

## Filtering azimuthal anisotropic velocity field

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### Summary

During the analysis of azimuthal anisotropy from migrated seismic 3D gathers, an automatic residual NMO correction is performed. Since it is done gather by gather, it often produces a noisy residual velocity field with high frequency of vertical stripes. Using this velocity field for further calculations may result in large artifacts in the final sections. It is thus necessary to filter the azimuthal velocity field, which is described, in the case of anisotropy, as an ellipse with three components for every point in the 3D space. To filter out the stripes and artifacts, we use a special implementation of the Vector Median Filter method. A straightforward calculation of the Vector Median Filter can be very expensive, and therefore we suggest an effective approximation.

### Introduction

The context of this paper is the analysis of azimuthal anisotropy from migrated seismic 3D gathers. There are two types of parameters which are conventionally used in the azimuthal anisotropy analysis of seismic gathers: Azimuthal Velocity Analysis (VVAZ) and azimuthal Amplitude vs. Offset/Angle (AVAZ). In this paper, we refer to azimuthal variations which can be characterized by three parameters ( $\alpha_1, \alpha_2, \beta$ ) and ( $G_1, G_2, \beta$ ).  $\alpha_1$  and  $\alpha_2$  are the primary and secondary axes of a velocity ellipse (schematic picture is shown in Fig. 1),  $G_1$  and  $G_2$  are the primary and secondary axes of an AVAZ gradient ellipse, and  $\beta$  is the orientation angle (Grechka and Tsvankin, 1998; Ruger, 1998). The source of these azimuthal variations can be HTI, TTI or orthorhombic anisotropy. This approach was described in a series of papers (Canning and Malkin, 2009a, 2009b, 2013).

In this paper we concentrate on one aspect of the workflow – the interpolation and filtering of the 3D parameter field: ( $\alpha_1, \alpha_2, \beta$ ) or ( $G_1, G_2, \beta$ ). While this is an interesting problem in general, we encountered it when trying to extend our conventional Automatic Residual NMO (ARMO) analysis to 3D gathers. The ARMO is done gather by gather, and often produces a quite noisy residual velocity field with high frequency of vertical stripes (Fig. 2a). Using this velocity field to NMO-stack the data, and even more so when performing AVA analysis, results in large artifacts in the final sections (Fig. 3).

In order to remove the stripes from the residual velocity field, our normal workflow for the case of isotropic data involves median filtering with a large horizontal 3D

window, followed by a regular smoothing filter. This is done prior to the application of the RMO correction to the gathers. When trying to extend this workflow to VVAZ, we had difficulty extending the median filter to such 3D data. Median filter is a non-linear operation and therefore filtering each component separately will not work. Moreover, the 3D parameter field is not a normal Cartesian field. One can imagine that this field contains an ellipse in each grid point of the 3D space (Fig. 4). The problem to be solved is how to interpolate and filter in 3D space a set of ellipses, while each ellipse may have different orientation and ellipticity.

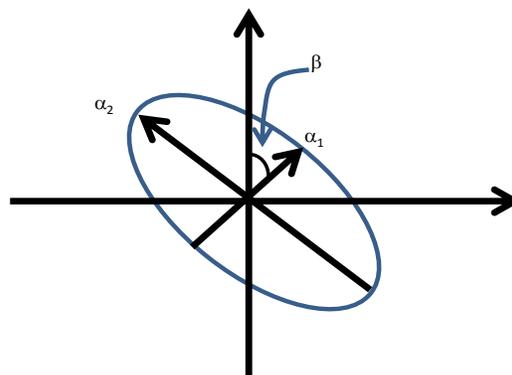


Fig. 1. The construction of each 3D residual velocity element.  $\alpha_1$  is the residual velocity in the azimuth direction,  $\alpha_2$  is the residual velocity in the perpendicular direction, and  $\beta$  is the azimuth. The velocity data at each location in the 3D seismic space is represented as three components  $\alpha_1, \Delta\alpha = |\alpha_1 - \alpha_2|, \beta$ .

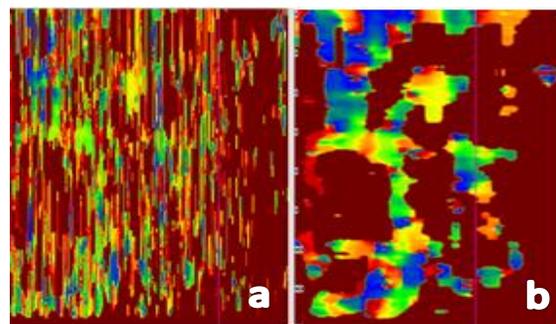


Fig. 2. (a) The residual velocity field after ARMO, with vertical stripes that cover the entire space and make it very difficult to see the real pattern of the data. (b) The same data after filtering using the proposed method. Note that the clarity of the right picture also comes from data in the other two  $\alpha_1, \alpha_2, \beta$  components.

## Filtering azimuthal anisotropic velocity

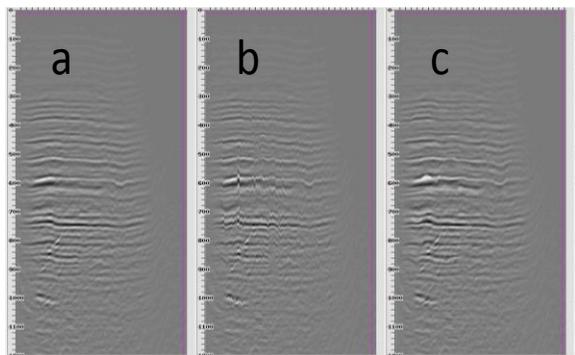


Fig. 3. AVAZ gradient from wide azimuth gathers. a) From original gathers. b) From gathers flattened with velocity obtained by VVAZ (Fig. 2a). c) From gathers flattened with velocity obtained by VVAZ and smoothed with vector median filter (Fig. 2b). Note how the frequency content and resolution of the result increases in b) due to the detailed RMO application. Note also the stripes artifact in this section. In c) the stripes are removed and the result is much improved compared to the original process a).

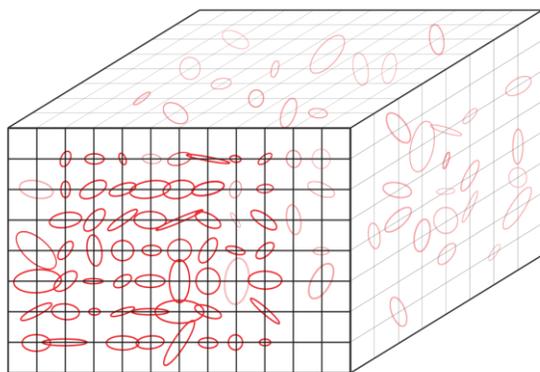


Fig. 4. A schematic picture of a set of ellipses, filling the grid points of the 3D space. This is an example of the input data we need to filter.

### Theory and Method

It seems that removing noise from multi-dimensional data may not be as simple as in the case of scalars. We have already said that median filtering of each component separately cannot work, since the output vector will not, in general, be one of the inputs. However, a straightforward approach can suggest median filtering that is based on one component of the 3D vector, but assigning the full  $(\alpha_1, \alpha_2, \beta)$  vector as the output. Since the output is one of the input vectors, this method provides a “legal” median. Using this approach we can define three different pseudo-1D

median filters, and apply them consecutively. However, this method is highly dependent on the order in which we choose to apply the consecutive filters (which component is first, second or third), and therefore problematic.

A better approach is to use the three components of the vector simultaneously. Indeed, there is an extension of the scalar median filter to multi-dimensional data, which is called Vector Median Filter (VMF). This method was first presented by Astola, Haavisto and Neuvo (1990). VMFs are mostly used for filtering colored images, but there are many other applications whose data is represented by vectors, and our VVAZ and AVAZ data are good such examples. The idea behind VMF is to find the vector which is “closest” to all other vectors in the filtering window. Such a vector is obtained by calculating the sum of distances between each vector and all other vectors, and selecting the vector with the minimal sum of distances.

In order to adopt the VMF method, one needs to precisely define the vector space of the problem, and the distance function to be used. Conventionally, the multi-dimensional data is projected over a Cartesian coordinate system, and  $L_1$  or  $L_2$  are used as the distance function. In our case the vectors represent ellipses, therefore two components can be considered as “distances” while the third component – the azimuth – is an angle.

**Transformation to Cartesian space:** We begin by analyzing the azimuth. It is necessary to emphasize that the azimuth angles in our problem are in fact between 0 and 180°, with a periodicity of 180°, since the ellipses obey 180° rotational symmetry. Therefore, for a correct projection of the azimuth over the spatial domain, one must multiply each angle by 2. This transforms the 180° periodicity to the “regular” 360° periodicity. An example is shown in Fig. 5.

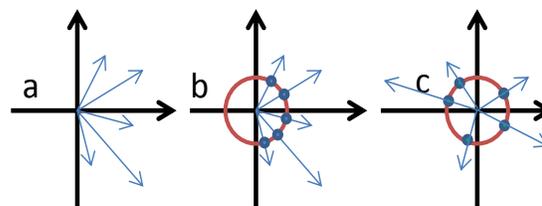


Fig. 5. An example of the azimuth pre-processing for ellipses with azimuths of 30°, 60°, 100°, 140° and 160°. (a) The  $\alpha_i$  vectors of the inputs; (b) for each vector we show the point on the unit circle of the vector's direction; (c) replacing each vector with a doubled-angle vector of the same distance.

## Filtering azimuthal anisotropic velocity

The next step is to add  $\alpha_1$  and  $\alpha_2$  to the analysis. As already shown in Fig. 5c, we use  $\alpha_1$  as the length of the Cartesian vector defined by  $\beta$ . The value of  $\alpha_2$  is then used as a vector perpendicular to the plain defined by vectors  $\alpha_1$  and  $\beta$ . Therefore, the full transformation may be formally written as:

$$(1) \quad \begin{aligned} x_i &= \alpha_{1,i} \cos(2\beta_i) \\ y_i &= \alpha_{1,i} \sin(2\beta_i) , \\ z_i &= \alpha_{2,i} \end{aligned}$$

The vector definition is illustrated in Fig. 6.

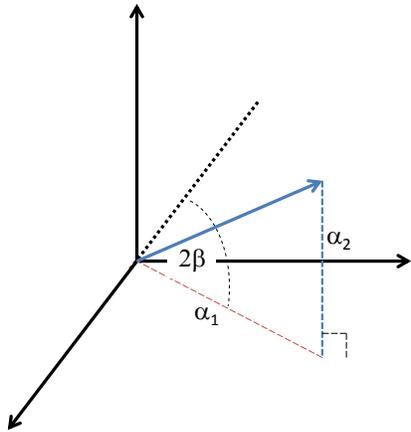


Fig. 6. A schematic drawing of the definition of the Cartesian-space vector representing the ellipse parameters of Fig. 1.

After the transformation of each ellipse to a 3D vector in real space, we use the  $L_2$  distance function to calculate the distances between all data vectors. The vector for which the sum of distances to all other vectors is minimal is defined as the median.

**Approximate VMF:** A straightforward implementation of the vector median filter to 3D seismic data can be quite expensive. The main issue in the computation load is the calculation of the distances between all pairs of vectors in the filter window. Since usually large horizontal windows are used, there may be a need to calculate hundreds of thousands of distances for each data point, making the entire process impractical. For example, we normally use for the filter a window composed of (21 inlines)  $\times$  (21-crosslines)  $\times$  (3-samples) = 1,323 elements. To calculate the VMF we need to calculate all distances from each element to all other elements in the window, requiring

1,323  $\times$  1,322/2 = 874,503 distance calculations, and such a calculation should be performed for each point in space.

To improve the computation time we introduce the Approximate VMF (AVMF) method. Instead of calculating the entire table of distances, composed of  $N(N-1)/2$  values (where  $N$  denotes the number of vectors in the filtering window), we calculate only a small portion of this space. We begin by calculating the average vector of all the vectors in the filter window. Then we calculate the distance for each data vector to the average vector. Let's denote the distance of element  $i$  from the average vector by  $H_i$ . We now sort the input vectors by this distance  $H$ , in increasing order.

Instead of considering all the vectors in the window ( $N$ ), we define a parameter  $0 \leq p \leq 1$ , which determines the number of vectors treated  $P = pN$ . Distances to all vectors are calculated only for the first  $P$  vectors when sorted by their  $H$  value. The number of distance calculations with this method is reduced to  $N + P(P-1)/2 + P(N-P)$ . The mathematical aspects of this filter are discussed in detail in Weiss and Canning (2015).

To use the AVMF method in various applications, the number of vectors considered ( $P$ ) needs to be set according to the specific problem. In order to obtain a good approximation of the VMF,  $P$  depends on the probability distribution of the data, and the probability distribution of the noise. While for noise removal in colored images the AVMF method has delivered good results with  $P/N \approx 0.2$ , for geophysical data the use of  $P=1$  is usually sufficient. This reduces the computational load dramatically, and makes the vector median filtering much more practical (Weiss and Canning, 2015).

### Example

In Fig. 7 we present typical results of the operation of 3D VMF and the proposed approximation. The left-hand column shows the results of an Automatic Azimuthal Residual Velocity analysis. This is a three-component residual velocity field:  $\alpha_1$  is the residual velocity in the azimuth direction,  $\alpha_2$  is the residual velocity in the perpendicular direction and  $\beta$  is the azimuth. Each component is displayed separately as a 2D section ( $x$ - $z$  cross-section of the 3D space). Note the stripes and artifacts which we want to remove. The central column represents the approximated VMF result. Note that the stripes were removed and that the cross-sections are much more coherent. The right column displays the exact VMF results. Note how the results of the exact and approximated VMF methods are similar.

## Filtering azimuthal anisotropic velocity

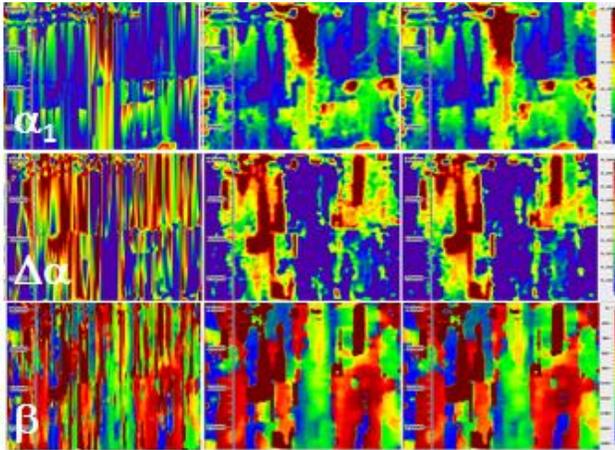


Fig. 7. The components of the anisotropy velocity ellipse  $\alpha_1$ ,  $\Delta\alpha=|\alpha_1|-|\alpha_2|$ ,  $\beta$ . Left column: the original values, with the vertical stripes. The results of median filtering are shown in the middle column (using approximated VMF) and in the right column (using exact VMF). Note the significant improvement from the left column to the other two, and the similarity between the VMF and the AVMF.

### Conclusions

In this paper we discussed the filtration of anisotropic velocity fields which are described by ellipses (three-component non-Cartesian vectors). The anisotropic velocity field is constructed using an automatic procedure that works on a gather-by-gather basis, and the result is therefore often contaminated with vertical stripes that need to be filtered out. We have shown how to transform the multi-dimensional data of ellipses to vectors in 3D Cartesian space, after which a VMF can be performed. We have also presented an approximation to the VMF that is much faster, and produces very good results.

## EDITED REFERENCES

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