Three-component processing and analysis tools for seismic data in SAC format

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This document outlines the mathematical background of three-component processing and analysis programs that I wrote for SAC binary waveform files (NMSAC). Features of these programs are three-component rotation (Section 1) and amplitude calculations (Section 2), polarization analysis based on the three-component covariance matrix (Section 3), and polarization filtering (Section 4). Programs are documented in Section 5.

1 Component rotation

Multicomponent data recorded by orthogonal sensors can be rotated from one coordinate system $\mathbf{U}$ to another system $\mathbf{W}$ via

$$\mathbf{W} = \underline{\underline{\mathbf{R}}}\mathbf{U} \tag{1}$$

with the rotation matrix $\underline{\underline{\mathbf{R}}}$ and the data vectors $\mathbf{W}$, $\mathbf{U}$ at each time sample. Typically three-component seismic data are recorded in a system consisting of a vertical component Z and of two horizontal components Y and X, e.g. in North and East directions (N, E). If ϕ is the angle from the receiver to the source (backazimuth), the operation

$$\begin{pmatrix} Z \\ R \\ T \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{pmatrix} \begin{pmatrix} Z \\ N \\ E \end{pmatrix} \tag{2}$$

rotates the data horizontally from the initial system (Z, N, E) into the new system (Z, R, T) comprising of the unmodified vertical component Z, a radial component R and a transverse component T. A further rotation around the T axis by an incident angle θ transforms the data into the local ray coordinate system (L, Q, T), in which P-wave energy is concentrated on the L component, SV energy on the Q component, and SH energy on the T component. In the expression

$$\begin{pmatrix} L \\ Q \\ T \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta)\cos(\phi) & -\sin(\theta)\sin(\phi) \\ \sin(\theta) & \cos(\theta)\cos(\phi) & \cos(\theta)\sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{pmatrix} \begin{pmatrix} Z \\ N \\ E \end{pmatrix} \tag{3}$$

the two rotations are combined in a single rotation matrix.

The theoretical backazimuth can be computed from the acquisition geometry. In Cartesian coordinates the backazimuth is given by

$$\phi = \arctan\left(\frac{y_s - y_g}{x_s - x_g}\right) \tag{4}$$

with the source coordinates (x_s, y_s) and the receiver coordinates (x_g, y_g) in units of length. In spherical coordinates the backazimuth can be calculated via

$$\phi = \arctan\left(\frac{\sin(x_s - x_g)\cos(y_s)}{\cos(y_g)\sin(y_s) - \sin(y_g)\cos(y_s)\cos(x_s - x_g)}\right) \tag{5}$$

where (x_s, y_s) represent longitude and latitude of the source and (x_g, y_g) the longitude and latitude of the receiver. The backazimuth may be stored in the SAC header field BAZ, if event and station coordinates are also available in the header. The incidence angle θ depends not only on the acquisition geometry but also on the seismic velocity structure below the receiver.

The program `sacrot3` rotates three-component seismograms by any specified horizontal and vertical rotation angle using Equation 3. Default is a horizontal rotation into (Z, R, T) by $\phi = \mathrm{BAZ} - \mathrm{CMPAZ}$ and $\theta = 0$.

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2 Amplitude parameters

The multicomponent amplitude or the total energy in a moving time window are simple means to visualize a multicomponent seismogram (e.g. Meyer, 1989). The program `sacmamp` can be used to compute the quantities defined in this section.

The absolute amplitude or modulus at each time sample of a three-component seismogram is given by

$$R_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2} \tag{6}$$

(instantaneous resultant). Its square R_i^2 is proportional to the energy of the wave field at the time sample (X_i, Y_i, Z_i). A smoother energy trace is obtained by averaging the energy in a mooving time window of N samples,

$$R_q^2 = \frac{1}{N} \sum_{i=1}^{N} \left(X_i^2 + Y_i^2 + Z_i^2 \right) \tag{7}$$

(quadratic resultant). Its square root R_q is also called the RMS amplitude.

Amplitude or energy ratios provide a different view on a multicomponent seismogram. The ratio between transverse and total energy in a moving time window of N samples is defined as

$$H = \frac{\sum_{i=1}^{N} \left(Q_i^2 + T_i^2 \right)}{\sum_{i=1}^{N} \left(L_i^2 + Q_i^2 + T_i^2 \right)} \tag{8}$$

(Diehl et al., 2009, supplementary material). (L_i, Q_i, T_i) denotes the time sample vector of the three-component seismogram rotated into the ray coordinate system (Section 1). The ratio H has values between zero and one, in particular $H \approx 1$ for the first arriving S-wave and $H \approx 0$ for the first P-wave.

For seismic stations at the surface it may be sufficient to avoid the rotation and to consider the ratio

$$\hat{H} = \frac{\sum_{i=1}^{N} \left(X_i^2 + Y_i^2 \right)}{\sum_{i=1}^{N} \left(X_i^2 + Y_i^2 + Z_i^2 \right)} \tag{9}$$

between horizontal and total energy (Wang and Teng, 1997), because in this case the P-wave energy is often mostly concentrated on the vertical Z-component.

3 Polarization analysis

One property of seismic phases is that of signal polarization. P-waves and S-waves show a high degree of linear polarization, whereas Rayleigh waves are generally elliptically polarized (e.g. Montalbetti and Kanasewich, 1970). Particle motion coincides with the propagation direction for P-waves, and it is perpendicular to the azimuth of propagation for S-waves. Rayleigh wave particle motion is within the vertical-radial plane, and Love waves are polarized in a horizontal plane perpendicular to the propagation direction. Due to signal-generated noise (reflections, scattering), rather a complex particle motion trajectory, the hodograph, is observed in real seismograms instead of pure polarization states. This hodograph can be fit to an ellipsoid in a least-squares sense by means of a covariance analysis (Flinn, 1965; Jurkevics, 1988; Cliet and Dubesset, 1988).

The three-component covariance matrix $\underline{\underline{\mathbf{M}}}$ for a time window of N samples centered around the signal can be written as

$$\underline{\underline{\mathbf{M}}} = \begin{pmatrix} Var(X) & Cov(X,Y) & Cov(X,Z) \\ Cov(Y,X) & Var(Y) & Cov(Y,Z) \\ Cov(Z,X) & Cov(Z,Y) & Var(Z) \end{pmatrix} \tag{10}$$

with the covariances, variances, and mean values

$$\begin{aligned} Cov(X,Y) &= \frac{1}{N}\sum_{i=1}^{N}(X_i-\mu_x)(Y_i-\mu_y) \\ Var(X) &= Cov(X,X) \\ \mu_x &= \frac{1}{N}\sum_{i=1}^{N}X_i \end{aligned}$$

(Montalbetti and Kanasewich, 1970; Kanasewich, 1981; Benhama et al., 1988). Jurkevics (1988) provides an equivalent formulation assuming zero mean values of all components within the time window of N samples. He defines the data matrix $\underline{\underline{\mathbf{X}}} = [X_{ij}]$ with $i = 1 \ldots N$, $j = 1 \ldots 3$, where X_{ij} is the ith sample of the jth component. Then the elements M_{jk} of the covariance matrix $\underline{\underline{\mathbf{M}}}$ can be evaluated as

$$M_{jk} = \frac{1}{N}\underline{\underline{\mathbf{X}\mathbf{X}}}^T = \left[\frac{1}{N}\sum_{i=1}^{N}X_{ij}X_{ik}\right] \tag{11}$$

where T denotes transpose.

The covariance matrix $\underline{\underline{\mathbf{M}}}$ is symmetric, has real non-negative eigenvalues, and its eigenvectors are the principal axes of an ellipsoid that is the best fit to the data in a least-squares sense. The three eigenvectors $\mathbf{V}_j$ and their associated eigenvalues λ_j satisfy the equation

$$\underline{\underline{\mathbf{M}}}\mathbf{V}_j = \lambda_j \mathbf{V}_j \tag{12}$$

which can be solved by Jacobi iteration (e.g. Press et al., 1996). The eigenvectors are orthonormal and unit length ($|\mathbf{V}_j| = 1$), while the length of each axis of the polarization ellipsoid is $\sqrt{\lambda_j}$. The eigenvalues are commonly sorted in decreasing order ($\lambda_1 \geq \lambda_2 \geq \lambda_3$) such that the eigenvector $\mathbf{V}_1$ associated with the largest eigenvalue λ_1 points into the main polarization direction, i.e. the long axis of the ellipsoid. The amplitude $R_e = \sqrt{\lambda_1}$ in the main polarization direction is also termed the eigenresultant.

The choice of the time window length and the frequency bandwidth are subject to trade-offs between resolution and variance (e.g. Wang and Teng, 1997). A short time window and a narrow bandwidth avoid averaging over different phases allow for the resolution of frequency-dependent polarization, whereas a longer window and a wider frequency band yield more stable polarization estimates. The time window (N samples) should include at least one cycle of the dominant signal period (e.g. Cichowicz, 1993). Besides that, any filtering before polarization analysis has to be applied in the same way to all three components and should not distort the signal significantly. Zero-phase bandpass filters are therefore recommended.

Several polarization attributes can be calculated from the eigenvalues and associated eigenvectors. The attributes defined in the following sections describe the main polarization direction and the degree of linear or planar polarization. The attribute names are chosen as in Maercklin (1999).

3.1 Direction of polarization

The direction of polarization is calculated from the components (direction cosines) of the eigenvector $\mathbf{V}_1$. The direction can be described by a horizontal azimuth angle Φ and by the deviation from the vertical direction or apparent incidence angle Θ as

$$\Theta = \arctan\left(\frac{\sqrt{x_1^2+y_1^2}}{z_1}\right) \tag{13}$$

$$\text{or} \quad \Theta = \arccos(|z_1|) \tag{14}$$

$$\text{and} \quad \Phi = \arctan\left(\frac{y_1}{x_1}\right) \quad . \tag{15}$$

Here, x_1 and y_1 denote the two horizontal components of $\mathbf{V}_1$ and z_1 its vertical component. To resolve the 180°-ambiguity of the azimuth angle Φ, Jurkevics (1988) suggests to evaluate the sign of the vertical component of $\mathbf{V}_1$. Instead of using Θ and Φ, Deflandre and Dubesset (1992) characterize the particle motion by the three Eulerian angles precession, nutation, and rotation.

The computed values for Θ and Φ depend on the order and orientation of the three components. For three-component seismograms comprising of one vertical and two horizontal components, e.g. (Z, N, E), the angle Θ gives the incidence angle of the P-wave. If the data are rotated into the ray coordinate system (L, Q, T), the angle Θ can be interpreted as the deflection from the P-wave propagation direction and should reach its maximum for S-waves (e.g. Cichowicz, 1993).

The angles Θ and Φ are usually given in degrees or radians. However, sometimes they are normalized to values between zero and one. Normalized long-axis and short-axis inclination angles can be written as

$$\mathrm{Inc}_1 = \frac{2}{\pi} \arccos(|z_1|) \quad (16)$$

$$\text{and} \quad \mathrm{Inc}_3 = \frac{2}{\pi} \arccos(|z_3|) \quad (17)$$

Wang and Teng (1997). For surface seismic stations and data in the (Z, N, E) or (Z, R, T) system, Inc_1 approaches zero for P-waves and one for S-waves, while Inc_3 shows the opposite behaviour,

The program `sacpolar` calculates the angles Θ and Φ in degrees, and the normalized angular parameters Inc_1 and Inc_3 within a moving time window along the seismogram.

3.2 Shape parameters and degree of polarization

The shape parameters describe the shape of the signal and its degree of linear or planar polarization, sometimes also termed quality of polarization. These parameters do not depend on the coordinate system of the three-component seismogram. It is assumed that the eigenvalues λ_j are sorted in decreasing order. The parameters defined in this section can be computed with the program `sacpolar` in a moving time window. Additional polarization parameters are listed in Section 3.3.

3.2.1 Ellipticities

The ratio between two axes of the polarization ellipsoid is called ellipticity and describes the shape of the ellipsoid. The three ellipticities are defined as

$$\text{principal ellipticity} \quad e_{21} = \sqrt{\frac{\lambda_2}{\lambda_1}} \quad (18)$$

$$\text{subprincipal ellipticity} \quad e_{31} = \sqrt{\frac{\lambda_3}{\lambda_1}} \quad (19)$$

$$\text{transverse ellipticity} \quad e_{32} = \sqrt{\frac{\lambda_3}{\lambda_2}} \quad . \quad (20)$$

The ellipticities have values between zero and one. For purely linear polarization $e_{21} = e_{31} = 0$, and for purely elliptical polarization yields $0 < e_{21} \leq 1$ and $e_{31} = 0$. A large value of e_{32} indicates that the event is unpolarized.

3.2.2 Rectilinearity

The rectilinearity RL is a measure of the degree of linear polarization of an event (Flinn, 1965). Montalbetti and Kanasewich (1970) and Kanasewich (1981) define RL as

$$RL = 1 - \left(\frac{\lambda_2}{\lambda_1}\right)^Q \quad (21)$$

with the two largest eigenvalues $\lambda_1 \geq \lambda_2$. With this definition the range of values is between $RL = 0$ for elliptical or undetermined polarization, and $RL = 1$ for exactly linear polarization. The contrast factor Q determines the sensitivity for certain degrees of polarization. Usually its value is set to $Q \leq 1$.

The rectilinearity definition by Jurkevics (1988) evaluates all three eigenvalues as

$$RL' = 1 - \left(\frac{\lambda_2 + \lambda_3}{2\lambda_1}\right)^Q \quad , \tag{22}$$

where a value of $RL' = 0$ indicates the absence of polarization and $RL' = 1$ again perfect linear polarization.

3.2.3 Global polarization parameter

Another measure of the rectilinearity of a signal is the global polarization parameter τ introduced by Samson (1973). It can be written in terms of ellipticities or in terms of the three eigenvalues as

$$\begin{aligned}
\tau^2 &= \frac{\left(1 - e_{21}^2\right)^2 + \left(1 - e_{31}^2\right)^2 + \left(e_{21}^2 - e_{31}^2\right)^2}{2\left(1 + e_{21}^2 + e_{31}^2\right)^2} \\
\tau^2 &= \frac{\left(1 - \frac{\lambda_2}{\lambda_1}\right)^2 + \left(1 - \frac{\lambda_3}{\lambda_1}\right)^2 + \left(\frac{\lambda_2}{\lambda_1} - \frac{\lambda_3}{\lambda_1}\right)^2}{2\left(1 + \frac{\lambda_2}{\lambda_1} + \frac{\lambda_3}{\lambda_1}\right)^2} \\
\tau^2 &= \frac{\left(\lambda_1 - \lambda_2\right)^2 + \left(\lambda_1 - \lambda_3\right)^2 + \left(\lambda_2 - \lambda_3\right)^2}{2\left(\lambda_1 + \lambda_2 + \lambda_3\right)^2} \quad .
\end{aligned} \tag{23}$$

The global polarization parameter τ has values between zero and one, where a straight line gives $\tau = 1$, a circle $\tau = 0.5$ and a sphere $\tau = 0$. Among others, the parameter τ is also used in Benhama et al. (1988), Cichowicz (1993), and Diehl et al. (2009).

3.2.4 Linearity and flatness coefficients, and planarity

Yet another measure of linear polarization is the linearity coefficient l_1 (Cliet and Dubesset, 1988; Meyer, 1989). In terms of ellipticities it is defined as

$$l_1 = 1 - \frac{3\left(e_{21} + e_{31}\right)}{2\left(1 + e_{21} + e_{31}\right)} \quad . \tag{24}$$

Its range of values is $0 \leq l_1 \leq$ with $l_1 = 1$ for exactly linear polarization, $l_1 = 0.25$ for a flat circle, and $l_1 = 0$ for an undetermined polarization.

The flatness or oblateness coefficient f_1 determines the degree of plane polarization (Benhama et al., 1988). The ground motion trajectory within this plane is not further specified. Like the other shape parameters

$$f_1 = \frac{\sqrt{\lambda_1} + \sqrt{\lambda_2} - 2\sqrt{\lambda_3}}{\sqrt{\lambda_1} + \sqrt{\lambda_2} + \sqrt{\lambda_3}} = 1 - \frac{3e_{31}}{1 + e_{21} + e_{31}} \tag{25}$$

has values between zero and one. In case of planar polarization the flatness coefficient is $f_1 = 1$ and in case of an undetermined polarization $f_1 = 0$.

Jurkevics (1988) describes the degree of planarity by the planarity measure

$$PL = 1 - \frac{2\lambda_3}{\lambda_1 + \lambda_2} \quad , \tag{26}$$

which has the same set of values as the flatness coefficient f_1.

3.3 Additional polarization parameters

Wu and Horiuchi (2008) list some polarization parameters that require the knowledge of the first P-wave vector. With λ_j being the eigenvalues of $\underline{\underline{\mathbf{M}}}$, sorted in decreasing order, an adjusting factor a equal to the largest eigenvalue in the background noise, the first P-wave vector $\mathbf{V}_p$, the eigenvector $\mathbf{V}_1$ and $|\mathbf{V}_p| = |\mathbf{V}_1| = 1$, they define

$$k_p = \frac{\lambda_1 - \lambda_2}{\lambda_1 + a} \tag{27}$$

$$k_1 = \frac{2}{\pi} \arccos\left(|\mathbf{V}_p \cdot \mathbf{V}_1|\right) \tag{28}$$

$$k_2 = \frac{(\lambda_1 - \lambda_3)^2 + (\lambda_2 - \lambda_3)^2}{\lambda_1^2 + \lambda_2^2 + \lambda_3^2 + a^2} \quad . \tag{29}$$

These parameters have values between zero and one. The parameters k_p and k_2 describe the degree of polarization, and k_1 is a normalized deflection angle. An additional parameter is

$$k_3 = 1 - \frac{\sum_{i=1}^{N} |\mathbf{V}_p \cdot \mathbf{U}_i|^2}{\sum_{i=1}^{N} |\mathbf{U}|^2} \tag{30}$$

where $\mathbf{U}_i$ is the three-component data vector at the ith time sample within an N sample long time window. Wu and Horiuchi (2008) use $k_i = k_1^2 \cdot k_3^2 \cdot k_3^2$ in an S-wave detection algorithm.

The experimental program `sacpolwh` computes the parameters defined in this section within a moving time window. Currently, $\mathbf{V}_p$ is taken as the steepest incidence in a short window around the time pick in the SAC header A, and a is estimated from the beginning of the trace.

4 Polarization filter

One parameter for the rectilinearity and for the orientation of the polarization ellipsoid in space can be used to construct a simple polarization filter (Flinn, 1965; Montalbetti and Kanasewich, 1970; Kanasewich, 1981). Such a weighted directivity filter is implemented in the program `sacpofilt`.

First define a weighting function of the form

$$R(t_i) = [F(\lambda_1, \lambda_2, \lambda_3)]^J \tag{31}$$

at each time sample t_i, where $F(\lambda_1, \lambda_2, \lambda_3)$ is a measure of the degree of polarization. This can be for example the rectilinearity RL or RL' (Equations 21 and 22) or the global polarization parameter τ (Equation 23).

As mentioned above, the components of the eigenvector $\mathbf{V}_1$ corresponding to the largest eigenvalue λ_1 determine the direction of polarization (direction cosines). With $|\mathbf{V}_1| = 1$ and $\mathbf{V}_1 = (v_{1x}, v_{1,y}, v_{1,z})$ three directivity functions can be defined as

$$D_j(t_i) = (|v_{i,j}|)^K \tag{32}$$

for each time sample and each component $j = x, y, z$.

A multiplication of $R(t_i)$ and $D_j(t_i)$ with the original data yields the filter result Flinn (1965). However, Montalbetti and Kanasewich (1970) to smooth the filter operators over a time window of length M to minimize contributions of anomalous spikes. The smoothing operators are given by

$$\tilde{R} = \frac{1}{M} \sum_{k=-L}^{L} R(t_i + k) \tag{33}$$

$$\tilde{D}_j = \frac{1}{M} \sum_{k=-L}^{L} D_j(t_i + k) \quad , \tag{34}$$

where $L = (M - 1)/2$ denotes the half window length. Now the filtered data can be written as

$$X_f(t) = X(t)\tilde{R}(t)\tilde{D}_x(t) \quad (35)$$

$$Y_f(t) = Y(t)\tilde{R}(t)\tilde{D}_y(t) \quad (36)$$

$$Z_f(t) = Z(t)\tilde{R}(t)\tilde{D}_z(t) \quad (37)$$

Before an application of the polarization filter the data are typically filtered with a (zero-phase) bandpass. Kanasewich (1981) suggests half of the correlation window length for the smoothing operator length, and for the weighting exponents he suggests $J = 1$ and $K = 2$. Defaults of the program `sacpofilt` are $J = K = 1$ and no smoothing.

5 Software description

The programs `sacrot3`, `sacmamp`, `sacpolar`, `sacpolwh` (experimental code), and `sacpofilt` are part of a small, self-contained collection of tools I wrote to process SAC files (NMSAC). The programs read and write evenly-sampled SAC binary waveform files, assuming NVHDR=6, IFTYPE=ITIME, and LEVEN=1. Input files are listed on the command line (`-f` option). Corresponding output files get the same name plus an additional suffix. Alternatively, the programs can read multichannel data from `stdin` and write to `stdout`. Typing any program name without further arguments prints a short documentation page with parameters and defaults. Relevant pages are reprinted below.

5.1 Component rotation

```
SACROT3 - SAC Rotation of three-component data

Usage: sacrot3 [parameters] -f sac_files
       sacrot3 <stdin [parameters] > stdout

Parameters and defaults:
  -f        list of SAC binary waveform files (or read from stdin)
  -a   BAZ  horizontal rotation angle in degrees (e.g. backazimuth)
  -i   0.0  vertical rotation angle in degrees (e.g. incidence angle)
  -h        flag: horizontal rotation of two-component data
  -o        flag: overwrite input files (default appends ".rot")
  -v        flag: verbose operation

Three subsequent files/traces are considered as one three-component
dataset with common trace length, start time, and sampling rate.
If option "-h" is set, only two subsequent files are considered as
one dataset of two horizontal components.
The first component of each three-component dataset is assumed to
be the vertical component. Output files have the suffix ".rot".
```

5.2 Amplitude parameters

```
SACMAMP - SAC Multicomponent Amplitude or RMS Amplitude calculation

Usage: sacmamp [parameters] -f sac_files
       sacmamp <stdin [parameters] > stdout
```

```
Parameters and defaults:
  -f        list of SAC binary waveform files (or read from stdin)
  -n     3  total number of components (N = 1...6)
  -m     0  if positive, compute ratio (last N-M)/(all N) components
  -w   0.0  RMS time window length in seconds
  -e        flag: write squared-amplitude trace (energy)
  -v        flag: verbose operation

N subsequent files/traces are considered as one N-component dataset
with common trace length, start time, and sampling rate.
Output files have the suffix ".ampN" with N = 1...6.
```

5.3 Polarization analysis

```
SACPOLAR - SAC Polarization analysis of three-component data

Usage: sacpolar [-p] attribute [...] [parameters] -f sac_files
       sacpolar <stdin [-p] attribute [...] [parameters] > stdout

Parameters and defaults:
  -f        list of SAC binary waveform files (or read from stdin)
  -p        list of one or more of the pol. attributes listed below
  -w   0.5  correlation time window length in seconds
  -q   1.0  contrast parameter of rectilinearity RL
  -z        flag: assume zero mean in correlation windows  (faster)
  -v        flag: verbose operation

  -b1    0  Butterworth low-cut frequency in Hz  (0 = no filter)
  -b2    0  Butterworth high-cut frequency in Hz (0 = no filter)
  -bp    3  number of poles of Butterworth filters
  -bz       flag: apply zerophase (two-pass) Butterworth filter

Polarization attributes:
  rl, rl2   rectilinearity RL                            [0, 1]
  tau       global polarization parameter tau            [0, 1]
  l1        linearity coefficient l1                     [0, 1]
  f1, pln   flatness coefficient f1 and planarity        [0, 1]
  inc1,inc3 normalized long- and short-axis inclination  [0, 1]
  theta     vertical polarization angle (incidence)  [   0,  90] deg
  phi, phi1 horizontal polarization angle            [ -90,  90] deg
  phi2      horizontal polarization angle            [-180, 180] deg
  phi3      horizontal polarization angle            [   0, 360] deg
  er        eigenresultant (polarization amplitude)  [   0, inf]

The polarization attributes are computed in a moving time window from
the eigenvalues and the principal eigenvector of the three-component
covariance matrix.
Three subsequent files/traces are considered as one three-component
dataset with common trace length, start time, and sampling rate.
For correct angles, the vertical component has to be the first trace.
Each output file has a suffix corresponding to the attribute name.
```

```
SACPOLWH - SAC Polarization analysis of 3-C data (Wu & Horiuchi, 2008)

Usage: sacpolwh [-p] attribute [...] [parameters] -f sac_files
       sacpolwh <stdin [-p] attribute [...] [parameters] > stdout

Parameters and defaults:
  -f        list of SAC binary waveform files (or read from stdin)
  -p        list of one or more of the polarization attributes
            kp, k1, k2, k3, and ki (ki = k1^2 * k2^2 * k3^2)
  -w   0.5  correlation time window length in seconds
  -z        flag: assume zero mean in correlation windows (faster)
  -v        flag: verbose operation

  -b1    0  Butterworth low-cut frequency in Hz  (0 = no filter)
  -b2    0  Butterworth high-cut frequency in Hz (0 = no filter)
  -bp    3  number of poles of Butterworth filters
  -bz       flag: apply zerophase (two-pass) Butterworth filter

The polarization attributes are computed in a moving time window from
the eigenvalues and the principal eigenvector of the three-component
covariance matrix.
Three subsequent files/traces are considered as one three-component
dataset with common trace length, start time, and sampling rate.
The vertical component must be the first trace, and it must contain
a P-wave arrival pick in the SAC header field A (attributes k1, k3).
Each output file has a suffix corresponding to the attribute name.
```

5.4 Polarization filter

```
SACPOFILT - SAC Polarization filter for three-component data

Usage: sacpofilt [parameters] -f sac_files
       sacpofilt <stdin [parameters] > stdout

Parameters and defaults:
  -f        list of SAC binary waveform files (or read from stdin)
  -w   0.5  correlation time window length in seconds
  -s   0.0  smoothing time window length in seconds
  -p    rl  rectilinearity attribute (rl, rl2, or tau)
  -q   1.0  contrast parameter of rectilinearity RL
  -pe  1.0  exponent of rectilinearity filter function
  -de  1.0  exponent of direction filter function
  -z        flag: assume zero mean in correlation windows (faster)
  -v        flag: verbose operation

  -b1    0  Butterworth low-cut frequency in Hz  (0 = no filter)
  -b2    0  Butterworth high-cut frequency in Hz (0 = no filter)
  -bp    3  number of poles of Butterworth filters
  -bz       flag: apply zerophase (two-pass) Butterworth filter

This is an implementation of the Montalbetti & Kanasewich (1970)
polarization filter.
```

```
Three subsequent files/traces are considered as one three-component
dataset with common trace length, start time, and sampling rate.
Each output file has the suffix ".pflt".
```

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