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TIME SEISMIC ANALYSES

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Dynamic Bayesian Filtering for Real-Time Seismic Analyses

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Abstract

State space modeling, which includes techniques such as the Kalman filter, has been used to analyze many non-stationary time series. The ability of these dynamic models to adapt and track changes in the underlying process makes them attractive for application to the real-time analysis of three-component seismic waveforms. We are investigating the application of state space models formulated as Bayesian time series models to phase detection, polarization, and spectrogram estimation of seismograms. This approach removes the need to specify data windows in the time series for time averaging estimation (e.g., spectrum estimation). We are using this model to isolate particular seismic phases based on polarization parameters that are determined at a spectrum of frequencies. We plan to use polarization parameters, frequency spectra, and magnitudes to discriminate between different types of seismic sources. We present the application of this technique to artificial time series and to several real seismic events including the Non-Proliferation Experiment (NPE) two nuclear tests and three earthquakes from the Nevada Test Site, as recorded on several regional broadband seismic stations. A preliminary result of this analysis indicates that earthquakes and explosions can potentially be discriminated on the basis of the polarization characteristics of scattered seismic phases. However, the chemical (NPE) and nuclear explosions appear to have very similar polarization characteristics.

1 Introduction

The purpose of this paper is to introduce a statistical approach to characterizing seismic waveforms that combines and extends several existing procedures. The approach utilizes a methodology which can be applied in real-time and which simultaneously extracts frequency, magnitude, polarization, and arrival time information from three-component seismograms. In this paper, the focus is on near real-time estimation of polarization and a graphical display of the results. A complete description of the entire methodology with applications is in progress.

The statistical model underlying the methodology is a state space formulation of a time series model. It is dynamic in the sense that the parameters of the model are not fixed, but are allowed to adapt and change over time. This alleviates the need for the often untenable stationarity assumption and for data windows, since model parameters are updated as each new observation is obtained. The updating algorithm

is a generalization of the Kalman filter. While the model could be developed from that point of view, we will adopt a more statistical exposition using a Bayesian approach to modeling.

These statistical models have had a wide area of application. They can be found in forecasting economic time series, real-time data quality control, target tracking, and remote sensing applications. In a sense, we seek to track the seismic signal in real time and extract relevant information; thus, these models are well suited to the task.

In order to test the plausibility of the methodology, several tests were run on artificial time series that were generated to have similar spectral and polarization characteristics to real data. We first apply the methodology to data recorded at Mina, Nevada, for the recent Non-Proliferation Experiment (NPE). We then apply the methodology to data recorded at Goldstone, California for three Nevada Test Site (NTS) explosions (including the NPE) and three aftershocks of the Little Skull Mountain earthquake that occurred at the NTS. Figure 1 provides a map showing the locations of events and stations.

Polarization estimates result from analysis of the eigenvalues and eigenvectors of the model-estimated 3x3 cross-covariance matrix of the three orthogonal components at each time increment. This method differs from previous approaches that use a covariance matrix calculated from three-component data within moving time windows. Once the cross-covariance matrix is estimated, we characterize the dimensionality of particle motion of the three-component seismogram in a manner similar to that of Jurkevics (1988) and Suteau-Henson (1991). Then by scaling the eigenvalues appropriately, we construct ternary diagrams which depict graphically the evolution of the dimensionality of particle motion over time. Waveform phase characterization proceeds from the resulting diagrams.

2 Bayesian Statistical Approach: The Dynamic Linear Model

A brief overview of the dynamic linear model will now be given. Details of the estimation algorithm can be found in the literature. Particularly relevant discussions of the model can be found in West and Harrison (1989) and Gordon and Smith (1988).

The state space formulation of the model is described by two equations, the first is the observation equation and the second is the state equation:

$$Y_t' = F_t' \Theta_t + \nu_t'$$

$$\Theta_t = G_t \Theta_{t-1} + \Omega_t$$

The components of the model are defined as follows:

$Y_t' = (Y_{t1}, Y_{t2}, \dots, Y_{tq})$ is a q -vector of observations taken at time t .

$\nu_t' = (\nu_{t1}, \nu_{t2}, \dots, \nu_{tq})$ is a q -vector of observation errors at time t .

$\Theta_t = (\theta_{t1}, \theta_{t2}, \dots, \theta_{tn})$ is an $n \times q$ state matrix at time t , also referred to as the system matrix.

The columns are the state vectors of each of the q component time series.

$\Omega_t = (\omega_{t1}, \omega_{t2}, \dots, \omega_{tn})$ is an $n \times q$ matrix whose columns are the state or system evolution errors of the q component time series.

At each time t , F_t is a known $n \times 1$ matrix, often referred to as the regression matrix. Also at each time t , G_t is a known $n \times n$ matrix referred to as the state or system evolution transfer matrix.

The vector ν_t is assumed to be normally distributed with mean vector 0 and covariance matrix $V_t \Sigma_t$. V_t is a known scalar at time t . It can be used to allow for common measurement scales, common sampling variation, common occurrence of missing values and outliers. In lieu of these considerations it is often taken to be identically 1. Σ_t is an unknown $q \times q$ matrix representing the covariance information across the q component time series. The vectors ν_t are assumed to be distributed independently over time. The matrix Ω_t is assumed to have a matrix normal distribution with mean matrix 0, a time-dependent left covariance matrix, and right covariance matrix Σ_t . The Ω_t are assumed to be distributed independently over time and they are assumed to be independent of the vectors ν_t .

Parameters of the model are estimated within a Bayesian context. That is, a prior distribution for the state matrix is assumed. Given an observation Y_t , the prior distribution is updated by applying Bayes' Theorem. The resulting posterior distribution is then used as the prior distribution for time $t + 1$. The recursive nature of this algorithm makes it amenable to real-time processing of the data.

3 The Dynamic Linear Model for Three-Component Seismograms

In order to implement the dynamic linear model for three-component seismograms, specification of certain matrices in the above formulation is necessary. First of all, $q = 3$, and the observed vector of observations $Y'_t = (Y_{t1}, Y_{t2}, Y_{t3})$ corresponds to the north, east and vertical components of the observed seismogram. If the data is measured k times per second, we can incorporate frequency information in the model by defining the state matrix to be the Fourier coefficients of each component at *specified* frequencies. The choice of which frequencies to include in the model is up to the investigator; in order to cover the relevant spectrum in the data sets we analyzed, we chose the frequencies at 0.5, 1.0, 2.0, 4.0 and 8.0 Hz. This means then that Ω_t is a 10×3 matrix. The matrix G_t is then a 10×10 block diagonal matrix, where each block is a 2×2 matrix of the form

$$\begin{pmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{pmatrix}$$

with ω corresponding to $(2\pi/2k)l$, for $l = 1, 2, 4, 8, 16$. The corresponding regression matrix is

$$F'_t = (1, 0, 1, 0, 1, 0, 1, 0, 1, 0).$$

Other approaches to modeling seismograms by way of statistical time series specify these matrices differently (Kitagawa and Gersch 1985). For example, it is well-known that any integrated autoregressive moving average (ARIMA) model can be phrased in state space form by specifying the component matrices of the model appropriately. (See for example, Chapter 9 of West and Harrison, (1989)). Thus, in fitting a model from the class of ARIMA models, a similar state space approach could be adopted, but the constituent matrices of the model would need to be modified accordingly.

3.1 Frequency Analysis

By tracking the estimated state matrix of Fourier coefficients, it is possible to monitor the frequency content of the waveform in real time. The elements of the state matrix can change and adapt to increases and

decreases in the amplitude of the wave at each of the chosen frequencies. This aspect of the analysis will not be discussed in this paper. However, in conjunction with the phase analysis below, it should be possible to extract useful information from the waveform for real-time and *a posteriori* analyses. This is an area of ongoing research.

3.2 Polarization Analysis

The 3x3 matrix Σ_t represents the cross-component covariance matrix at time t . As such, its eigenvalues and eigenvectors at each time t provide information on the nature of the polarity of the waveform at that time.

We investigated the structure of Σ_t by constructing plots of functions of the eigenvalues and eigenvectors of S_t , the estimate of Σ_t produced by the model. We used the eigenvector corresponding to the largest eigenvalue to obtain time series plots of azimuth and incidence angle. We used the eigenvalues to obtain a ternary time series plots for phase characterization.

Specifically, let λ_{1t} , λ_{2t} , and λ_{3t} be the eigenvalues of S_t . Let $\lambda_{(1)t} \geq \lambda_{(2)t} \geq \lambda_{(3)t}$ denote the ordered eigenvalues of S_t . Define the quantities

$$l_t = \frac{\lambda_{(1)t}}{\lambda_{1t} + \lambda_{2t} + \lambda_{3t}}$$

$$c_t = \frac{\lambda_{(2)t}}{\lambda_{1t} + \lambda_{2t} + \lambda_{3t}}$$

$$s_t = \frac{\lambda_{(3)t}}{\lambda_{1t} + \lambda_{2t} + \lambda_{3t}}$$

The values l_t , c_t , and s_t measure the locus of particle motion represented by the seismogram at time t in terms of its linear, circular, and spherical polarization characteristics, respectively. Since the relative size of the three eigenvalues determines the dimensionality of the particle motion, displaying l_t , c_t , and s_t in a ternary coordinate system provides a simple mechanism for tracking dimensionality through time. Figure 2 illustrates the use of the equilateral triangle ternary diagram for this purpose. The three vertices (1, 0, 0), (0, 1, 0), and (0, 0, 1) are the limiting mixture points where only a single eigenvalue is non-zero. When we order the eigenvalues, this constrains the coordinates to a subset of the triangle. For $l_t \geq c_t \geq s_t$, we are constrained to the region defined by the bold triangle. The vertices of this triangle define the three limiting polarization characteristics, linear, circular, and spherical. For linear polarization, one eigenvalue is non-zero and the corresponding eigenvector defines the direction of the one-dimensional rectilinear motion. Examples of such polarization include initial P-waves with near vertical incidence and the S-wave with near-horizontal incidence. For circular polarization, the two non-zero eigenvalues are equal and the particle motion is in the plane determined by the corresponding eigenvectors. Elliptical polarization is represented along the edge of the triangle between the linear and circular vertices. Examples of elliptical polarization include the Rayleigh wave and other surface waves. For spherical polarization, the eigenvalues are equal with unconstrained spatial motion. Examples include diffuse P-coda, crustal Lg wave, and some instances of noise.

In practice, few real particle motions are any of these classical polarization extremes. There is always at least a small amount of noise and there will be competing phases arriving close together. Thus, real P-wave, Rayleigh wave and scattered wave phases will be in the neighborhood of linear, circular (elliptical), and spherical polarizations, respectively.

4 Model Test Examples

We applied these modeling techniques to a variety of waveforms; several simulated seismic signals, the NPE recorded at Mina, Nevada, and NTS earthquakes and explosions recorded at Goldstone, California.

4.1 Simulated Seismic Signals

To test the model, we generated a time series of pulses embedded in noise. The pulses were chosen to have approximately the same amplitude spectrum as the Hunter's Trophy and Non-Proliferation Experiment waveforms at the Livermore network station KNB (Kanab, Utah). The pulses were approximately one second long and placed at time intervals of approximately 2 seconds. The placement was varied randomly within ± 0.5 seconds to eliminate spectral scalloping in the whole-signal spectrum. The noise was generated using a random sequence filtered to approximate the noise in the target recordings. The pulses were separated by intervals of background noise 0.5 to 1.5 seconds in duration. Figure 3 shows the resulting three-component waveform.

The sequence of seven three-component pulses as generated had slightly different azimuths and angles of incidence: the azimuths of the seven pulses were 290, 280, 290, 300, 290, 290, and 290 degrees; and the angle of incidence was 20 degrees, except for the next to last pulse where it was changed to 30 degrees.

The ternary diagram for this series showed a random scatter of points in the center of the plot reflecting the noise prior to the event. This was followed by a concentration of points at the linear vertex. Thus it captured the marked linearity during the onset of each of the impulsive spikes. Figure 4 illustrates the ability of the model to track changing incidence angle and azimuth. The solid line in each plot represents the true underlying structure. It is clear that the model can detect and track changes in incidence angle and azimuth, although its performance is better for azimuth tracking. Note that the plot in Figure 4 fails to show that the polarization returns to a random direction between the pulses. Experiments were made in the tuning of the response time of the model to allow for a more rapid adjustment, but this tended to degrade the stability of the azimuth during the periods of strong polarization.

4.2 NPE at Mina, Nevada

The NPE vertical-component waveform recorded at the Livermore network station MNV is shown at the top of Figure 5, where windows are selected to represent various types of seismic waves. The ternary plot in the lower portion of Figure 5 shows the relative amount of linear, circular, and spherical polarization for these windows. This example shows clear separation of different seismic phases: noise is three-dimensional, initial P-waves are nearly linear, and later-arriving scattered P-waves (the P-coda) are progressively more spherical with elapsed time. (This polarization can be visualized as "cigar-shaped.") At the onset of shear and surface waves, the mix of polarizations shifts to a combination of circular and spherical, that remains stable throughout the later parts of the waveform. (This last polarization can be visualized as "disc-shaped.")

On the basis of these observations, it appears that the polarization mixtures typify different combinations of waves: purely linear P-waves approaching the station on a direct line, followed by progressively scattered P-waves approaching from increasingly variable angles. As the amplitude of the scattered P-waves decreases, the onset of S-waves (generated near the explosion or as a result of other P- to S- conversions) and surface waves increases gradually. These wave types may tend to have a more two-dimensional (circular) polarization

and therefore the mixture of scattered, two-dimensional polarizations lies very near the edge of the ternary diagram between circular and spherical.

4.3 Earthquakes and Explosions at Goldstone, California

Figures 6a, 6b, and 6c show the seismograms recorded at Goldstone, California (GSC), from three aftershocks of the June 28, 1992, Little Skull Mountain Earthquake. Figures 6d, 6e, and 6f show the seismograms from this station for three NTS explosions. Time windows labeled A, B, and C correspond to our selection of sections of Pg, P-coda, and S-coda that exhibited relatively stable polarization.

Figures 7a, 7b, and 7c show polarization diagrams for the three earthquakes. These three earthquakes all have magnitudes of approximately 4.4. The initial P-waves all exhibit a brief period of highly linear polarization, but the polarization appears to be much more chaotic than shown previously in Figure 5. Each of the three earthquakes has later P-wave coda and S-wave coda that are also very stable, but it is apparent that the P-coda and S-coda do not separate into different mixture types as shown previously.

Figures 7d, 7e, and 7f show polarization diagrams for three NTS explosions: Hunter's Trophy (magnitude 4.4), the NPE (4.1), and Bristol (4.6), respectively. These data do not show an initially linear polarization for the P-waves. This is very different from the previous examples that exhibited at least brief periods of linearity in the P-wave. However, specific frequency polarization plots of the data indicate that the linear polarization is only evident at higher frequencies (above 5 Hz), while these diagrams are based upon an average of the polarization over frequencies between 0.5 and 8 Hz.

Although the P-wave polarization of these explosions appears to be limited to high frequencies, the P-coda and S-coda polarizations appear to be qualitatively similar to the example from MNV (Figure 5). The P-coda is mostly a mixture of linear and spherical polarization, while the S-coda is mostly a mixture of circular and spherical polarizations. A comparison of the NPE at MNV (Figure 5) and at GSC (Figure 7e) with Figures 7d and 7f shows that the NPE had the clearest separation between P-coda and S-coda of any of the three explosions. In fact, it appears that each of the three explosions maintains the relative mixture of P, P-coda, and S-coda polarizations, but that the event's entire pattern can shift position on the polarization diagram. Conversely, it is observed for the earthquakes (Figures 7a, 7b, and 7c) that P-coda and S-coda polarizations cannot be separated and can even reverse their relative positions on the polarization diagrams.

In summary, there appear to be several wave generation and wave propagation phenomena that can affect the mixture of polarization of seismic phases. These phenomena are probably different for explosions, where shear waves are generated by scattering in a near-surface, low velocity medium; and for earthquakes, which occur at greater depth and which directly radiate dominantly shear energy. Some of these differences appear to be exhibited in the relative mixture of polarization of different portions of the seismic waveforms presented above. However, data from additional stations and events are needed to fully understand these effects. Also, a refinement of the approach is needed to separate different frequency components.

5 Conclusions

We introduced a statistical approach to characterizing seismic waveforms that can be applied in real-time and which simultaneously extracts frequency, magnitude, polarization, and arrival time information from three-component seismograms.

We feel the application of dynamic Bayesian filtering to seismic analysis shows great promise. The models do need to be expanded to extract information relevant for phase characterization. We plan to use the model to detect and track compressional, shear, and scattered (coda) phases.

We have found that in specifying the tuning parameters of the model, there is a trade-off between precision in determining the azimuth and incidence angles and the capability of the model to adapt to rapid changes, a result common to other researcher's efforts.

We plan to improve the current spectral power model by incorporating elements of the physics of the local and regional wave propagation (Vidale 1986; Jepsen and Kennett 1990) to detect frequency-dependent polarization effects.

There is obvious potential for application of these techniques to a variety of seismic problems, such as seismic array azimuth and velocity determination, including three-component arrays. In addition, it appears to be possible to devise various outputs of the model to discriminate between earthquakes, chemical explosions, and underground nuclear explosions.

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Figure 1. Location map showing the locations of NTS explosions Hunter's Trophy and the NPE, the locations of the Little Skull Mt. aftershocks, and the locations of several broad-band seismic stations that recorded the data used in this study.

Figure 2. Ternary plot for display of particle motion eigenvalues. First, Second, and Third eigenvalues, as unordered, plot unconstrained in the equilateral triangle. As ordered with First largest, they plot in the bold triangle. Here, LINEAR, CIRCULAR, and SPHERICAL vertices define symmetric 1-, 2-, and 3-d motion, respectively.

Figure 3. Artificial three-component seismogram for the seven pulse signal.

Figure 4. Theoretical (solid curves) and predicted (dots) incidence angle and azimuth estimates for the seven pulse artificial seismogram.

Figure 5. Dimensionality of particle motion of several NPE seismic phases as recorded at Mina, Nevada.

Figure 6. Seismograms of three Little Skull Mt. aftershocks and three NTS explosions as recorded at Goldstone, California. Windows A, B, and C sample Pg, P-coda, and S-coda phases, respectively.

Figure 7. Dimensionality of particle motion of several phases of three Little Skull Mt. aftershocks and three NTS explosions as recorded at Goldstone, California.

a. Vertical Component of Waveform

b. Ternary Plot of Particle Motion Eigenvalues

a. June 29, 1992, Aftershock

d. Hunter's Trophy

b. July 5, 1992, Aftershock

e. NPE

c. September 13, 1992, Aftershock

f. Bristol

a. June 29, 1992, Aftershock

d. Hunter's Trophy

b. July 5, 1992, Aftershock

e. NPE

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