Computers & Geosciences 40 (2012) 138–145

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Splitting parameter yield (SPY): A program for semiautomatic analysis of shear-wave splitting

Lucia Zaccarelli [a,*], Francesca Bianco [a], Riccardo Zaccarelli [b]

[a] Istituto Nazionale di Geofisica e Vulcanologia, sezione di Napoli "Osservatorio Vesuviano", Italy
[b] Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingènieur, Orsay (Paris), France

ARTICLE INFO

Article history:
Received 5 March 2010
Received in revised form
7 June 2011
Accepted 3 August 2011
Available online 27 August 2011

Keywords:
Crustal anisotropy
Waveform analysis
Seismic monitoring
Stress field

ABSTRACT

SPY is a Matlab algorithm that analyzes seismic waveforms in a semiautomatic way, providing estimates of the two observables of the anisotropy: the shear-wave splitting parameters. We chose to exploit those computational processes that require less intervention by the user, gaining objectivity and reliability as a result. The algorithm joins the covariance matrix and the cross-correlation techniques, and all the computation steps are interspersed by several automatic checks intended to verify the reliability of the yields. The resulting semiautomation generates two new advantages in the field of anisotropy studies: handling a huge amount of data at the same time, and comparing different yields. From this perspective, SPY has been developed in the Matlab environment, which is widespread, versatile, and user-friendly. Our intention is to provide the scientific community with a new monitoring tool for tracking the temporal variations of the crustal stress field.

1. Introduction

Shear-wave splitting is the elastic analogue of the birefringence phenomenon: a shear-wave entering an anisotropic volume is split into two perpendicularly polarized waves that travel with different velocities (see Fig. 1). The polarization direction of the faster wave and the time delay between the two split shear-waves are the two measurable effects of anisotropy along the volume sampled by the seismic ray (e.g., Crampin and Peacock, 2008, and references therein).

Seismic anisotropy has been detected all over the world independent of the geological setting, either in the crust or mantle, through the analysis of *S* or *S*-converted phases, respectively. In the first case, almost vertical seismic rays are influenced by a hexagonal anisotropy with a horizontal axis of symmetry. One of the major causes for this kind of anisotropic system has been identified as the presence in the crust of vertical penny-shaped fluid-filled microcracks that open along the direction of minimum horizontal stress (Crampin and Peacock, 2008). On the other hand, SKS splitting parameters depend on mantle anisotropy, which is due essentially to crystals or lattice preferred orientation. Therefore, SKS study may be informative of mantle flow and geodynamic processes (Silver, 1996). Here, we concentrate on direct *S*-wave analysis, since our interest is in tracking the stress field evolution on a shorter time scale and to investigate how it changes the seismic propagation characteristics of the crust. Significant variations of the crustal anisotropy characteristics have been observed before/after the occurrence of critical events such as earthquakes (Crampin et al., 1999) or eruptions (Bianco et al., 2006; Gerst and Savage, 2004). Consequently, the temporal evaluation of the splitting parameters can be regarded as a new monitoring tool (Gerst and Savage, 2004; Teanby et al., 2004a), especially for volcanoes, which are well-constrained geographic areas. For this purpose, it would be necessary to supply the monitoring systems with software able to provide splitting parameter estimates routinely. SPY is a first attempt to answer this need, since it has been projected for managing even a huge number of data in a semiautomatic way. Furthermore, it may work in quasi-real time when coupled to a seismic network and a monitoring system that performs automatic pickings and locations, such as those operating in many volcano observatories.

2. SPY philosophy

The master idea is to provide a background tool for getting homogeneous estimates (suitable for comparison) on different datasets. Therefore, we conceived a program that is able to ensure widespread applicability together with maximum reliability of the results. First of all, we made use of the Matlab environment (The Mathworks, Inc., 2011), which is widespread, user-friendly, provided with easy graphic interfaces, and above all, system-independent (we tested SPY correct functionality on Linux, Mac, and Windows OS). We also considered SAC (Seismic Analysis

* Correspondence to: Institut de Physique du Globe de Paris, Paris, France.
E-mail address: zaccarelli@ipgp.fr (L. Zaccarelli).

0098-3004/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cageo.2011.08.006

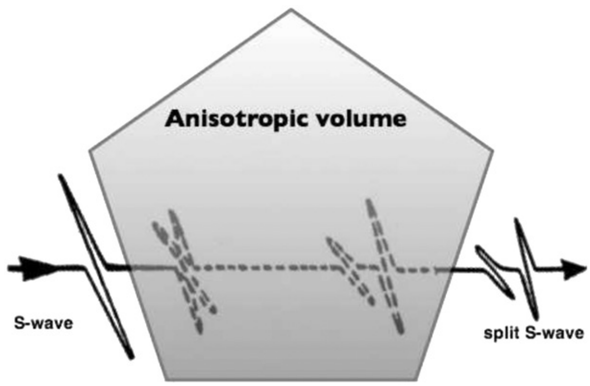

Fig. 1. Shear-wave splitting of an *S*-wave when entering an anisotropic medium. Fast and slow split waves are perpendicularly polarized.

Code by Goldstein and Snoke, 2005) file input by default, as it is one of the most popular standard file formats for seismic waveforms. Finally, we intended to gain objectivity through a semiautomatic analysis where the whole processing is executed by the program by simply providing as inputs the 3-component waveforms, their *P* and *S* pickings, and the event locations. Moreover, SPY has been supplied with many different checks for the goodness of each analysis step, which take the place of subjective validation of the measures operated by the user.

Among the several techniques existing in the literature, we excluded all the display techniques that require expert eye guidance. Following Crampin and Gao (2006)'s designation, the automatic techniques include cross correlation, aspect ratio, linearity interval, covariance matrix, and single-value decomposition. Each one presents its weakness based either on its leading assumption, e.g., the similarity of the two split shear-waves (cross-correlation technique) or their orthogonality (linearity methods), or on the window choice for the analysis (covariance matrix techniques). We combined the covariance matrix and the cross correlation, thus separating the estimates of the two splitting parameters, exploiting the different qualities of these techniques and allowing discriminated management of the computation phases and accuracies. The covariance matrix technique has the advantage of being independent of both similarity and orthogonality between the waveforms; hence it is the ideal algorithm for retrieving the polarization direction (Jurkevics, 1988). On the other hand, the cross-correlation methodology can provide more precise estimate of time delays, once the horizontal components have been transformed into fast and slow ones (Crampin and Gao, 2006).

Until now only a few attempts at automating the splitting parameter estimates have been performed. Teanby et al. (2004b) realized a cluster analysis to automatically select the optimum window before applying the Silver and Chan (1991) algorithm. Hao et al. (2008) instead exploited an expert system to automatically evaluate the arrival of the split shear-waves. This algorithm is a rule-based computer technique that depends on the definition of many threshold values chosen by experience and that may vary from case to case. Furthermore, the user can make a visual adjustment to any final estimate. Recently, Savage et al. (2010) presented an automatic shear-wave splitting measurement tool for local earthquakes, with the sole manual step of choosing an S arrival time. Their algorithm applies an eigenvalue minimization technique over multiple measurement windows and a cluster analysis able to determine the best solution. But even this new tool needs several parameter values to be set by the guidance of an expert user.

We ideally looked for an algorithm based on a reduced number of fixed parameter values, and thus able to overcome the dependence on user control. The SPY algorithm can be set for the analysis through two separate groups of values, named parameters and options. We emphasize their different meanings: the parameters depend on the common features of the whole data set under study, while the options are linked to the specific resolution required for the results. The parameters are composed of the path to the dataset (Path); the extension of the files to take into account (who); the flag for visual checking (PLOT); the covariance window length for the analysis (T1); the error in the *S*-wave picking (PTS); the year of the measurements (YEAR); the flags for resampling and filtering the signal (RESAMP and FILT); and the window length for testing the goodness of the signal (ISEL). The options are values that the user may require for his/her particular analysis, depending on his/her interest, such as a well-defined cone of incidence angles (SWW); the level of similarity between the two split waves (ROTH); the minimum acceptable time delay (RESOL); or the associated error to the event locations (ERRLOC). A detailed description of all of them has been supplied in Appendixes A and B, while some examples of possible values are discussed in the remainder of the text.

3. Semiautomation achievement

The diagram in Fig. 2 illustrates the algorithm flow chart. A gray background highlights the steps ruled by the user control: input information and optional visual inspections. The algorithm can be divided into four modules, which are shown as squared frameworks in Fig. 2: data check; computation; result check; and statistics. All of them are executed automatically, eventually

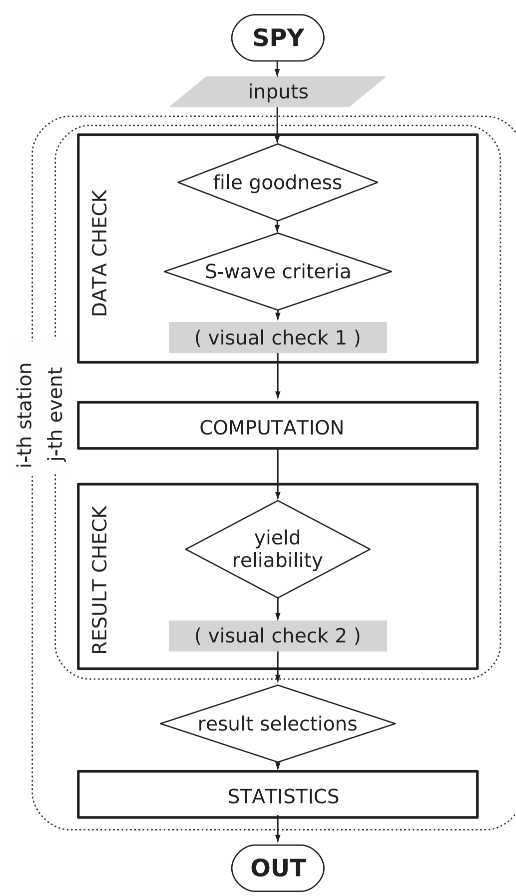

Fig. 2. SPY flow chart algorithm. A gray background highlights the user-dependent operations: input value definitions and the two optional visual checks. A square identifies each of the four moduli, while the diamond-shaped steps visualize the automatic checks. All operations are executed inside the loops over available events and/or stations (dotted lines).