Research Article

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Virtual resolution enhancement: A new enhancement tool for seismic data

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Abstract: Virtual resolution enhancement (VRE) is a new poststack cosmetic tool that can be applied to different types of seismic data. VRE emphasizes major reflections, enhances temporal resolution of seismic events, and suppresses reverberation noise, leading to better visualization of the entire seismic data. VRE is based on simple mathematical rule, and its parameters can be tweaked to suite the vast variety of seismic data available today. Although VRE does not reveal new or hidden features on seismic section, it significantly enhances the existing ones, which improves the interpretation and assists automatic horizon picking process. The only disadvantage of VRE is the long computational time. However, given the giant advances in the computational power and speed expected in the near future, this problem should be negligible. Tests conducted on seismic sections, collected from different regions in the world and went through different data acquisition and processing routines, prove the effectiveness of the VRE procedure.

Keywords: processing, contrast, visualization, interpretation

1 Introduction

In a perfect world, a seismic source should produce a zero-phase spike-like seismic wave that travels through the subsurface and bounces back, unchanged, to a receiver that senses and sends only primary reflections to a seismic recorder capable of storing the exact received signal. In practice, however, this is hardly possible.

A perfect source that creates an infinitely short signal does not exist. All land and marine seismic sources create signals with a finite width, which causes reflection from closely spaced interfaces to interfere and reach the receiver as a complex sum of different reflections. Moreover, seismic receivers and recorders have their own response time that causes the recorded signal to be smeared over a period of time larger than that of the reflected wavelet. Source and receiver coupling in land seismic survey is an additional problematic factor in this issue. Another reason of the signal smearing is that the earth is not a perfectly elastic medium, which is another reason for natural distortion of seismic signal as it travels through the earth. In addition, reflections from deep interfaces and at far source–receiver offsets come from larger areas and are averaged during the recording process as a single smeared reflection. The fact that high frequencies are attenuated in higher rate than lower frequencies while traveling through earth is an additional complication that prevents acquiring the ideal seismic section. Near-surface structures in the vicinity of seismic source and/or receivers may cause additional smearing effect to the recorded seismic signal.

Some seismic processing steps also contribute to the distortion of the seismic signals. Stacking of imperfectly aligned reflections and normal moveout correction-induced frequency stretch are good examples of such processes.

Several conventional and unconventional seismic processing tools are designed and successfully applied to restore the seismic reflection to a close approximation of minimum-phase spike-like wavelet. Spiking deconvolution [1], inverse Q filtering [2], loop reconvolution [3], curvature attribute [4], spectral blueing [5], and squash plotting [6] are some of the processing steps aiming to a better visualization of seismic reflections [7].

The pursue of unconventional tools and techniques to enhance the resolution and/or the visualization of seismic data through the application of new algorithms drastically increased in the past two decades [8–16].

Virtual resolution enhancement (VRE) is a new process that can be applied to final stacks as an optional

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process that enhances vertical resolution of major reflection, smooths out wave distortion and irregularities, and increases lateral coherency of reflections. The process is based on a simple mathematical rule and does not alter neither the true amplitude nor the phase of major reflections.

2 VRE concept and procedures

The idea of VRE is based on the simple mathematical fact that when one is raised to any power, it remains constant, while raising decimal digits to power results in decimal digits with smaller values that get smaller with increasing the power value. Assume a positive portion of a typical distorted seismic reflection, as shown in Figure 1a. Now, let us normalize this wavelet, so that its peak value is at one by dividing all its samples by its peak amplitude value. When all the samples of the normalized wavelet are raised to power, the peak amplitude value remains intact while the rest of the wavelet sample values become significantly smaller and closer to each other. The higher the power, the smaller the values of all samples, except for the peak value that remains constant. Figure 1b–d show the result of applying this simple process to the wavelet shown in Figure 1a using the power of 4, 8, and 16, respectively. The original amplitude of the wavelet can then be restored by multiplying all the samples of the resultant wavelet by the original peak amplitude value.

This example clearly illustrates the effect of the VRE process to a typical deformed seismic reflection. The example shows that the VRE process has two major effects on the wavelet: (1) it sharpens the reflection and (2) it removes any irregularities along both wings of the wavelet. The example also shows that the VRE process

has no effect on neither the peak amplitude nor its position. Obviously, the sharpening and smoothing effects, resulting from the VRE process, increase with raising the power value of the samples (Figure 1).

When applying the VRE process to a seismic section, however, the process gets relatively complicated, mainly due to the presence of alternating positive and negative values along every seismic trace. A seismic section can be thought of as a matrix consisting of positive and negative numbers, where traces are represented by columns and time samples are represented by rows. Any data element in this matrix can be referred to as $x_j(t)$, where t is the time value and subscript j is the trace number. Then, the seismic section is defined as $x_j(t)$, $1 \leq j \leq J$, $0 \leq t \leq T$, and the procedure of applying VRE to this section is summarized as follows.

1. Assume an arbitrary trace for some j (Figure 2a).
2. Split the arbitrary trace to generate two traces representing the positive $A^+ = \{a^+(t)\}$ and negative $A^- = \{a^-(t)\}$ values, as shown in equations (1) and (2), and fill the gaps in each trace with Not-a-Numbers (NaNs) (Figure 2b and c).

$$a^+(t) = f^+(a(t)); \quad f^+(x) = \begin{cases} x & x \geq 0 \\ \text{NaN} & \text{Otherwise} \end{cases}. \quad (1)$$

$$a^-(t) = f^-(a(t)); \quad f^-(x) = \begin{cases} x & x < 0 \\ \text{NaN} & \text{Otherwise} \end{cases}. \quad (2)$$

3. Run a vertical sliding window operator with a user-defined length and sliding step along each of the two traces. At each step of the operator, run the VRE procedures that are normalization, raising to the user-defined power and then restoring original values. Normalization is done by dividing all values within the sliding window by the peak value (maximum for positive trace and minimum for negative trace). Restoration is conducted by multiplying all resultant values within the operator by the peak value used for

Figure 1: Simple example explaining the mechanism of VRE. (a) Original wavelet and (b–d) VRE processed with power of 4, 8, and 16, respectively.

normalization. Update the values of A^+ and A^- by the implementation of operators $\varphi(A^+, l, \Delta, r)$ and $\varphi(A^-, l, \Delta, r)$, which are given by

$$\begin{aligned} \varphi(A^+, l, \Delta, r) &= p_i \left(\frac{\check{a}_i^+}{p_i} \right)^r \text{ and } \varphi(A^-, l, \Delta, r) \\ &= q_i \left(\frac{\check{a}_i^-}{q_i} \right)^r \quad i = 1, 2, \dots \end{aligned} \quad (3)$$

$$\check{a}_i^\circ = a_i^\circ (1 + (i-1)l : (i-1)l + \Delta), \quad (4)$$

$$p_i = \max(\check{a}_i^+) \text{ and } q_i = \min(\check{a}_i^-), \quad (5)$$

where $\circ = \{+, -\}$, l represents the phase shift of the sliding window, Δ is the length of the sliding window, p_i is the maximum data value within the sliding window i , q_i is the minimum data value within the sliding window i , and r is a power operator, which is greater than 1.

- Save the results of every operator step in a virtual matrix and fill the gaps with NaNs (represented by N in Figure 2d and e) and slide the window operator

down the trace with the user-defined sliding step repeating the previous step till the end of the trace.

- Average the columns of each virtual matrix into a single column ignoring NaNs (Figure 2f and g) using the following equation:

$$a_{\text{avg}}^\circ = \frac{1}{I} \sum_{i=1}^I a_i^\circ. \quad (6)$$

- Construct the new trace (Figure 2h) by summing the positive and negative columns, as follows:

$$x_j = a_{\text{avg}}^+ + a_{\text{avg}}^-. \quad (7)$$

- Move to the next trace and repeat steps (2–6) for all traces in the entire seismic section.

This sequence of simple mathematical procedures results in a seismic section in which major reflections are sharper, more coherent and with higher fidelity than the original section. Moreover, this enhancement does not affect neither the amplitude nor the phase of seismic events.

Figure 2: Application of the VRE procedure to a single trace.

Figure 3: Nara Basin land seismic section (a) before and (b) after VRE. Black rectangles indicate areas magnified in Figure 4.

3 Results

The VRE technique is examined using three seismic sections collected in different locations of the world using different data acquisition field parameters and procedures. The first seismic section is collected during a land seismic survey over a fault plane in Nara Basin, Japan. The second

section is a marine seismic section imaging the northern Atlantic margin, offshore the eastern coast of the United States. The third section is a land seismic section collected over faulted sedimentary layers in the Nile Delta, Egypt, near the Mediterranean Sea coast.

The Nara Basin land seismic section is collected by the Geological Survey of Japan over a thrust faulted

Figure 4: Magnified views of the rectangular areas marked in Figure 3 before (left) and after (right) VRE.

sequence composed of alternating marine sand and clay layers underlain by granitic basement rocks [17]. The source used in this survey is a *P*-wave impactor with a shot interval of 5 m. Data are collected using geophone spacing of 10 m where six inline geophone arrays are

used in every geophone location. A 60-channel Bison seismograph is used to record the data at sampling rate of 1 ms.

A standard processing routine is applied to these seismic data. The processing sequence starts with

Figure 5: Amplitude spectra of the seismic section shown in Figure 3 (a) before and (b) after VRE.

geometry input and gain recovery followed by routine data editing. The static correction applied to the data utilizes both elevation and refraction statics. Moreover, residual static correction is applied to the data after normal moveout (NMO) correction. Predictive deconvolution is applied to the data. The data are then sorted into common midpoints (CMPs), and the velocity analysis is performed using combined velocity semblance, constant velocity scans, and hyperbolic fitting techniques. NMO correction is performed using the velocity information obtained from the velocity analysis. The data are then stacked, bandpass filtered, and migrated. The resultant seismic section is shown in Figure 3a.

The aforementioned data collection and processing procedures and parameters have resulted in a fairly high-quality seismic section displaying interesting subsurface features. The seismic section clearly shows two reverse faults at CMP 200 and 1,100. It also shows the alternating sedimentary layers unconformably overlying the irregular basement rock surface dipping from west to east in the time intervals between 350 and 550 ms. Folded ductile clay layers in the vicinity of the fault planes are clear and well defined.

The seismic section, shown in Figure 3a, is then subjected to the VRE procedure using a window length of 40 samples and a power of 1.8. These parameters are chosen using trial and error as they yield the best results. The VRE section is displayed in Figure 3b, while Figure 4 displays the magnified views of some parts of the sections before and after the VRE process.

In general, major reflection on the VRE section appears sharper and better defined than those on the original section (Figure 3). Moreover, granular random noise covering the background of the section seems to be

attenuated after the VRE procedure. In addition, termination of reflections near the faults are stronger and clearer on the VRE section, which makes it easier for the interpreter to track and mark fault lines in the VRE seismic section.

The five rectangular areas marked in Figure 3a are magnified in Figure 4 along with their corresponding areas on the VRE section. Figure 4I clearly shows how the weak undefined reflection that is embedded in fuzzy granular noise between CMPs 0 and 250 at time interval of 120–170 ms (Figure 3) becomes totally different after the VRE procedure. The reflection appears more incise, and the random granular noise is completely smoothed away. This is also the case with the folded reflection between CMPs 300 and 550 and time interval 260–310 ms, where the reflection termination is clearer, and the random noise causing the granular appearance and fuzzy look of the background is highly attenuated after applying the VRE procedure (Figure 4II).

Figure 4III is a magnified view of a group of closely spaced reflections terminated by faulting. The reflections themselves and their fault termination are easier to interpret and to track at the section subjected to VRE. The basement rock reflection in addition to its relationship to the reflections from overlying sedimentary layers are better defined, sharper, and easier to interpret on the VRE section than on the original section (Figure 4IV and V).

Figure 5 shows the amplitude spectra of the entire section before (a) and after (b) performing the VRE process. The low-frequency portions of both spectra (0–50 Hz) are almost similar, while high frequencies (50–150 Hz) have been significantly amplified after the VRE procedure. The increase of the frequency bandwidth is a direct result of the spiking of reflections after VRE.

Figure 6: US Coast marine seismic section (a) before and (b) after VRE. Black rectangles indicate areas magnified in Figure 7.

The broadening of the amplitude spectrum after conducting the VRE procedure is an indicative of increasing temporal resolution of the VRE section. Broadening the spectra may, in many cases, broaden the noise as well. In this case, however, the spectrum has been broadened, as evident from Figure 5, while the noise is attenuated as shown in Figure 4.

The second seismic section used for testing the VRE approach is a part of the geophysical database of the eastern coast of the United States imaging the northern Atlantic margin [18]. The data of this seismic line are collected using an airgun array and a 3,600 m-long 48-channel streamer with a shot interval of 50 m. The total length of this seismic line is 135 km, but the portion used

for examining the VRE procedure is only 10 km long. These data are subjected to a routine seismic processing strategy that starts with editing, gain recovery, predictive deconvolution, velocity analysis, and NMO correction. The data are then stacked, bandpass filtered, and scaled.

The original seismic section is displayed in Figure 6a, while Figure 6b shows the same section after conducting

the VRE procedure using a widow length of 35 samples and a power of 2.7. In general, all reflections are sharper and more reliable on the VRE section. This is most evident at the sea bottom reflection, especially in the area between CMP's 600 and 1,000. Moreover, the group of closely separated reflections at the shallow part of the section is better distinguished at the section treated with

Figure 7: Magnified views of the rectangular areas marked in Figure 5 before (left) and after (right) VRE.

Figure 8: Amplitude spectra of the seismic section shown in Figure 6 (a) before and (b) after VRE.

the VRE procedure. This can be clearly seen at the group of shallow reflections between CMP's 200 and 400 between 3 and 3.5 s. It can also be seen between CMP's 600 and 1,000 at 2.5 and 3 s.

Figure 7 displays magnified views of the rectangular areas marked in Figure 6a. The left-hand groups are for portions before VRE and the right-hand groups are for the same portions after performing the VRE procedure. Figure 7I clearly shows that the sharp and strong sea bottom reflection becomes more distinguished after conducting the VRE process. The few thin closely spaced reflections below the sea bottom reflection are sharper and can be separated in a much easier manner in the section treated with VRE than those on the original section.

Deeper reflections, shown in rectangles II, III, and IV, are also spikier, clearer, and more distinguishable on the section treated with the VRE procedure. Moreover, all the magnified views, shown in Figure 7, show that the granular random noise and the fuzzy appearance of major reflections have significantly disappeared after applying the VRE procedure. Figure 7I and III is a good example of the disappearance of fuzziness after applying the VRE procedure, while the disappearance of granular random noise is clearly shown in Figure 7II and IV.

The amplitude spectra, shown in Figure 8, show a notable increase in the high-frequency portion after performing the VRE procedure, specifically, the frequency band between 40 and 100 Hz. The frequency band between 100 and 200 Hz also shows relative increase in the data treated with the VRE procedure. The low-frequency band (0–40 Hz) is almost similar on both amplitude spectra.

The third seismic section used for examining the VRE technique in this study is collected in the northern part of

Nile Delta near the coast of the Mediterranean Sea, Egypt, as a part of a land seismic survey conducted to explore oil and gas potential in this area. The section is 1,300 m long and extends to 1.5 s. The data are collected using a vibroseis with a linear upsweep of 10–80 Hz and a sweep length of 10 s. Both shot interval and receiver spacing are 20 m, and each receiver station consists of 12 inline geophone arrays. The processing of this dataset involves editing, designating, resampling, and gain recovery followed by CMP sorting. The sorted data are then subjected to the velocity analysis, NMO correction, and stacking. The stacked data are bandpass filtered and subjected to predictive deconvolution followed by migration and scaling.

The migrated seismic section (Figure 9a) is then treated with the VRE procedure using 24 samples operator length and 1.6 power. The VRE section is displayed in Figure 9b. Hence, the VRE process has resulted in a seismic section with higher temporal resolution in which reflections are sharper and well separated from each other. In addition, the VRE section has less fuzzy and smeared areas than the original section.

In general, the VRE section has better identifications of fault locations and geometries, and bed terminations are better defined. The enhancement of vertical resolution is relatively more significant in the deeper part of the section, probably because of more loss of higher frequencies in this part of the section. The magnified views of rectangles, marked in Figure 9 and displayed in Figure 10, show some interesting features. A group of parallel, closely spaced reflections are more separable on the VRE section than those of the original section (Figure 10I and II). The exact location of bed termination induced by faulting is much easier to determine on the

Figure 9: Obaiyed Field land seismic section (a) before and (b) after VRE. Black rectangles indicate areas magnified in Figure 10.

VRE section than on the original section (Figure 10III and IV). Moreover, the granular random noises in the original section are highly attenuated in the VRE section leaving clear-cut sharp reflections that can be easily detected, traced, and mapped.

Figure 11 displays the amplitude spectra of the entire seismic section before (left) and after (right) the VRE procedure. The low-frequency band (0–40 Hz) remains

intact, while the high-frequency band (80–120 Hz) shows significant improvement. The middle-frequency band (40–80 Hz) also shows relative improvement after conducting the VRE procedure.

Examining the VRE procedure using these three seismic sections shows that the VRE process has a positive impact on the temporal resolution of different seismic sections collected using different field acquisition

Figure 10: Magnified views of the rectangular areas marked in Figure 5 before (left) and after (right) VRE.

procedures and parameters and at different environments. These seismic sections are also treated using different processing routines and have different vertical and horizontal scales and resolutions. In all three cases, the VRE procedure has resulted in improved seismic sections in terms of temporal resolution, clarity and coherence of reflections, suppression of granular random noise, and general appearance of the seismic section.

4 Discussion and conclusions

This study introduces a new powerful processing tool to enhance the visualization of seismic data. The new tool is called VRE tool. VRE enhances the temporal resolution of reflection and smooths away the distortions of seismic wavelets. By doing so, it brings about a seismic section with sharper reflections and less random

Figure 11: Amplitude spectra of the seismic section shown in Figure 9 (a) before and (b) after VRE.

noise and fuzziness caused by smeared reflection and reverberations.

The VRE procedure is based on the simple fact that decimal digits get smaller in value when raised to power, while one remains constant despite the power to which it is raised. The technique utilizes a sliding window of user-defined length and variable sliding step to be capable of dealing with the large variety of seismic data available today. The method involves five major steps: (1) splitting the seismic section into a positive matrix and a negative one; (2) normalizing the data within each window position; (3) raising all samples inside the window to the user-defined power; (4) restoring original amplitudes; and (5) merging the two matrices to get the VRE section.

The VRE technique is examined using three different land and marine seismic sections collected in different regions of the world using different data acquisition and processing parameters and having different temporal and spatial scales and resolutions. The results clearly show that VRE enhances the general appearance of seismic sections and makes them easier to interpret, sharpens major reflections, makes it easier to track and map them, attenuates random granular noises, and reduces smearing effect on reflections. Magnified views of some parts of the three seismic sections used to test the VRE technique show significant enhancement in terms of reflections' sharpness, entity, and periphery recognition. Moreover, amplitude spectra of the three seismic sections show substantial amplification of the high-frequency portion in all of them after applying the VRE tool.

Even though the proposed VRE procedure does not reveal hidden features or expose new reflections, it definitely enhances the present ones and makes the picking, tacking,

and mapping processes of existing major reflections much easier, especially if automatic event tracking is used. VRE is data dependent and does not involve the application of a foreign operator that is either designed by the user or preset by the software, which is the case in most other seismic data processes involving a sliding window operator. Moreover, the window length, sliding step, and power parameters can be tweaked by the processor to facilitate dealing with different sorts of seismic data.

The only drawback of such a technique is the long computation time. A 500×500 matrix needs between 100 and 130 min, based on the window length, to process on a PC with a 3.4 GHz Core i7 processor. However, given the huge progressions occurring every day in computer power and speed, this should not be a problem at all in the near future. In addition, the VRE procedure can be tested on a small segment of the seismic section until the optimum VRE parameters are reached, and then, the selected parameters can be applied to the entire seismic section. It is worth mentioning that increasing the operator length and adjusting the sliding step to skip one or two samples drastically decreases the computation time. However, the results are not always satisfactory.

Finally, VRE procedure comes last in any seismic processing routine and can be used as an additional or optional step to create an impressing or even a client-appealing final section. It can be also used to prepare the data for a more precise automatic event picking and tracking.

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