Directional Scale Analysis for Three Dimensional Seismic Interpretation

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Summary
A combined space-Fourier representation focused on directional scale analysis is presented. The method leads to a space vs. log polar frequency distribution. Application to three dimensional seismic data shows differentiation in scale and dip direction. Attributes are extracted to illustrate this differentiation.

Introduction
A widespread tool in signal and image processing is multi-scale decomposition. These time-frequency distributions provide a new tool to get more insights into seismic data (Steeghs, 1997). Three dimensional seismic data contains three basic components: amplitude, frequency and geometry. We try to find seismic attributes to describe the data in terms of these three components. The motivation for the use of a multi-scale decomposition is that the earth’s response appears through different scales of resolution, and the structural information through different angles (van Spaendonck and Baraniuk, 1999).

We use a polar scale decomposition or 'steerable pyramid'. The operator results in a scale decomposition along certain bands of orientations, and can hence be used for directional scale analysis. The filters are designed in the Fourier domain.

In this paper we focus on the extraction of local (polar) scale and local geometrical information to improve conventional 3-D interpretation methods. In the next sections we will shortly address 2-D polar scale decomposition, followed by the extension to three dimensions. We conclude with some examples of the extracted attributes, performed on 3-D migrated seismic data.

Steerable Pyramid
The wavelet transform is basically a set of bandpass filters applied to the input image and down sampled subsequently. If these filters are applied in the Fourier domain we speak of filterbanks. The bandpass fil-

![Figure 1](attachment:image.png)

Figure 1: Two-stage spectral decomposition of a steerable pyramid. $H_2$ is a low-pass filter, $H_j^\alpha$ are the oriented wavelet sub bands at scale $j$ and angle $\alpha$, $H_0$ indicates the residual band.
form is performed by applying the operator 

\[ \text{can perform a Hilbert transform along the polar axes of the orientated bandpass filters.} \]

seismic image as:

\[ \frac{\omega_x}{2x} \]

\[ \frac{\omega_y}{2y} \]

\[ \frac{\omega}{2\omega} \]

\[ \frac{\omega_L}{2\omega} \]

\[ \frac{\omega_T}{2\omega} \]

\[ \frac{\omega_m}{2\omega} \]

\[ \frac{\omega_n}{2\omega} \]

\[ \frac{\omega_p}{2\omega} \]

\[ \frac{\omega_q}{2\omega} \]

\[ \frac{\omega_r}{2\omega} \]

\[ \frac{\omega_s}{2\omega} \]

\[ \frac{\omega_t}{2\omega} \]

\[ \frac{\omega_u}{2\omega} \]

\[ \frac{\omega_v}{2\omega} \]

\[ \frac{\omega_w}{2\omega} \]

\[ \frac{\omega_x}{2\omega} \]

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\[ \frac{\omega_z}{2\omega} \]

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\[
\tan(\beta) = \frac{y}{x} \iff \tan(\beta) = \frac{\omega_x}{\omega_y}
\]

The 3-D steerable pyramid is constructed by cascading (and subsequently down sampled) polar low- and high-pass filters. The resulting bandpass filters are divided into \( M \) dip bands. For one dip band the azimuthal sub bands are polar separable. The \( M \) dip bands in turn are divided into \( K \) azimuthal bands. The low- and high-pass filters are indicated by \( L(\omega) \) and \( H(\omega) \), the bandpass filters by \( B^{\alpha,\beta}(\omega) \), and \( \omega = (\omega_x, \omega_y, \omega_t) \). The filterbanks \( H_j^{\alpha,\beta}(\omega) \) are then computed by:

\[
H_j^{\alpha,\beta}(\omega) = L(\frac{\omega}{2^j})H(\frac{\omega}{2^j})B^{\alpha,\beta}(\omega)
\]

The filters are designed in such a manner that we can reconstruct the original image by applying the same filters to the filtered data. For perfect reconstruction we constrain the filters by:

\[
\sum_{\alpha=\alpha_1}^{\alpha_M} \sum_{\beta_1}^{\beta_K} |B^{\alpha,\beta}(\omega)|^2 = 1,
\]

in which \( N \) is the number of scales, \( \alpha_M \) gives the number of dip-bands and \( \beta_K \) gives the number of azimuth-bands. Furthermore, we constrain the filters to be real. A schematic view of this 3-D steerable pyramid is given in figure (2).

The 3-D steerable pyramid representation can be made complex by applying a Hilbert transformation. We applied a Hilbert transform in the \( \omega_t \) direction:

\[
U(\omega_x, \omega_y, \omega_t) = \{0, 1, 2\} \quad \text{for} \quad \{\omega_x < 0, \omega_y = 0, \omega_t > 0\}
\]

As in the 2-D case the steerable pyramid returns a real and an imaginary part in quadrature, which has advantages for attribute extraction.

**Seismic data example**

With the complex steerable pyramid we can extract several attributes. We extracted attributes for local dip, local azimuth and local scale from the 3-D steerable pyramid. Local dip, local azimuth and local scale are computed by the first moment over dip and over scale for a migrated field data set. We used 4 dips (ranging from 0 to 90 degrees) and 3 scales. Figure (3) shows the original data, the local dip representation and the local scale representation. The local dip representation gives a clear indication of the steepness of events, and can hence be used in the analysis of time slices, because vectors are observed instead of scalars.
Figure 3: Upper left: seismic data. Upper right: local dip attribute obtained from the data, with the colorbar indicating absolute dip value, independent of azimuth. Bottom: local scale attribute obtained from the data.

The local scale representation gives a good indication of the local frequency content, perpendicular to the structure.

References


Spaendonck, R. van, and Baraniuk, R., 1999, Directional scale analysis for seismic interpretation: SEG Expanded abstracts, 1844-1847.