\text{bef}} \). If \( d_{\text{fast}}/d_{\text{bef}} \geq r_d \), \( Q_t \) is set to 1. If \( d_{\text{fast}}/d_{\text{bef}} < r_d \), \( Q_t = 2 \), where \( r_d \) is a ratio coefficient, set by experience (2.8 in this study). We also use the same two parameters for the slow shear-wave. If \( Q_t = 1 \) for both fast and slow shear-waves, the identifying quality of the time-delay is set to 1.

A.4. Calculation of polarisation of fast shear-wave

The polarisation of the fast shear-wave, \( \Phi \), is calculated by weighting the vibration direction of every point in the time-delay by the amplitude difference in the polarisation diagrams. We have:

\[
\phi = \frac{\sum_i Z_{\text{amp}}(i)\varphi(i)}{\sum_i Z_{\text{amp}}(i)}; \quad (A13)
\]

where \( Z_{\text{amp}}(i) \) and \( \varphi(i) \) are defined in Eq. (A10); \( i \) is summed over time samples in the fast split shear-wave before the arrival of the slow wave.

A.5. Conclusions

We have shown that the ES technique is effective in identifying and measuring shear-wave splitting. Tables 1 and 2 show that:

(1) The polarisation measurements are satisfactory for \( \sim 80\% \) of earthquake records with errors less than 15\(^\circ\).
(2) The phase arrivals of fast and slow shear-waves (and consequently time-delays) are satisfactory at 64\% for errors of \( \pm 3 \) data points, and provide reliable initial values for further visual adjustment.
(3) The accuracies suggest that the ES measurements are not over-sensitive to quality factors. As long as the records are acceptable (\( Q_p, Q_t = 1, 2 \)), both polarisations and time-delays can be easily be optimised by visual adjustment. The ES technique provides polarisations, shear-wave arrival times, and hence time-delays, for initial values for visual adjustment in SWAS. Note that visual adjustments of all \( Q_p, Q_t = 1, 2 \) records give acceptable measurements. Only earthquake records with \( Q_p \) and/or \( Q_t = 3 \), typically the result of low signal-to-noise ratios, are rejected.

References


