Polarization filter for multi-component seismic data

D. T. Nguyen, R. J. Brown, and D. C. Lawton

ABSTRACT

The application of three-component seismic data has gained a growing interest in exploration geophysics. The common use of three-component recordings in seismic survey gives access to the real movements of the free surface of the Earth, hence we can deduce the trajectory of this particle displacement which is the response from a complex incoming wavefield. This wavefield is the superposition of body waves and surface waves as well as other disturbances. Conventional filtering processes, such as bandpass filtering, and frequency-wavenumber filtering, are often not very efficient in separating them.

The polarization is characterized by parameters that determine the trajectories of the particle motion of a medium. The trajectories of particle motion are in most cases represented by complex three-dimensional curves. The tracking components of each wave are found by combining the discrimination of waves, based on the direction of propagation, with that according to their type of polarization. The optimum component will correspond to the vector of oscillations.

Polarization filtering of waves based on the combination of characteristics of particle motion at a point, with their direction of propagation in space, makes it possible to separate regular waves with different polarizations propagating in different directions and with different velocities.

INTRODUCTION

In the past, the theory of polarization has been studied in many different fields, such as electromagnetic, optics, and earthquake seismology. With recent advances in seismic field recording, three-component data allows us to study the polarization parameters of a medium to extract more information about the subsurface layers from surface data (Gal'perin, 1977). Many papers have shown that lithology, porosity, anisotropy etc. can be extracted from combined P- and S-wave observations (Meissner and Hegazy, 1981; Helbig and Mesdag, 1982).

Body waves can propagate in practically every direction through the medium, whereas the surface waves are bound to some surface or some layer during their propagation. Besides their way of propagation, the different wave types also have different particle motion and propagation velocities.

The P wave is longitudinal, i.e. particle motion is linearly polarized in the propagation direction. The S wave is tranverse, i.e. particle motion is confined to a plane perpendicular to the direction of propagation. Furthermore the S wave may become split into fast and slow shear waves. Love and Rayleigh waves follow the free surface and the boundaries during their propagation. Love waves cannot exist on a surface of a homogeneous medium, and they require at least one other layer or a velocity increase with depth. Love waves are polarized in the horizontal, transverse direction. For Rayleigh waves, the particle motion is retrograde elliptic, with the plane of the ellipse vertical and lying in the plane of propagation (Bullen, 1963).

With regard to speed of propagation in a homogeneous isotropic medium, the P wave is fastest, followed by the S wave, the Love wave and finally the Rayleigh wave. In multilayer media, the above order may vary due to the fact that surface waves are bound to the low-velocity near-surface layer and the recording geometry. Different SV and SH velocities may exist in an anisotropic medium. The effects of surface-wave velocity dispersion and their higher modes can further complicate the recorded seismogram (Bullen, 1963).

MULTICOMPONENT RECORDING

In three-component seismic exploration, the source energy is propagated from a point (or an array) on the surface or within the low-velocity layer. By using three-component geophones, the incoming complex wavefield is recorded on three component channels, the radial (x-) component, the horizontal (y-) component and the vertical (z-) component (Figure 1).

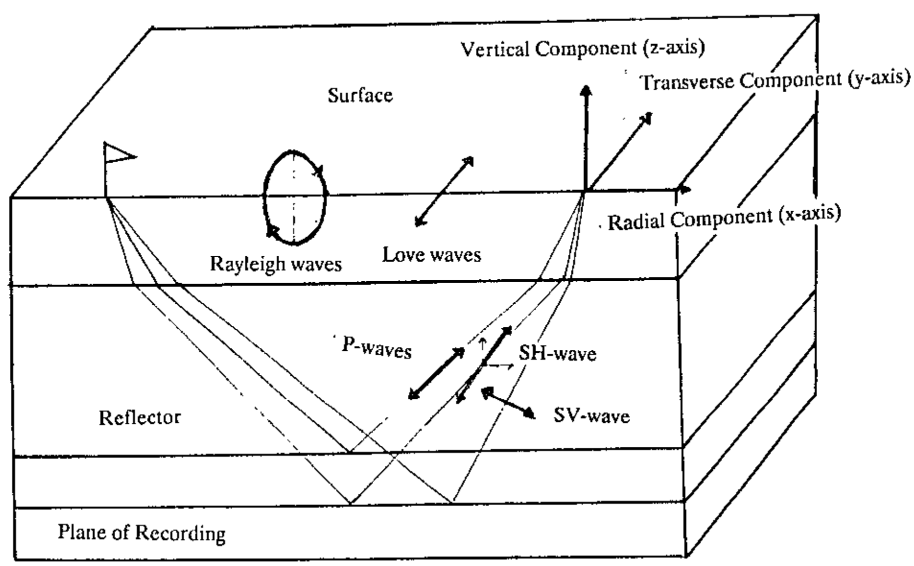
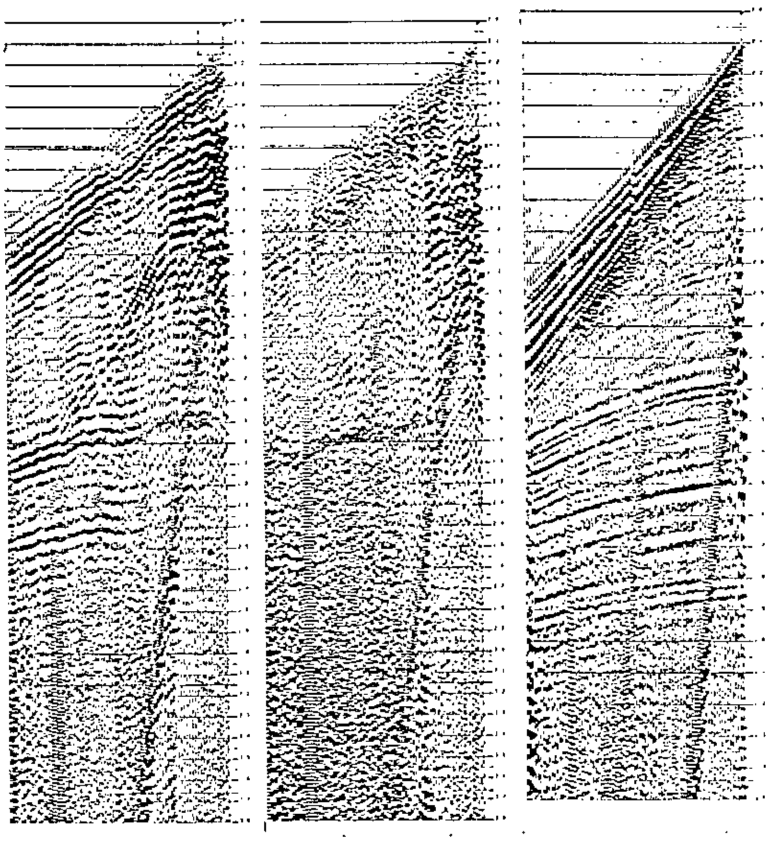


Fig. 1 Polarization of Seismic Waves and Three-Component Geophone Recording

All data recorded by geophysical instruments contain various amounts of noise. The difficulty in ascertaining characteristics of the noise becomes more serious when mulichannel data are involved. Seismograms are generally composed of broadband, time variant and overlapping signals. This can be seen from a shot record of three component data from the Carrot Creek area in Alberta (Figure 2).



(a) (b) (c)

Fig. 2 Three-component seismic data from Carrot Creek

(a) Radial component

(b)Transverse component

(c) Vertical component

PARTICLE TRAJECTORY

In the case of an elastic wave traveling inside a solid medium, there are three possible polarization states, one longitudinal and two transverse in the plane perpendicular to the direction of propagation . In such a case, one can record each of the three polarizations, or any combination of their superposition on any one channel, in addition to elliptically polarized Rayleigh waves and linearly horizontally polarized Love waves and their higher modes. The output trace particle of three-component geophone makes it possible to reconstruct the actual motion of the free surface of the Earth known as the particle trajectory. The particle trajectory is a curve in the three-dimensional space given by its parametrical equations (Cliet and Dubesset, 1987)

$$\begin{aligned} \mathbf{X}_1 &= x(t) \\ \mathbf{X}_2 &= y(t) \\ \mathbf{X}_3 &= z(t) \end{aligned} \tag{1}$$

Where $\mathbf{X}_1$, $\mathbf{X}_2$, $\mathbf{X}_3$ are three orthogonal vectors whose components are the time series of radial, transverse and vertical recording channels from a particular three-component geophone. This curve is in fact the hodogram corresponding to the true trajectory since it describes the terminus of a moving vector as a function of space and time. The hodogram is a useful tool for analysis of time-variant signals; it allows the simultaneous analysis of amplitude, polarization and relative orientation. In practice, a sliding time window whose length have to be greater than or equal to the dominant signal is used (Montalbetti and Kanasewich, 1970).

POLARIZATION ELLIPSOID EQUIVALENT TO THE PARTICLE TRAJECTORY

Consider a short sliding time window of length T, starting from t_1 to t_2, from a digital recording of sample interval s, the number of samples in this time window is denoted by N, Then

$$N = (t_2 - t_1)/s + 1 \tag{2}$$

If the trajectory is considered as a cluster of points of coordinates be the data matrix in one window, where x'_{ij} is the i^{th} sample of jth component and N is the number of samples, and m_j is the mean values of j^{th} channel.

$$Xj = [x'_{ij} - m_j] = [x_{ij}] \quad (i=1,...,N;\ j=1,...,3) \tag{3}$$

The covariance m_{ij} (zero-lag crosscorrelation) is evaluated as:

$$m_{jk} = \mathbf{X}_j^T \mathbf{X}_k / N = \frac{1}{N} \sum_{i=1}^{N} x_{ij} . x_{ik} \tag{4}$$

where ^{T} denotes transpose

If j = k, we have the variance (zero-lag autocorrelation). The covariance matrix $\mathbf{M}_c$ is a 3x3 matrix, real and symmetric. Explicitly, the terms of $\mathbf{M}_c$ are the cross-variances and autovariances of the three components of motion.

$$\mathbf{M}_c = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{5}$$

The covariance matrix is positive definitive, which means the eigenvalues are real and non-negative (some may be zero). This matrix is, in fact, the matrix associated with a quadratic form, namely an ellipsoid, obtained when computing the energy of the cluster of points in relation to the three coordinate planes. This ellipsoid is called the covariance ellipsoid. The covariance matrix is found to be well conditioned in practice because seismic noise and scattering distortions tend to be uncorrelated among three components over a window (Jurkevics, 1988).

The polarization ellipsoid which models the trajectory is not the covariance ellipsoid. It has its semi-axes inverse to those of the covariance ellipsoid and is proportional to the three eigenvalues λ_1, λ_2 and λ_3, of the covariance matrix, where $\lambda_1 \geq \lambda_2 \geq \lambda_3$. Its three principal axes in space are the three normalized eigenvectors , $\mathbf{u}_1$, $\mathbf{u}_2$, $\mathbf{u}_3$ of the covariance matrix. The three eigenvectors define a new Cartesian coordinates (Cliet and Dubesset, 1987).

The corresponding eigenvalues represent the average energies of the seismic event in the three previously defined directions. Purely linear polarization has only one non-zero eigenvalue; purely elliptical has two non-zero eigenvalues. In real application, all three eigenvalues are generally non-zero and non-equal.

Information describing the characteristics of the particle motion is extracted using the attributes computed from the principal axes (Jurkevics, 1988).

The degree of rectilinearity L is defined as:

$$L = 1 - \left(\frac{\lambda_2 + \lambda_3}{\lambda_1}\right)^n \tag{6}$$

which is equal to unity when there is only one non-zero eigenvalue, as for pure body waves. In the case of an elliptical polarized Rayleigh wave, the λ_1 and λ_2 are much greater than λ_3, so their degree of rectilinearity is small, $(L \geq 0.5)$.

The azimuth of a wave A corresponding to the largest eigenvalue λ_1, can be estimated from the orientation of rectilinear motion given by eigenvector $\mathbf{u}_1$:

$$A = \arctan \frac{u_{21} \mathit{sign}\ u_{11}}{u_{31} \mathit{sign}\ u_{11}} \tag{7}$$

where u_{j1}, j = (1, 2, 3) are the three direction cosines of eigenvector $\mathbf{u}_1$.

The *sign* function is introduced to resolve the ambiguity by taking the positive component of $\mathbf{u}_1$. Similarly, the apparent incidence angle of rectilinear motion, I, as measured from the corresponding axis, may be obtained from the corresponding direction cosine of $\mathbf{u}_1$:

$$I = \arccos |u_{11}| \tag{8}$$

In practice, real data show that waves are seldom rectilinearly polarized but rather are polarized in a plane called main plane of polarization defined by two eigenvectors associated with the two largest eigenvalues. The degree of planarity , P, is defined as:

$$P = 1 - \left(\frac{2\lambda_3}{\lambda_1 + \lambda_2}\right)^n \tag{9}$$

The correlation coefficient is determined from the usual definition (Jenkins and Watts 1968)

$$\rho_{12}^2 = \frac{[m_{12}]^2}{m_{11}m_{22}} \tag{10}$$

All the above parameters, the covariance matrix $\mathbf{M_c}$, the degree of rectilinearity L, the corresponding eigenvector $\mathbf{u}_1$, and the correlation coefficient ρ are the polarization characteristics of the particle motion. When the off-diagonal terms of the covariant matrix are significant, the diagonalization will introduce a rotation. After the rotation, the orientation in place of the principal axis of the covariance matrix will be given by the components of its eigenvector $\mathbf{u}_1$ relative to the original coordinate system. The rectilinearity ,L will give an estimate of the degree of polarization along the major axis. By combining the degree of linearity and the appropriate eigenvector, the measures of rectilinearity and directionality can be obtained. Determination of a suitable filter function is then possible (Montalbetti and Kanasewich ,1970).

DESIGNING A POLARIZATION FILTER

Considering the patterns of particle motion and their propagation directions, various workers have designed polarization filters for the enhancement of seismic data (Flinn, 1965). Applying this analysis to three component seismic data, the covariance matrix is computed for a specific time window of length Ns centered about t_0 where t_0 is allowed to range over the entire record length of interest. Eigenvalues and the corresponding eigenvectors of this matrix are then determined. The measure of rectilinearity $R_L(t_o)$ for the time t_0 is given by:

$$R_L(t_0) = L^J \tag{11}$$

where L is defined in equation (6).

If we represent the eigenvector of the principal axis with respect to x, y, z coordinate system by $\mathbf{E} = (e_1, e_2, e_3)$ then the direction functions at time t_0 are given by:

$$D_i(t_0) = (e_1)^K \tag{12}$$

$$i=1, 2, 3 = x, y, z$$

The exponents n, J, K are determined empirically. Once these functions are computed, the window is moved down one sample interval and the calculations are repeated. Weighting functions of this form are used by Flinn (1965).

Montalbetti and Kanasewich (1970) then modified the newly calculated values by using a boxcar filter of length equal to half of the original window length to get the modified seimograms. The modified rectilinearity and directionality operators are $R_L^*(t)$ and $D_i^*(t)$. The operators are then used as a point by point gain control to modulate the rotated records so that at any time t, the filtered seismograms $x_i^f(t)$ are given by:

$$x_i^f(t) = x_i(t) \,.\, R_L^*(t) \,.\, D_i(t) \tag{13}$$

The data were bandpass-filtered to get rid of unwanted noise before applying the polarization filter. The window length could be specified so as to be consistent with one or two cycles of the dominant period. Values of J and K were 1 and 2. For rectilinearity , n= 0.5 or 1 was used.

FUTURE WORK

Polarization filters can be more useful than conventional filters (frequency filters, and f-k filters) in enhancing signal-to-noise ratio in three-component recording where signal and noise have similar spectral characteristics. A program using this algorithm is currently being developed at the University of Calgary for the CREWES project to test three-component data sets recorded in Alberta. The next step is to investigate another method studied by René et al.,(1986), using the complex trace analysis.

REFERENCES

Bullen, K.E., 1963, An introduction to the theory of seismology, Third edition, Cambridge University Press.

Cliet, C., and Dubesset, M., 1987, Polarization analysis in three component seismics: Application to well seismic profiles, Presented at the 49th Annual EAEG Meeting, Belgrade, Yugoslavia.

Flinn, E.A., 1965, Signal analysis using rectilinearity and direction of particle motion, Proc. I.E.E.E., 53, 1874.

Gal'perin, E.I., 1984, The polarization method of seismic exploration, Translated from 1977 edition of Poliarisatsionnij metod seismicheskikh issledovanij, Nedra, Moscow, by B. Kutzenov and M. Samokhvalov, D. Reidel Publishing Company.

Helbig, K., and Mesdag, C.S., 1982, The potential of shear wave observations, Geophysical Prospecting 30, 413-431.

Jenkins, G.M., and Watts, D.G., 1968, Spectral analysis and its application, San Francisco, Holden-day Co.

Jurkevics, A., 1988, Polarization analysis of three component array data, Bull. Seism. Soc. Am. 78, 1725-1743.
Kanasewich, E.R., 1975, Time sequence analysis in geophysics, The University of Alberta Press.
Meissner, R., and Hegazy, M.A., 1981, The ratio of the PP- to the SS-reflection coefficients a a possible future method to estimate oil and gas reservoirs, Geophysical Prospecting 29, 533-540.
Montalbetti, J.F., and Kanasewich, E.R., 1970, Enhancement of teleseismic body phases with a polarization filter, Geophys. J. R. Astr. Soc. 21, 119-129.
Rene, R.M., Fitter, J.L., Forsyth, P.M., Kim, K.Y., Murray, D.J., Walters, J.K., and Wasterman, J.D., 1986, Multicomponent seismic studies using complex trace analysis, Geophysics 51, 1235-1251.
Samson, J.C., and Olson, J.V., 1980, Some comments on the descriptions of the polarization states of waves, Geophys. J. R. astr. Soc. 61, 115-129.
Samson, J.C., and Olson, J.V., 1981, Data-adaptive polarization filters for multichannel geophysical data, Geophysics 46, 1423- 1431.