From noise to clarity: A velocity-dependent mute approach in 3D Tau-p domain with signal protection in FK domain for denoising OBC data

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Keywords

3D linear Tau-p transform, Radon transform, FK transform, OBC, OBS, PZ summation, UDD, Velocity dependent mute, Radon mute, Geophone Noise attenuation, Matching Pursuit Fourier Interpolation

Abstract

Addressing noise in multicomponent OBS (Ocean Bottom Seismic) data is crucial for accurate seismic imaging and interpretation. Noise in OBC (Ocean Bottom Cable) data can arise from various sources and can significantly affect the quality and interpretation of the acquired seismic signals. These noises can come from internal or external sources. The internal noises can come from faulty instruments, cable crosstalk, problem in analog-to-digital converters and other acquisition related issues; whereas external noises can get introduced from ocean currents, biological activities etc. The severity of the noise again depends upon the acquisition environment, especially for shallow marine environment the data gets greatly affected by noise. In case of vertical component data, especially with some of the early acquisitions, with the technological limitations, the acquired vertical component data used to be very noisy. Sea-bed currents, poor geophone coupling with the sea bed – were great challenges to cope with in acquisition stage. Today with advancement in processing techniques and resources, those noises can be tackled well. This paper explores one such resource intensive noise attenuation technique based on 3D linear Tau-p transform where a priori knowledge of velocity at each receiver location has been used to delineate the signal zone in the transformed domain with further signal protection with the help of FK filter design for an OBC data.

Introduction

With the advantage of wide to rich azimuth acquisition, monitoring of established field with 4D surveys and avoidance of data gap instead of presence of platforms or other obstacles; Ocean Bottom Cable (OBC) seismic data acquisition has gained quite a prominence in the field of geophysics. In terms of processing of the data, multicomponent OBC has the advantage of opposite polarity of downgoing wavefields in hydrophone and vertical geophone data. Whereas upgoing wavefields do have the same polarity in both the components. Thus combining these two data can help for better preservation of the signal attenuating receiver side ghosts and surface multiples. With the introduction of UDD (Up-Down Deconvolution) technique for processing of OBS data; PZ summation, Surface multiple attenuation, 3D Source deghosting and zero-phasing (provided deghosted and zero-phased source signature is supplied in the flow)– all can be done in a single flow. Because of this all the downgoing wavefields, including direct arrivals have to be kept intact in the input data of UDD flow. The UDD process itself work on receiver point by point basis for a parallel shooting geometry, in 3D Tau-p domain.

This very preparation of the data for UDD which itself is resource intensive, has inspired the attempt of this innovative noise attenuation technique. While preparing data for UDD receiver point wise, the central velocity function of each receiver location has been dumped separately to call later on to define the mute zone in Tau-p domain. Because the output of UDD combines P and Z component to finally output a single entity, the effectiveness and efficiency of the noise attenuation technique has been established individually on both the components to explore how it brings clarity to our data attenuating the noise.

In this paper, the noise attenuation technique not only explores the effectiveness to attenuate noises (mostly linear and some random noises) while bringing back data from 3D Tau-p domain to x-t domain while performing UDD; but also, as a standalone process, especially for old OBC geophone data, how beautifully it can bring clarity to data overcoming presence of excessive noise, that also has been explored.

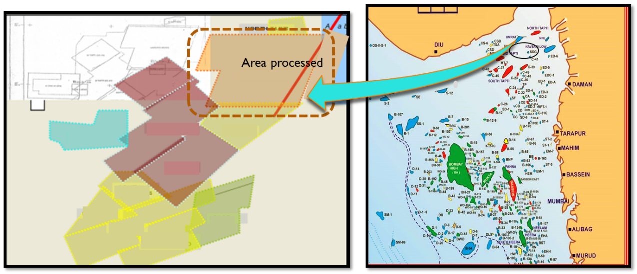
This study has been carried out in OBC data, acquired in late 1990s in Kutch Saurastra basin, where two different data blocks were acquired with two different acquisition geometry (Parallel & Orthogonal shooting). Effectiveness of this technique has been shown using data from both the geometries and how a priori velocity information can be used along with additional signal protection in FK domain filter design, that have been discussed in this paper.

Acquisition geometry

The data used for the study in this paper has the following acquisition parameters:

Acquisition Mode	Ocean Bottom Cable 3-D Swath
Nominal Fold	60
Shot Interval	25
Size	Approx. 1500skm
Bin Size	25*25
Receiver Line Spacing	400m
Receivers	Dual Sensor
Group Interval	50m inline
Shot Interval	50m inline
Source-Line Interval	50m
Min. Continuous Offset	375m
Max. Nominal Offset	3000m (with the intrinsic nature of the OBC survey, offset up to 12km was available as the cable was active throughout the spread)
Record Length	5s
Sampling Rate	2ms
Low- Cut Filter	3Hz-6dB/octave
High- Cut Filter	206-276dB/octave
Geophone Type	Geospace GS-PVI-S
Hydrophone Type	Geospace GS-PVI-S
Group Length	4 meters

The geophone sensors used in this survey were velocity sensors. Only z-component geophone has been used in this survey, thus no shear component has been recorded in this OBC survey.



FigureA: Area location

Theory

The Radon transform is a mathematical operation that facilitates the mapping of seismic data from t-x-y space to τ-p-q space. When considering a single spatial dimension, typically the source-detector offset, the Radon transform can be interpreted as a line integral:

$$m(\tau,p) = \int_{-\infty}^{+\infty} d\big(x, t = \tau + g(p,x)\big)dx \qquad \ldots (1)$$

The symbol τ denotes zero-offset time, t refers to two-way travel time, and x represents a spatial coordinate, such as offset. The function g(p,x) governs the linearity or nonlinearity of the Radon transform. In the case of a linear Radon transform, $g(p,x) = px$, whereas for a parabolic Radon transform, it takes the form of $g(p,x) = px^2$. The function d(x,t) corresponds to the input seismic data, while m(τ,p) signifies the transformed data in Radon space.

Extending this equation to two spatial dimensions yields:

$$m(\tau,p,q) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} d\big(x,y,t = \tau + g(p,q,x,y)\big)dx\,dy \qquad \ldots\ldots (2)$$

where, y is a second spatial dimension, and $g(x,y) = px + qy$ for a linear transform and $g(x,y) = px^2 + qy^2$ for a parabolic transform. In the case of linear transforms, p and q denote the curvature in units of slowness (1/seismic velocity or seconds/meter) along the x and y directions, respectively. However, for parabolic transforms, p and q indicate the curvature in units of seconds per square meter along the x and y directions, respectively.

An effective approach for implementing the forward and inverse transforms can be achieved in the frequency domain. By converting the initial seismic data from the (t,x,y) space to the (f,x,y) space, where 'f' represents temporal frequency, the Radon

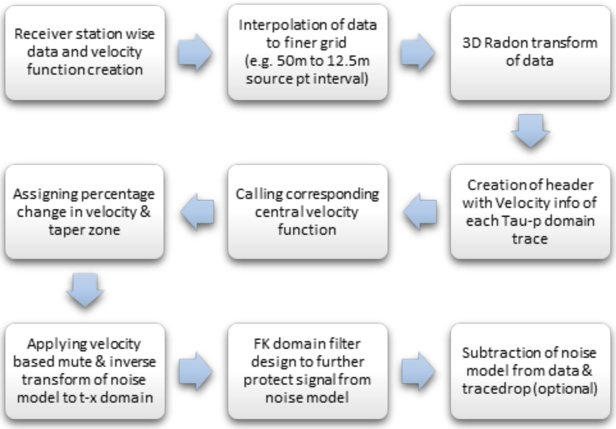
transform can be carried out in the frequency domain. At each frequency ω = 2πf, a system of linear equations can be established as follows: $d = Am$ .. (3)
Where d represents the seismic data vector (in this instance, a frequency slice), m denotes the model vector, and A signifies the Radon operator, formulated in three dimensions as follows:

$$A_{pl} = e^{i\omega(g(p_l q_l x_p y_p))} \quad \ldots (4)$$

The forward transform is determined by selecting an appropriate value for m in order to minimize the discrepancy between the observed seismic data, d, and the model data obtained through the inverse transformation, Am. This process entails solving the equation: $(A^H A + kI)m = A^H d$ …… (5)
where, k is a "white noise" parameter and I is the identity matrix.
As described in the explanation of variables of equation (2), for a linear 3D Tau-p transform, the p and q denotes the curvature in units of (1/seismic velocity); thus if a header can be assigned to each Tau-p transformed trace for its corresponding seismic velocity and the corresponding central velocity function for the receiver location can be called, a mute zone can be defined for the Tau-p transformed data as per the variation of velocity with time in the central velocity function, as both t and τ are same for the central velocity function, i.e. the zero-offset time.
Also, instead of applying the exact velocity function, a percentage increased or decreased velocity value can also be used depending upon how hard or mild the mute needs to be applied. Also a taper zone can also be defined to apply the mute, as can be seen in Figure5.
Thus even for a data, where very accurate velocity is not available, even central velocity function from brute onboard velocity can be used for applying mute.
The manual mute picking do have the chances of man-made error, again the mute cannot be picked at all the locations, nor can it be picked in a surface consistent manner throughout thoroughly. The velocity based mute approach thus brings much more robustness in defining the signal zone, making it more accurate for each of the receiver location, consistent with the geology of the area as well.
Moreover, the noise model after applying velocity based mute in Tau-p domain can additionally be conditioned in FK domain to protect if there be any signal leakage by designing a polygon filter or fan filter in FK domain, as can be seen in Figure6. Chances of losing any diffraction legs thus reduces to great extent which is a very important aspect of noise attenuation, as can be seen in Figure7.

Method/ Processing Steps

High resolution 3D linear radon transform needs some pre-processing of the data as well. To map the events in Tau-p domain in a better manner a better spatial sampling of the data is also needed. Thus, interpolation of input data to a finer grid is a very important step in 3D radon transform. If the overall process has to be summed up in a workflow, it can be done using the following flowchart.



The above mentioned interpolation is a very key step in this noise attenuation approach. Not only proper interpolation of data helps to get rid of noises like aliasing, it also ensures stable domain transfer of data associated with other processing steps moving forward.

In this study, 3D interpolation has been done on receiver gathers, reducing sot interval and source line intervals from 50m to 12.5m. The algorithm used for the interpolation is MPFI (Matching Pursuit with Fourier Interpolation); where the following steps are followed for the interpolation:

(a) The desired output traces are grouped into spatial windows based on their values of the interpolation literals
(b) This data is further divided into time windows
(c) Each small spatial/temporal 3D, 4D or 5D data volume (based on our choice of interpolation variables; in this case 3D interpolation has been done) or spatial-

temporal window is considered as processing units

(d) For each output spatial window, the corresponding input traces will be selected from the input data set

(e) 1D FFT for each trace along the time direction (to frequency domain)

(f) 2D discrete Fourier transform the f-x-y data to f-kx-ky along the 2 spatial dimensions for each frequency

(g) Pick the Fourier coefficient (kx, ky) that has the largest amplitude and this component to the estimated spectrum

(h) Transform this component back to the input locations

(i) Subtract the component from the input data

-and this process is repeated for several iterations as supplied by the user.

The choice of 12.5m target interval for interpolation has been done after rigorous testing with different parameters; the final decision has been made based on the (a)Inline offset vs. cross-line offset distribution study and (b)pre and post interpolation data comparison of hydrophone and geophone data, following are some pictures of the decisive study:

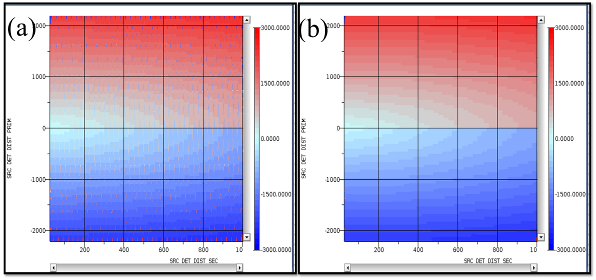


Figure1: Inline vs. Xline offset distribution (a) before interpolation; (b) after interpolation

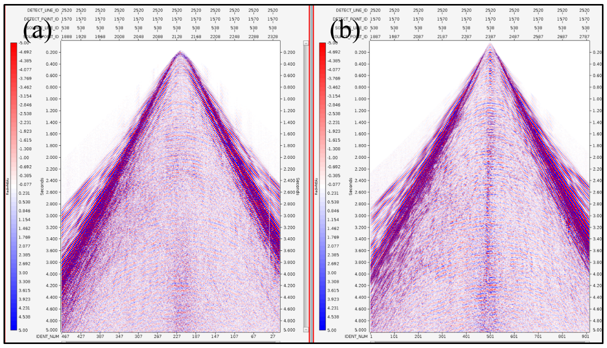


Figure2: Hydrophone data showing decrease in aliasing noise (a) before interpolation; (b) after interpolation

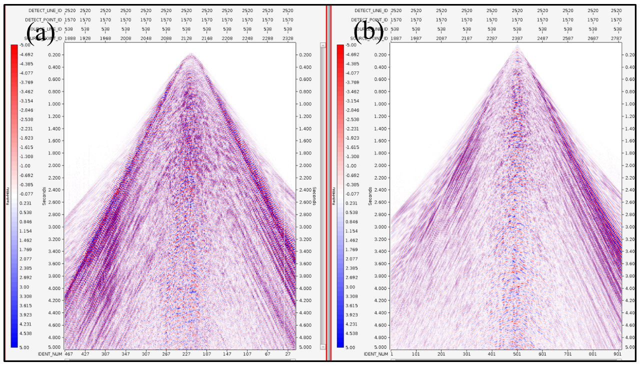


Figure3: Geophone data showing decrease in aliasing noise and better spatial resolution (a) before interpolation; (b) after interpolation

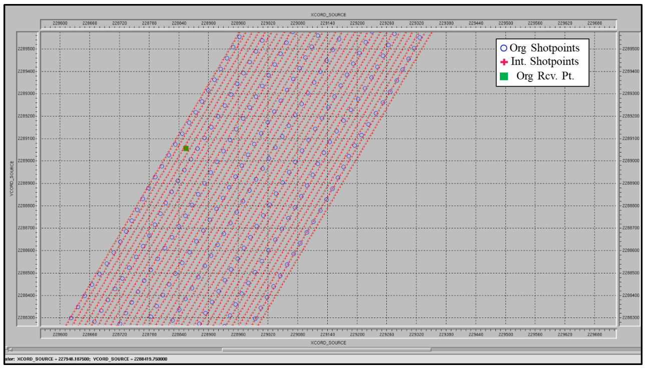


Figure4: Position of interpolated shot points with respected to actual shot points and receiver position

In case the noise is being attenuated as part of UDD flow as described earlier in introduction part, both UDD output of Tau-p domain i.e. UDD Tau-p data with mute and without mute have to be used to map their difference to x-t domain, and defined signal part of that data in FK domain have to be added back with the x- t transformed muted UDD output to ensure there is no data leakage in noise model.

Examples & Discussion

This study has been conducted on the Matching, Merging and Pre-stack Time Migration (PSTM) processing project of 3D OBC seismic data (P & Z component only) for two different areas acquired in late 1990s in Kutch Saurastra basin, where geophysical objective has been to process the data using UDD technique. The overall processing flow includes - Geometry merge, Debubble, random & coherent Noise Attenuation, Geometry Correction, Spectral Decompose, PZ calibration, UP-Down Deconvolution, Residual LNA, Static Correction, Surface Consistence

Decon, Matching, Merging , 3D Regularization, Anisotropic Migration, Post processing on gather & stack.

The noise attenuation technique discussed in this paper has been established as a standalone random and linear noise attenuation technique, although in production sense the technique has been used in UDD workflow itself to attenuate the noises while bringing back data from Tau-p domain to x-t domain. But as discussed earlier, output of UDD not only attenuates noise in Tau-p domain, but it also performs Upgoing & Downgoing wavefield separation, 3D source Deghsoting, Surface multiple attenuation and Zero-phasing of data. Thus to explain the effectiveness of this noise attenuation technique, results of this noise attenuation technique as a standalone has been showcased.

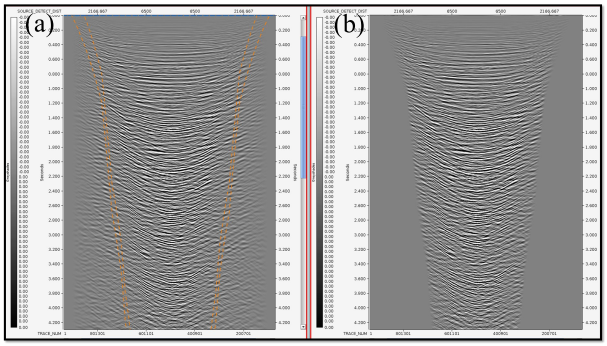


Figure5: 3D Tau-p transformed data shown in a 2D planar view with velocity function overlaid with taper and mute applied.

As can be seen from Figure5 (a), the called central velocity function overlaid with some taper exactly fits an ideal mute for the data, as can be seen in Figure5 (b) which is mute applied data.

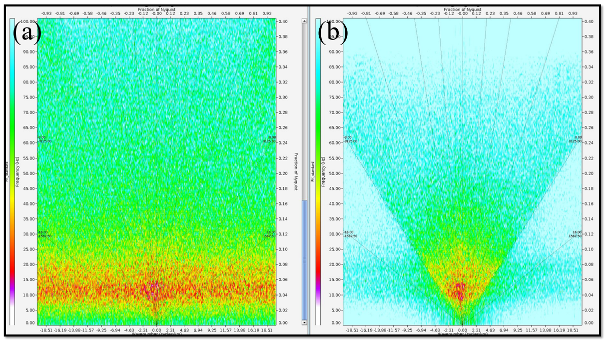


Figure6: (a) FK spectrum of the noise model (b) fan-filter designed to protect any signal leakage in the noise model.

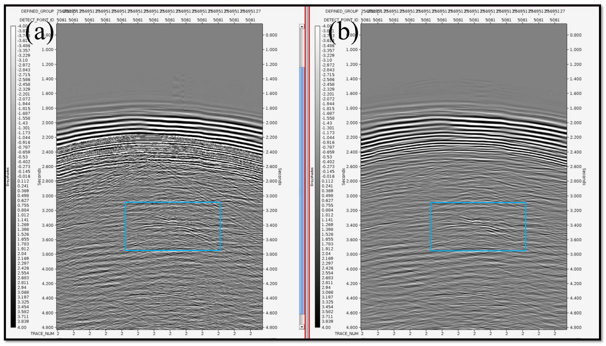


Figure7: Highlighting the signal protection efficiency (a) Receiver gather of P component before noise attenuation (b) after noise attenuation

As can be seen from the highlighted box in Figure7 (a) and (b), the diffraction events have not been affected with application of this noise attenuation technique, whereas other random and liner noises have been attenuated successfully.

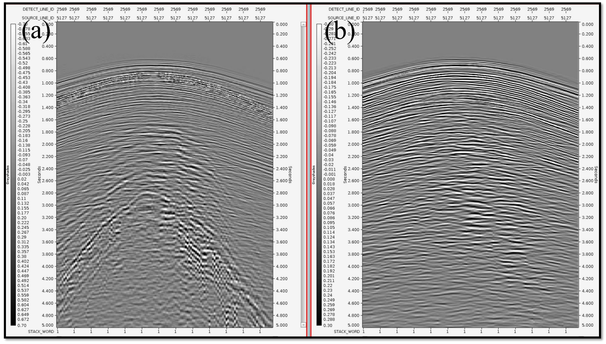


Figure8: Highlighting the effectiveness in attenuating linear noises (a) Receiver gather of P component before noise attenuation (b) after noise attenuation

Figure8 clearly depicts the effectiveness of this technique to bring clarity in data attenuating the noises. As can be clearly seen the low velocity noises present in the gather (a) has been attenuated very effectively unveiling the signals (b) which were masked behind.

As discussed earlier in abstract, old OBC vertical component data used to get severely affected by noises due to various factors. The following figures show effectiveness of this technique to bring certain clarity to such data attenuating the noises.

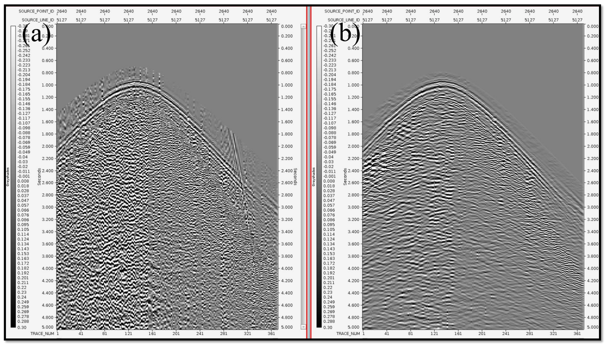


Figure9: Highlighting the power of this technique to bring clarity to the severely noise affected Z component data of an old acquisition (a) shot gather of Z component before noise attenuation (b) after noise attenuation

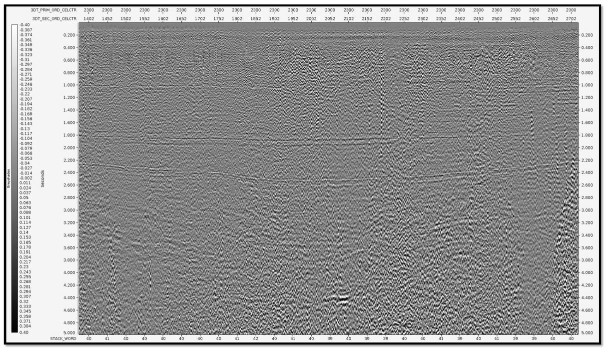


Figure10: Stack of crossline-2300 before noise attenuation

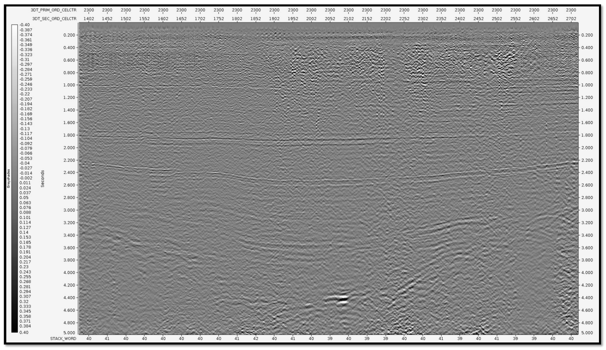


Figure11: Stack of crossline-2300 after noise attenuation

From Figure 10 and 11, the effectiveness of this noise attenuation technique can be clearly seen at stack level itself. All the major reflectors, which were not visible initially can be clearly seen after noise attenuation.

Also the overall clarity in the data has improved quite visibly, especially at the right-bottom part of the data, the improvement in imaging is really significant. The effectiveness of the technique can be more appreciated if a closer look of the mentioned part of the stack can be observed. The following images contains the same, with image of a spectra of the said zone.

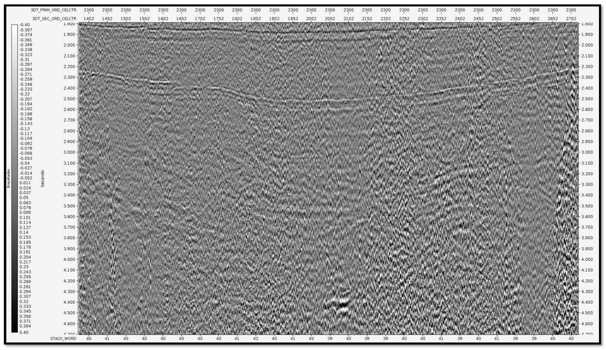


Figure12: Zoom of stack of crossline-2300 before noise attenuation

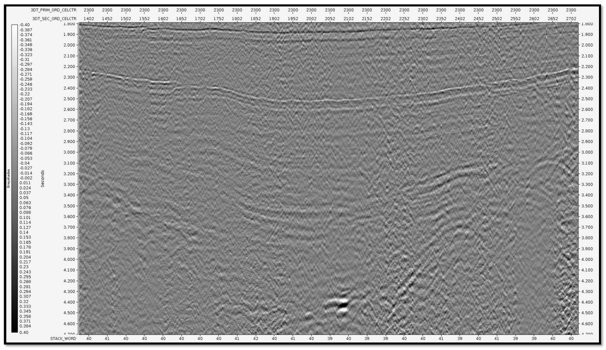


Figure13: Zoom of stack of crossline-2300 after noise attenuation

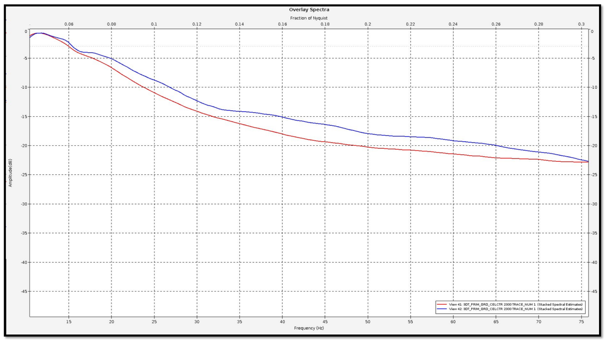


Figure14: Improvement of spectra in the major bandwidth range; red – input, blue – after noise attenuation

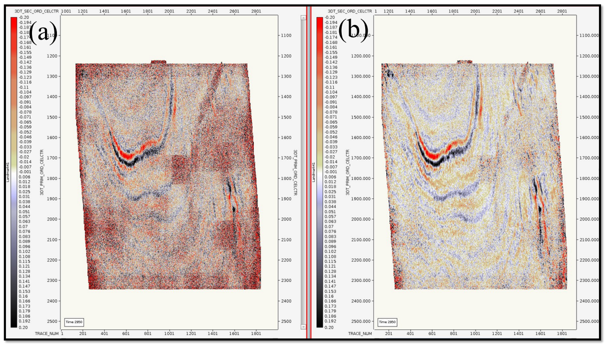


Figure15: Time Slice (2950ms) (a) before & (b) after noise attenuation.

A clear depiction of the enhancement of the signal to noise ratio in the overall data after application of this noise attenuation technique can be seen from the Figure 15. As we can see in (a) before application of the process there were several noise patches throughout the time slice, masking all the geological event;, whereas after application of this innovative noise attenuation technique, there is a clear enhancement in the data clarity, unveiling all the major geological events attenuating the noises.

Conclusions

In conclusion, the removal of different noises in OBC (Ocean Bottom Cable) seismic data is a crucial step in ensuring the accuracy and quality of seismic imaging and interpretation. This noises can get generated due to various internal or external factors, such as cable crosstalk, ocean currents, biological activities, source/receiver coupling etc.

The effectiveness of this 3D linear Tau-p transform based velocity dependent muting technique, depends on how this velocity information is being used, i.e. the percentage change in velocity used to apply the mute and choice of tapering zone along with the design of the FK filter to protect any signal leakage in the noise model. Whereas the efficiency of the technique depends whether there is any need of such resource intensive process for the kind of noise present in the data. In terms of applying the technique for a wide to rich azimuth data, the use of 3D Tau-p modelling of the data can unleash its true power, e.g. OBC, OBN data. Especially if a process like UDD is being used which anyhow uses 3D Tau-p domain along with a receiver station by station approach, this process can be used easily without any extra cost.

Similarly for some old acquired OBC data, where the geophone component is highly affected by noises, this process may come out very helpful, rather than trying many other noise attenuation techniques which in combination may cost the same in long run.

By effectively mitigating such noise in OBC seismic data, the quality and dependability of the resultant subsurface images and interpretations can be greatly enhanced. This, in turn, facilitates more precise geological and geophysical analysis, fostering a deeper comprehension of subsurface structures, reservoirs, and potential hydrocarbon resources. Ultimately, these advancements offer substantial benefits to the exploration and production activities within the oil and gas industry.

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