# Time-frequency vector median filtering and its application to noise attenuation

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Coherent and incoherent seismic noise complicates the analysis of seismic data and attenuation of this noise is one of the primary objectives of seismic data processing prior to imaging. Seismic noise often varies in space as well as in frequency and time, which can be exploited for noise removal. Here, we present a novel noise attenuation method that makes full use of these properties. The new method combines a short time Fourier transform, an extension of the vector median filter to complex numbers, an efficient thresholding method, and a fast dip scan in the frequency domain. This novel method allows the exploitation of variability in seismic noise inside a single process and the attenuation of seismic noise all the way to the spatial alias frequency. This paper introduces the new noise attenuation method with a special focus on the extension of the vector median filter. It then demonstrates the effectiveness of the new processing algorithm for low and intermediate frequency noise attenuation using a field data example from offshore Namibia. The new noise attenuation method facilitates imaging of deep crustal reflectors crucial to meeting the imaging objectives.

## Introduction

Seismic data always comprises both signal and noise; seismic data processing usually concerns itself with the competing objectives of conserving the desired signal whilst attenuating the undesired noise. One approach to seismic noise attenuation exploits time and frequency differences between signal and noise (e.g. primary and multiple arrivals or interfering seismic sources) and the incoherency of the seismic noise in a specific domain (e.g. swell noise in receiver domain). While these properties can be exploited for effective noise attenuation (e.g. Elboth et al. 2010; Gulunay 2008), time-frequency noise attenuation has received relatively little attention as compared to other noise attenuation techniques.

Vector median filtering (Kasparis and Eichmann 1987; Astola et al. 1990), an efficient noise attenuation algorithm, has recently been applied in seismic data processing (Huo et al. 2012; Liu, 2013; Zhang et al., 2013). Since this new algorithm promises improved results compared to conventional median filters, this new methodology merits further research. However, previous studies have focused on the time or frequency domain application of the vector median filter (VMF) and to our knowledge no attempt has been made to extend this method to the time-frequency domain.

In this study, we present a novel time-frequency noise attenuation method based on an extension of the VMF. While previous work focused on the application of the VMF to real numbers in the time domain, the method has been recently extended to filtering complex numbers, which allows noise attenuation in the frequency domain (Perez Ortega 2017). Furthermore, combining this complex VMF with a short-time Fourier transform (Gabor 1946) has allowed attenuating noise in specific frequency bands and specific time windows (Perez Ortega, 2017). Here, we present the extension of the time-frequency VMF with a fast-dip scan that honours the local dip of events in the seismic data. This modification allows noise attenuation in spite of spatial aliasing. Additionally, we have introduced an effective thresholding scheme, which prevents primary damage during noise attenuation.

We start this paper with a review of the frequency and time-frequency VMF and describe how the algorithm has been improved using a fast dip scan and thresholding method. We then apply the method to a field dataset from offshore Namibia and effectively attenuate swell and other low frequency noise. Last, we finish with a short discussion and conclusion.

## Vector median filter for complex numbers

The VMF (Kasparis and Eichmann 1987; Astola et al. 1990) is an improvement over the conventional median filter, because it processes the information not as individual samples, but as vectors and exploits the correlation between signal components. The VMF was introduced to seismic processing by Huo et al. (2012) and Liu (2013). Unlike the conventional sort-based median filter, the VMF is based on the sum of distances between adjacent time-windowed traces around a central sample:

$$D(\boldsymbol{X}_j) = \sum_{i=1}^{N} \|\boldsymbol{X}_j - \boldsymbol{X}_i\|. \tag{1}$$

Here, $\boldsymbol{X}$ denotes a real vector of seismic samples in a time window and the indices $i$ and $j$ refer to seismic traces in a spatial window. The median corresponds to the vector with the smallest distance value $D$ (Huo et al. 2012; Liu 2013). We extend this distance function by replacing the real vector with a complex vector $\boldsymbol{Z}$. Instead of filtering the time samples, we apply a Fourier transform and apply the filter to the complex samples (Zhang et al. 2013). The distance function then becomes:

$$D(\boldsymbol{Z}_j) = \sum_{i=1}^{N} \|\boldsymbol{Z}_j - \boldsymbol{Z}_i\|. \tag{2}$$

The median value can be derived using:

$$\boldsymbol{Z}_m = \underset{\boldsymbol{Z}_j}{\operatorname{argmin}}\, D\left(\boldsymbol{Z}_j\right). \tag{3}$$

Without any further modifications, the complex median allows low frequency noise attenuation in the frequency offset domain.

This frequency-offset VMF works well for flat seismic structures and low frequencies. However, seismic events usually have significant moveout associated with them and application of the above filter may damage these events. Huo et al. (2012) recognized this problem and solved it using a time-domain dip scan. However, in the frequency domain such a dip scan is not feasible.

To implement a complex VMF that honours the dip of seismic events, we first transform the data into the time-frequency domain using a short-time Fourier transform (Gabor 1946). This transform converts each seismic trace into a time-frequency matrix, where each column holds a frequency vector for a constant time. We then apply the VMF to each column of this matrix separately yielding a time-frequency VMF. Having transformed each seismic trace into the time-frequency domain, a dip scan can be implemented using a frequency domain time shift for each column of the time-frequency matrix. After applying a range of trial moveouts, we can find the vector median for all adjacent traces and moveouts. With this modification the distance can be defined as:

$$D\big(\boldsymbol{Z}_j(p)\big) = \sum_{i=1}^{N} \left\| \boldsymbol{Z}_j(p) - \boldsymbol{Z}_i(p) \right\|. \tag{4}$$

Here, the indices $i$ and $j$ refer to seismic traces and $p$ denotes a trial moveout. The median can be found by finding the smallest distance for all adjacent traces and all trial moveouts.

$$\boldsymbol{Z}_m = \underset{\boldsymbol{Z}_j(p)}{\operatorname{argmin}} D\left(\boldsymbol{Z}_j(p)\right). \tag{5}$$

Last, we point out that it is a common problem for noise attenuation algorithms to be overly aggressive in some parts of the data. This effect can be mitigated using a threshold. Therefore, we only apply the filter, if the absolute value of the unfiltered data is significantly larger than the absolute value of the filtered data. This procedure leaves small variations intact and only targets anomalous variations.

**Low frequency noise attenuation using the vector median filter**

In the following section, we will use the new filter for noise attenuation along a 2D seismic line acquired offshore Namibia. The seismic data is part of a large 2D seismic survey and a description of the local geology is given by Hodgson and Rodriguez (2017) and Intawong and Hodgson (2017). The 2D line used in this study consists of 3555 shots acquired with a shot spacing of 25 m. The shots were recorded on 480 receivers with a trace spacing of 12.5 m and the total record length was 8.2 s. While the data were processed using a broadband processing sequence all the way to pre-stack time migration, this study focuses on the early part of the processing flow (i.e. noise attenuation). Prior to noise attenuation only minimal processing was required (navigation merge and trace editing).

The low frequency noise attenuation sequence used in this study included a Fourier transform and two passes of frequency VMF. We started by applying a frequency domain VMF to common channel records from 0 to 8 Hz and to common mid-point gathers from 0 to 6 Hz. The lower cut-off frequency was chosen, because the common mid-point gathers exhibit more dip than the common channel records. The spatial window width was 23/11 traces for common channel/mid-point records and the frequency window width was 0.3 Hz. This effectively attenuated most of the low frequency swell noise visible in the seismic records.

To attenuate higher frequency noise, we applied a Gabor transform followed by a time-frequency VMF between 0-60/0-30 Hz for common shot/receiver records. The cut-off frequency corresponds to the spatial alias frequency for a trace spacing of 12.5 m in the shot domain and 25 m in the receiver domain. The spatial window with was 11/7 traces and the frequency window width was 40/22 Hz for the common shot/receiver gathers. The larger frequency window width for the time-frequency method as compared to the frequency method was due to the coarse frequency sampling of the Gabor transform compared to the Fourier transform. The time-frequency VMF included a dip-scan using 11 velocities between -1.5 km/s and +1.5 km/s. The low frequency noise attenuation sequence was completed by applying a high-pass filter with a low-cut frequency of 2 Hz and a slope of 18 dB.

The results of the new noise attenuation workflow are shown in Figure 1. Seven shot gathers show the effect of applying our processing sequence (Figures 1a-c). Most of the low frequency noise has been effectively attenuated. The small primary damage to the direct wave energy (Figure 1c) caused by the high-pass filter is negligible, since the direct wave is removed in a subsequent processing step. We stress that, although noise attenuation was applied all the way to 60 Hz, no high frequency primary signal was attenuated. Last, the residual low frequency noise visible in the filtered data (Figures 1b) is related to the threshold used to mitigate primary damage.

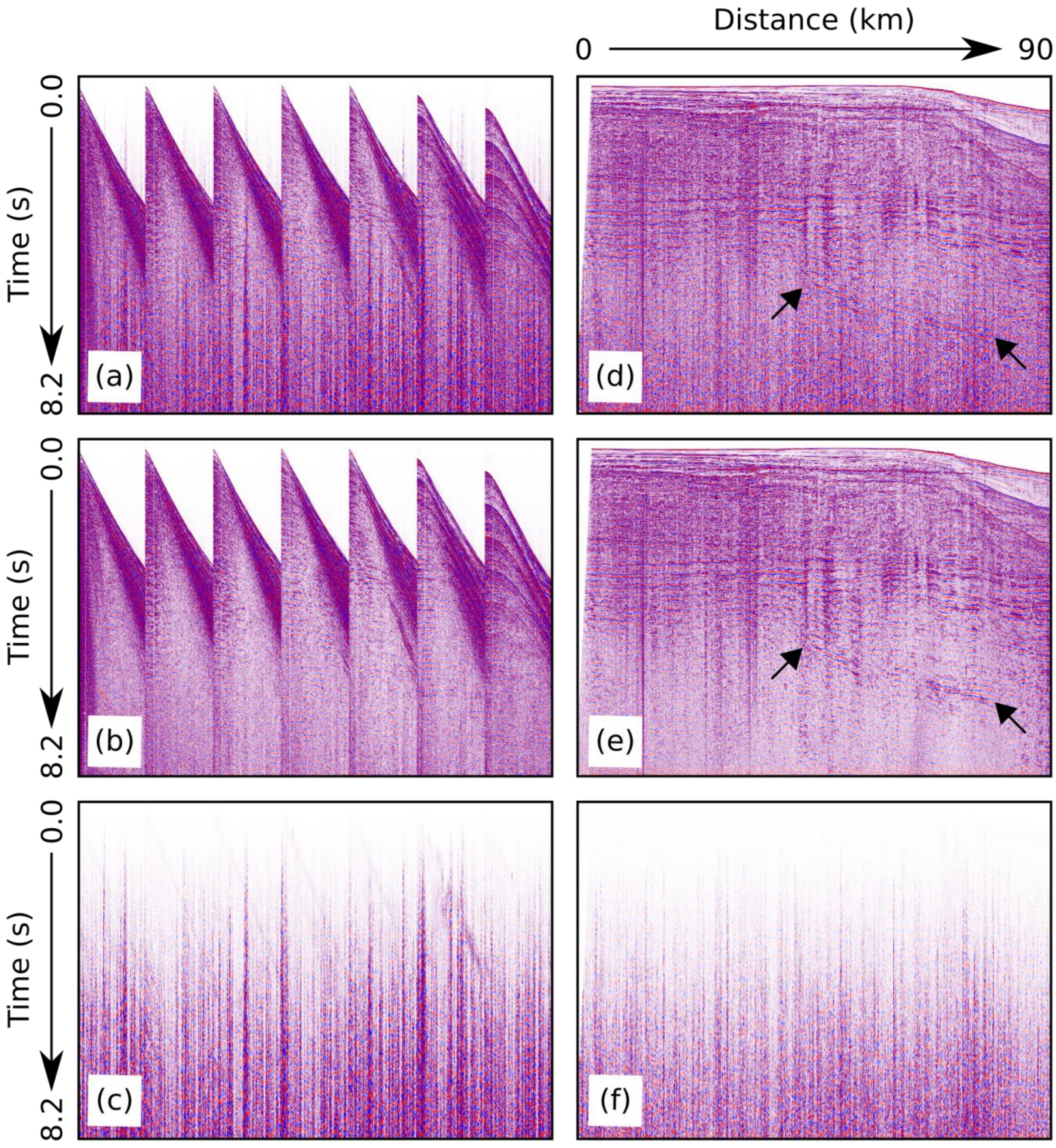


***Figure 1*** *Low frequency noise attenuation using frequency and time-frequency VMF. Figures a and b show seven shots gathers before and after application of the noise attenuation processing flow. The maximum offset recorded for each shot is 6 km. Figure c shows the removed seismic energy. Figures d and e show brute stacks before and after noise attenuation and Figure f the removed seismic noise. The black arrows mark a deep reflector. All data were high-pass filtered with a 2 Hz low-cut and a linear gain was applied with time.*

To illustrate the effect of low frequency noise on the seismic image, we stacked the seismic data before and after noise attenuation using a one dimensional stacking velocity function (Figures 1d-f). The vertical stripes (Figure 1e) are related to high frequency reverberations and are handled at a later processing step. In general, low frequency noise attenuation has considerably improved the seismic image. In particular, the dipping reflector around 6 s was hardly visible underneath the noise and is clearly visible after noise attenuation.

## Discussion and Conclusion

In this paper, we have presented an extension of the VMF to the time-frequency domain. This extension allows attenuating noise that varies with both time and frequency. A comparison with other noise attenuation methods is not included due to a lack of space, but our method performed at least as good as these other methods. Furthermore, an efficient dip scan has allowed us to apply the VMF filter all the way to the spatial alias frequency. This extension is a major improvement over the time domain VMF, since an implementation of a dip scan in the time domain would require pre-filtering the input data to protect against spatial aliasing. In contrast, the time-frequency implementation allows targeting a specific frequency band at a specific time. Finally, we want to stress the flexibility of the VMF framework, which can be handle complex or hypercomplex numbers.

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