# HIGH RESOLUTION STACKING OF SEISMIC DATA

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## ABSTRACT

The stacking procedure is a key part of the seismic processing. Historically, this part of the processing is done using seismic acquisition data (traces) with common features such as the common midpoint between source and receiver. These traces are combined to construct an ideal trace where the source and receiver are virtually placed at the same place. The traditional stacking only performs a simple sum of the traces. This work proposes a different way to perform the stacking, which uses the singular value decomposition of a data matrix to create an eigenimage where the noise and interferences are attenuated. The proposed technique is called Eigenstacking. Results of the stacking and eigenstacking are compared using synthetic and real data.

***Index Terms*—** SVD, stacking, high resolution, seismic

## 1. INTRODUCTION

The main way of extracting information of the subsurface for gas and oil exploration is from the data provided by seismic acquisition. In figure 1 we can observe some of the key features involved in this kind of acquisition. The main system is made by one source (or transmitter) and several geophones (or receivers). The acquisition process starts with the detonation of the seismic source, generating a seismic wave that travels through the substructure where it undergoes refraction, reflection and diffraction. The resulting wave field returns to the surface and is recorded by the geophones. This procedure is repeated, moving the seismic source and the geophones in discrete increments, until the achievement of an accurate coverage of the substructure. Each detonation of the source is called a shot and the signal recorded by the geophone, corresponding to one shot, is called trace.

The recorded traces contain information that can be related with the path of the wave in the subsurface, which generates recorded events such as primary reflections (waves that suffer only one reflection and are thus directly related to the subsurface structure), multiple reflections, diffractions, waves that only propagates on the surface, and sources of noise [2]. It is this relationship that enables the estimation of the geological structures from data recorded at the surface. However, the relationship is not immediate, and the traces are also corrupted by noise, and by several distortion suffered by the wave during its propagation. Thus, several signal processing techniques may be employed to generate a good image of the subsurface.

Several seismic processing techniques work with groups of traces which present a common feature. For instance, we may organize the data using the midpoint between the source and the geophone that generate the trace. This configuration, or family, is called common midpoint, or CMP. If we organize the traces in this configuration, we may say that if the wave suffered a reflection at a given point, all the recorded CMP traces will present that same reflection, at different time instants. A CMP family and a reflection event are shown in figure 2.

A traditional procedure in a CMP family is called stacking, wherein we correct the traces of a CMP family for the time differences in the reflections events and average their amplitudes. As a result, stacking produces a new trace, with less noise, which simulates a seismic experiment wherein source and receiver are placed at that midpoint coordinate. This is known as a zero-offset trace. (More details about this procedure will be seen on section 2.) Also in the stacking procedure, it is common practice to use more than one CMP at each time. For example, we may use one neighbor CMP at each side of the given CMP and consider the reflection point to be located at the central CMP. This practice is called *supergather*.

As an alternative to the traditional stacking procedure, our proposal is to use more information of the traces to create the trace with zero-offset. The traditional stacking only sums selected time instants of the traces. We propose to generate a data matrix for each time instant and apply a singular value decomposition in this matrix, in order to attenuate interferences in that matrix and select only aligned events for the stacking operation. The main particularity of that matrix is that its columns are time samples above and bellow the time instant being considered for the stacking. We named this method *Eigenstacking*. More details about the Eigenstacking are shown in section 3. A similar method was proposed

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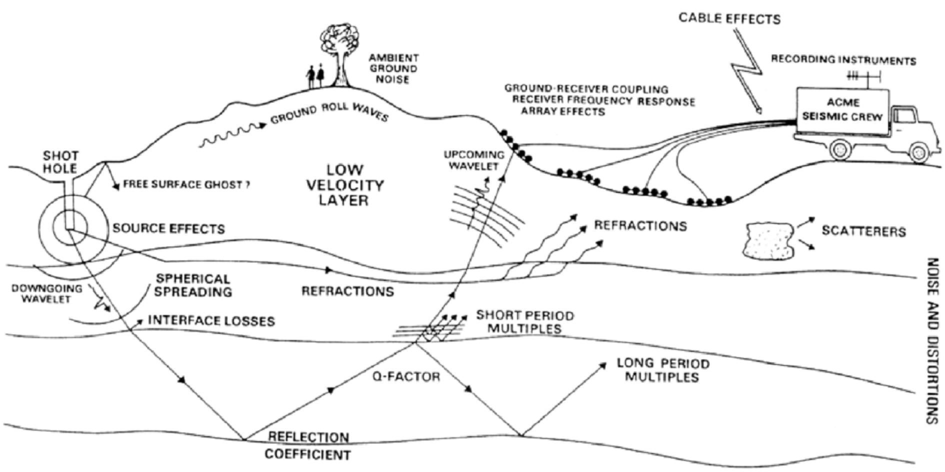



**Fig. 1**: Seismic acquisition and the several distortions that the seismic wave suffers. Extracted from [1].

in [3]. However, in that paper, the SVD was applied only to few neighboring traces and to all time instances simultaneously.

The article is organized as follows: on section 2 we discuss the traditional stacking; on section 3 our proposal will be discussed; on section 4 our results will be shown and, finally, on section 5 we will make some comments about the method.

## 2. STACKING

In this section we describe the stacking procedure. As mentioned in the introduction, in this work we will use CMP families. In figure 2 we illustrate the geometry of the traces from a CMP family. In this figure, the sources are represented on the left and the receivers on the right. Each pair source-receiver represents a trace. If we consider the horizontal reflector shown in figure 2, [4] we see that all reflections in a CMP family occur on the same position. This is a good approximation even if the velocities are not homogeneous and the reflectors are not exactly horizontal [2].

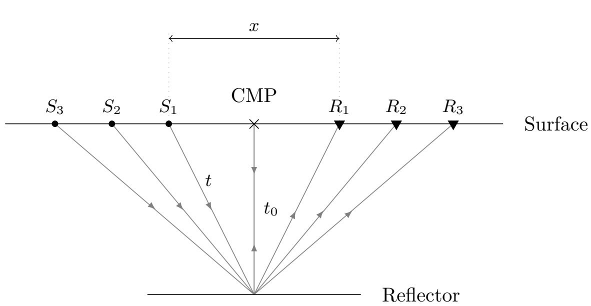



**Fig. 2**: A horizontal reflector and an CMP family traces that reach this reflector.

The main feature of the CMP method is to combine all the traces from a CMP family to create an ideal trace with source and receiver at the same point, called zero offset (ZO) trace. The amplitude of the ZO trace at time instant $t_0$ is the average of the amplitudes of the traces of the CMP family taken at appropriate time instants. We select the time instants on each trace assuming that every $t_0$ in the ZO trace represents a reflection. This procedure is called stacking, and it is similar to the concept of spatial diversity used in communication systems to increase signal-to-noise ratio [2].

To find the exact instant of time that represents the reflection on each trace, we use a normal moveout (NMO) traveltime, which can be evaluated as

$$t^2(x) = t_0^2 + \frac{x^2}{v^2}, \tag{1}$$

where $v$ is called stacking velocity, $t(x)$ is the time that the wave travels from the source, reflect, and returns to the receiver and $x$ represents the trace offset. As we can see on figure 2, equation (1) can be obtained using simple geometrical analysis. If we place all the corrected traces of a CMP together we form a data matrix where all the columns correspond to the traces. This data is called *NMO panel*. If the velocity is correct all events are horizontal aligned.

Clearly, equation (1), and hence the stacking procedure, depends on the velocity $v$, which needs to be estimated from the data. For a given $t_0$, the search can be done with a coherence analysis [5], using a data matrix with $L$ time instants below and above the time travel calculated in (1) and testing for a range of values of $v$. The idea is that, for the correct velocity, all the events in the window will be coherent, in that they will all correspond to the same reflection. The most widely used measure of coherence is the semblance [6].

The stacking procedure sums the traces amplitudes at the time instants calculated using equation (1) with the velocity which led to the maximum coherence value. But, if the velocity tracking was made, in some aspects, in incorrect way, we will not sum the correct reflections on the CMP family.

To avoid this, we can select a data window using $L$ time samples up and above the calculated time, as shown in figure 3, and make some combinations with this window. One of the possible combination will be shown on the next section.

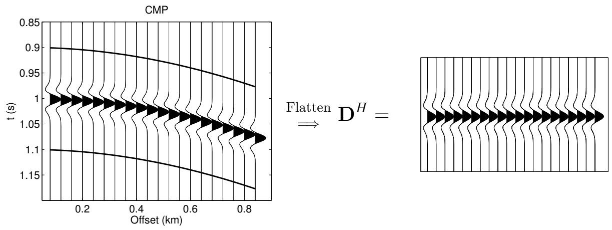



**Fig. 3**: This figure illustrates how the matrix is selected from the data.

## 3. EIGENSTACKING

As seen on previous section, for a given $t_0$ and $v$, we select a data matrix, named $\mathbf{X}$, from the traces of the CMP family. One of the many data manipulation that we can apply to $\mathbf{X}$ is the singular-value decomposition, which can be written [7]

$$\mathbf{X} = \sum_{i=1}^{r} \sigma_i \mathbf{u}_i \mathbf{v}_i^T = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T \qquad (2)$$

where $r$ is the rank of $\mathbf{X}$, $\mathbf{u}_i$ is $i$-th eigenvector of $\mathbf{X}\mathbf{X}^T$, $\mathbf{v}_i$ is the $i$-th eigenvector of $\mathbf{X}^T\mathbf{X}$ and $\sigma_i$ is the $i$-th singular value of $\mathbf{X}$. The matrices $\mathbf{U}$, $\mathbf{\Sigma}$ and $\mathbf{V}$ correspond to the matrix notation of the eigenvectors and singular values.

According to [7] we may denote the outer product $\mathbf{u}_i\mathbf{v}_i^T$ as the $i$-th eigenimage of the matrix $\mathbf{X}$ and $\sigma_i^2$ is the energy of the $i$-th eigenimage. This outer product produces a matrix with rank one and, consequently, the lines of this matrix will be linearly dependent and have the capability to capture horizontal events of $\mathbf{X}$. These eigenimages form an orthogonal basis that can be used to reconstruct the matrix $\mathbf{X}$ using equation (2). If we analyze the singular values resulting of the SVD of $\mathbf{X}$ we note that their magnitude decreases, so we may say that the largest singular values are linked with the first eigenimages.

If there is a seismic event perfectly horizontal on the selected matrix and with the correct velocity, the first eigenimage will contain all columns with the same event. If we analyze the energy of the matrix, we observe that the first eigenimages contain a large amount of the matrix energy based on the value of the singular value. We may observe that the first eigenimage $\sigma_1\mathbf{u}_1\mathbf{v}_1^T$ will reconstruct the matrix $\mathbf{X}$ and the others eigenimages will present lower levels of energy and noise energy, predominantly. We may associate this particularity to the proposal of using only one eigenimage to reconstruct the matrix [7].

As before, we consider a seismic event perfectly horizontal, but if the event is not perfectly horizontal the energy will not be concentrated on the first eigenimages. We may say that on the first eigenimages there will be a large amount of signal and a little of noise energy. As we analyze the last eigenimages, there will be a lot of noise energy. So, if an event is not precisely horizontal, we use only the first eigenimages and discard the last eigenimages. This elimination will increase the signal-to-noise ratio of the resulting matrix.

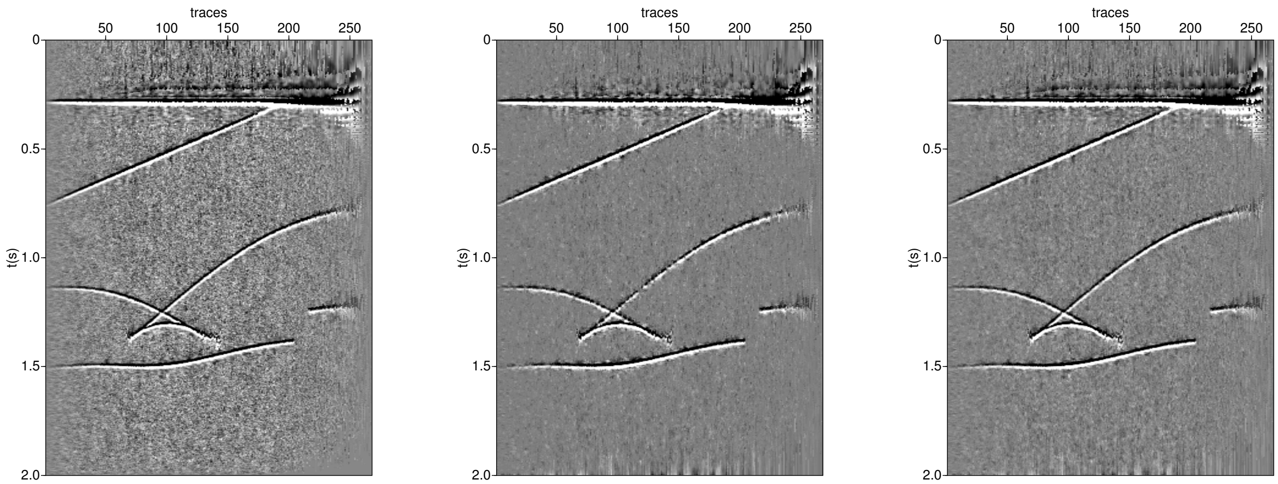
Considering the discussion above, we propose substitute the matrix $\mathbf{X}$ by its first eigenimages and then perform the stacking procedure. In our studies and tests, we chose two configurations to test how effective is the use of few eigenimages to the stacking procedure. In the first configuration we use only one eigenimage to create a new matrix and apply the stacking. In the second configuration we use three eigenimages to then apply the stacking operation. These two choices have, respectively, the minimum number of eigenimages and the number of eigenimages that may contain almost all of the energy of the data matrix.

In our tests and simulations, we used a synthetic environment with the presence of additive white Gaussian noise (AWGN), $501$ time samples and the maximum number of $90$ traces in a CMP family. We also tested our methods in a real data set of a seismic line, acquired at Alaska, which has $2501$ time samples and the maximum number of $12$ traces in a CMP family.

## 4. SYNTECTIC AND REAL DATA RESULTS

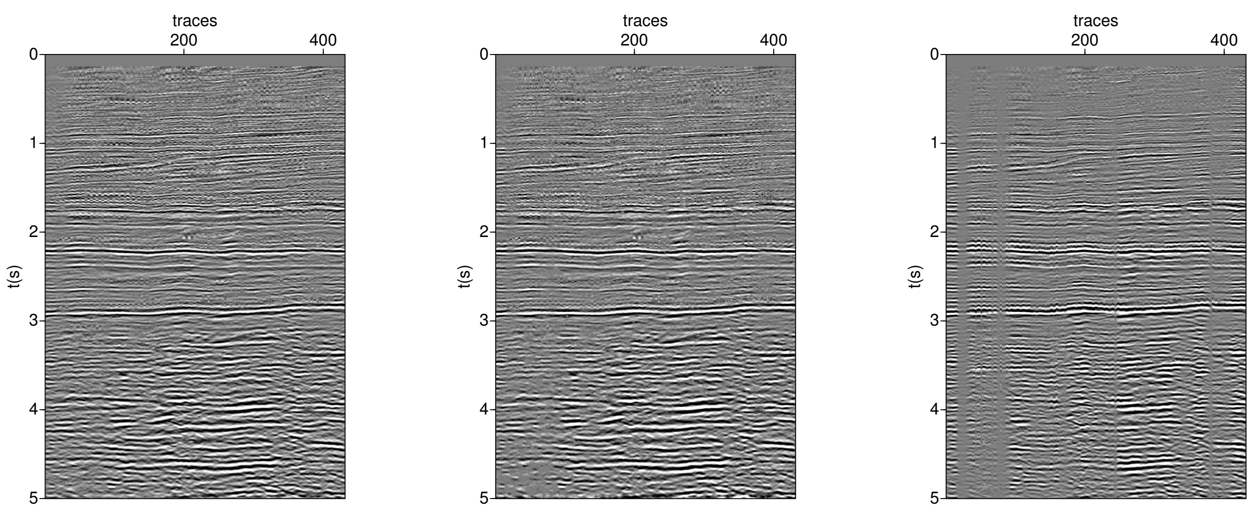
In figure 4, we show the results of the traditional stacking, a modified stacking with one eigenimage and with three eigenimages, for the synthetic data. We can observe in figure 4(b) that by using only one eigenimage we filter a large amount of noise, and the reflectors can be better detected, when compared to traditional stacking in figure 4(a). On the proposed procedure with three eigenimages, reported on figure 4(c) we also observe a filtering of the noise, but the resulting figure is noisier than figure 4(b).

On figures 5 and 6 we show some results of a real data seismic line in Alaska. On figures 5(a) and 6(a) are shown the traditional stacking, repeated to have a better view of the results. On figures 5(b) and 6(b) we show the results of the stacking procedure applying the SVD decomposition on the window of data with one and three eigenimages, respectively. We notice, on both results, the noise was filtered but an amount of signal was lost on figure 5(b) near five seconds when compared with the same area on figure 6(b). The results of the stacking applying the SVD decomposition and creating eigenimages on the NMO panel are shown on 5(c) and 6(c). We noticed a washout in the seismic image but with some horizontal faults. In both cases, we use a supergather of 3 CMP families.



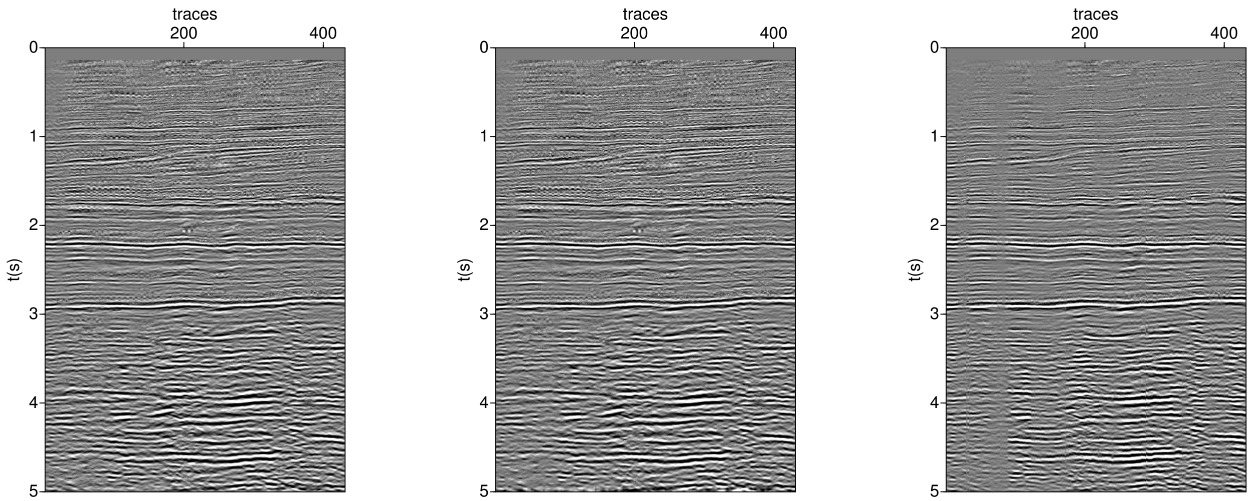

(a) Stacking (b) 1 EigenImage (c) 3 EigenImages

**Fig. 4**: Results of the synthetic data. In (a) the traditional stacking, in (b) the proposed method using only one eigenimage and in (c) using 3 eigenimages.




(a) Stacking (b) Data Matrix (c) NMO Matrix

**Fig. 5**: Results of our simulations using real data of a seismic line in Alaska. In part (b) the SVD is applied in the data window, the first eigenimage is obtained and replace the $\mathbf{X}$ matrix. In part (c) the SVD is applied on the NMO matrix.




(a) Stacking (b) Data Matrix (c) NMO Matrix

**Fig. 6**: Results of our simulations using real data of a seismic line in Alaska. In part (b) the SVD is applied in the data window, the three firsts eigenimages are obtained and replace the $\mathbf{X}$ matrix. In part (c) the SVD is applied on the NMO matrix.

## 5. CONCLUSION

The stacking procedure on a seismic image performs a key feature of the seismic imaging. It increases the signal to noise ratio of the acquired signal that will be used to reconstruct the substructure of an area of interest. Our proposal is to perform a high resolution form of calculating this step using an singular value decomposition, resulting in a seismic representation with no loss in the elements of interest.

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