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Water Bottom Multiple Elimination and Data Quality Enhancement Using Parabolic Radon Transform: A Case Study of 3D Seismic Data from Offshore Niger Delta

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Abstract The aim of seismic data processing is to obtain accurate image of the subsurface which can be interpreted in terms of subsurface structures favourable to hydrocarbon accumulation. Multiples destructively interfere with primary reflections and their removal from reflection seismograms has been a longstanding problem to seismic processing geophysicists. If not eliminated, their presence could make seismic data interpretation difficult and lead to erroneous results. In this study, an attempt was successfully made to eliminate water bottom multiples by application of a specially derived parabolic radon filter on a 3D streamer seismic dataset acquired from offshore Niger Delta with the objective of improving the quality of the seismic data. Comparison of CMP gathers before and after application of the radon filter shows significant improvement in data quality which, if stacked, would create a volume more representative of the subsurface structures.

Keywords: *seismic data processing, water bottom multiples, Radon filter, data quality, Niger Delta*

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1. Introduction

A multiple is a seismic energy which has been reflected more than once in its path to the detector. Multiples occur where there are seismic boundaries with large reflection coefficients arising from large velocity and/or density contrasts. In marine or offshore areas, the sea-bed and free water surface have large acoustic impedance contrasts and as such, generate multiples which are recorded together with the desired primary reflections. Multiples give rise to false seismic events and if they are not eliminated in processing, they can make interpretations of the final processed seismic sections difficult and give false results. This underscores the need for their removal.

Imaging in deep water environments poses a specific set of challenges, both in the data pre-conditioning and imaging among which is "hard" water bottom, which results in high amplitude multiple reflections relative to primary energy [1].

Several multiple removal techniques are in the literature, all of which utilize different characteristics of the multiples and primaries. Some techniques are based on the fact that multiples are periodic in nature as opposed to the assumed random nature of the reflectivity series [2], and based on their periodicity, the multiples can be predicted and then subtracted from the primaries [3,4], leaving ideally seismic data that is free from multiple energy. This is the basis of the use of predictive deconvolution technique in the elimination of multiples. Given an input time series $x(t)$, [5] showed that the value of $x(t)$ at some future time $x(t+m)$, can be computed by solving the matrix equation for an n-long prediction filter and m-long prediction lag given by:

$$\begin{bmatrix} r_0 & r_1 & r_2 & \cdots & r_{n-1} \\ r_1 & r_0 & r_1 & \cdots & r_{n-2} \\ r_2 & r_1 & r_0 & \cdots & r_{n-3} \\ . & . & . & . & \\ . & . & . & . & \\ r_{n-1} & r_{n-2} & r_{n-3} & \cdots & r_0 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ . \\ . \\ a_{n-1} \end{bmatrix} = \begin{bmatrix} r_m \\ r_{m+1} \\ r_{m+2} \\ . \\ . \\ r_{m+n+1} \end{bmatrix} \quad (1)$$

where:

r_i = i^{th} lag of the autocorrelation of x(t)

$x(t+m)$ = prediction filter

a_i = prediction filter series

n = length of the prediction filter and

m = prediction lag (or delay)

By convolving the computed filter series $\{a_0, a_1, a_2, ,,,,,,, a_{n-1}\}$ with the input time series and applying the desired predictive lag m, the periodicity of the multiple can be estimated [6]. The predictive deconvolution methods are effective in suppressing short-period, free-surface multiples generated at shallow reflectors but are generally less effective in deep water environments where the period of the multiples is longer relative to the length of the record [7].

Multiple removal has also been based on differences in residual moveout between the primaries and multiples from near to far offsets of CMP gathers. These methods, which include the radon transform methods rely on velocity differences between the primaries and multiples; the primaries map from offset space to the zero residual moveout in Radon space whereas multiples map to the positive residual moveout zone, allowing the multiples to be well modeled in Radon space, and attenuation can thereafter be achieved by subtraction of the modeled multiples from the data.

In the present work, we used the approach of parabolic Radon transform to successfully model and attenuate water bottom multiples from seismic data acquired in offshore Niger Delta and by this process, improved the seismic data quality.

2. Review of Radon Transform Methods

In seismic data processing, Radon transform algorithm is typically employed to transform seismic data from the offset-time (x,t) domain to the time-moveout domain. Radon transform was first introduced by Radon [8]. The mathematical formulations of the transform was given by [9] while [10] investigated the fundamental properties of the transform. Till date, three different approaches of the Radon transform have been employed for multiple elimination. These approaches include the linear, slant-stack or tau-P, hyperbolic and parabolic Radon transform. Each of these approaches requires seismic velocities to be sufficiently accurate for the transform to be able to distinguish the primaries from multiple energy; the multiples have slightly slower velocities than primary reflections.

The linear approach maps linear events in the input seismic data into a point in the tau-p domain [11] where they can be separated by muting before inverse transform back to the x-t domain. In this way, the approach is capable of attenuating ground rolls and other linear noise events from the input gather [12,13,14]. [15] utilized the hyperbolic Radon transform as a velocity analysis tool and [16] described a hyperbolic Radon transform in stacking NMO-corrected domain. Unfortunately, stacking does not eliminate all multiples [7]. The parabolic Radon transform was applied for the first time as a multiple attenuation technique by [17]. In the parabolic approach, NMO correction is applied to CMP-sorted seismic gathers. With an optimum NMO velocity, this is intended to flatten the primary events whereas the multiples will become approximately parabolic. The gathers are then transformed into the Radon space (which is frequency-space, f-x domain) where the data is decomposed into a series of parabolas, with the energy in each parabola being mapped to a P (or moveout) trace. In essence, the data are summed along a series of parabolas in the frequency-space domain; whereas, the primaries map to the zero residual moveout while multiples map to the positive residual moveout zone. On the basis of the difference in residual moveout from near to far offset, a mute could then be defined in the Radon space which could be used for subtracting the multiples from the primaries upon an inverse transform from the Radon space.

In this paper, we describe a procedure in which we derived a specially designed parabolic Radon filter and successfully applied it to attenuate water bottom multiples from CMP-sorted seismic gathers obtained from offshore Niger Delta basin, where average water depth was 1600m.

3. Method

In a simplified form, 2-D generalized Radon transforms are of the form:

$$m(\tau,p) = \iint d(t,h)\,\delta[t - t^{!}(t,p,h)]\,dtdh \qquad (2)$$

where the function d denotes the CMP input signal in t-h or *data* space and m denotes the output function in *model* space [18].

Parabolic transform involves summation along curves (parabolas) such that $t' = \tau' + qh^2$. Substituting for t' and by setting $q = p$, Eq. (2) becomes:

$$m(\tau,q) = \iint d(t,h)\,\delta(t - \tau' - qh^2)\,dtdh \qquad (3)$$

where q is the moveout and τ is the zero-offset time for a particular summation curve (parabola).

In implementing the parabolic Radon algorithm, NMO correction is first applied to pre-conditioned input CMP gathers to flatten the primaries leaving the multiples to have residual moveout from near to far offset. In Radon space, the energy along a parabola is mapped to a moveout-trace $(q-\text{trace})$ corresponding to each frequency band in the input $(t-h)$ data, where perfectly flattened primaries events map from offset space to the zero residual moveout $(q=0)$ while multiples map to a range of positive moveout $(q>0)$. Primary events which are over-corrected based on the NMO application map to a range of negative residual moveout, $q<0$, in the Radon space.

A 50-fold synthetic CMP gather with offset increment of 100 m and maximum offset of 5,350 m is generated to analyze the effectiveness of the Radon transform and subsequent filtering. The reflection events and their velocities are shown in Table 1.

Table 1. Model for event generation

Reflection event	TWT (m sec)	Velocity (m/s)
Water Bottom Reflection	1800	1500
Primary reflection-1	2412.5	2800
Primary reflection-2	3612.5	3500
Primary reflection-3	4000	4200
Water Bottom multiple-1	4200	1500
Water Bottom multiple-2	4250	1500
Water Bottom multiple-3	4300	1500
Water Bottom multiple-4	4400	1500
Water Bottom multiple-5	4600	1500
Primary Reflection-4	6000	5500

Figure 1a shows the synthetic CMP gather and its radon transform (Figure 1b). The transform shows a clear distinction between the primaries and multiples.

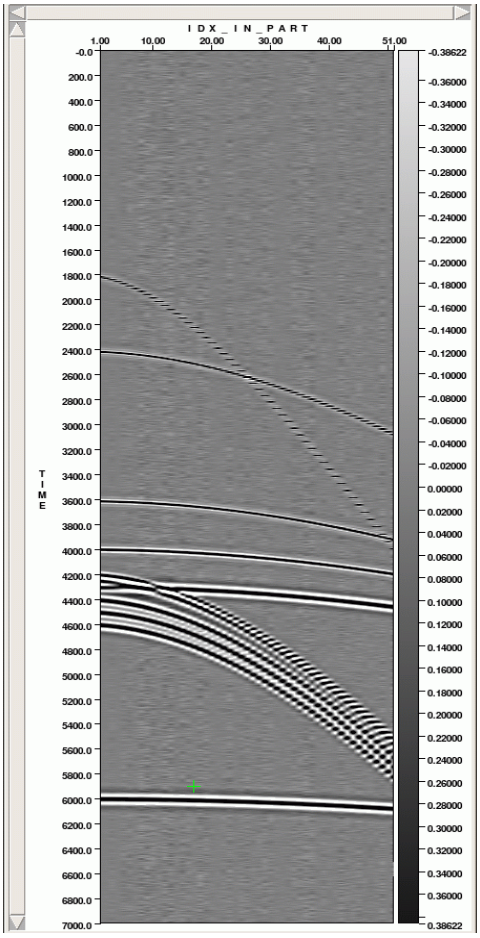

Figure 1 a: Synthetic CMP gather

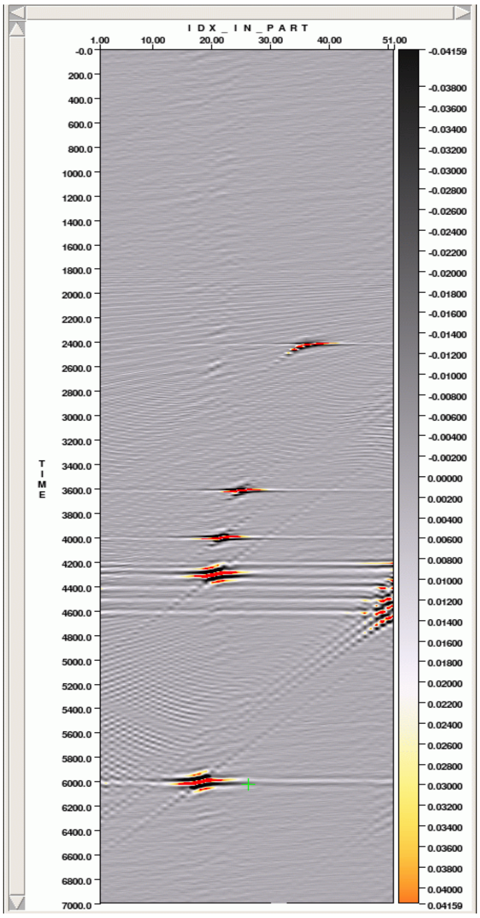

Figure 1 b. Radon transform of synthetic

4. Field Data

The field data utilized for this study was acquired from offshore Niger Delta using a dual source and ten streamers. The source and streamer depths are 5 m and 6 m, respectively. Streamer length is 5,350m with group interval of 12.5m and streamer separation is 100m. Shooting was in flip/flop mode at an interval of 25m, producing a 50-fold data. Prior to the Radon demultiple, the data was pre-conditioned and was free of swell and other low frequency noise, and linear nise.

To carry out the multiple suppression procedure, we initially applied NMO correction to the CMP gathers using NMO velocity derived from velocity analysis of the seismic gathers after the data pre-conditioning. The primary events were reasonably flattened after the NMO correction whilst the water bottom multiples became evidently clear, showing up from the near to far offsets in the gathers. Figure 2 shows a CMP gather after application of the NMO correction. The water bottom reflection time in the record is about 2.4s and strong water bottom multiples occur between 5.1s and 6.18s.

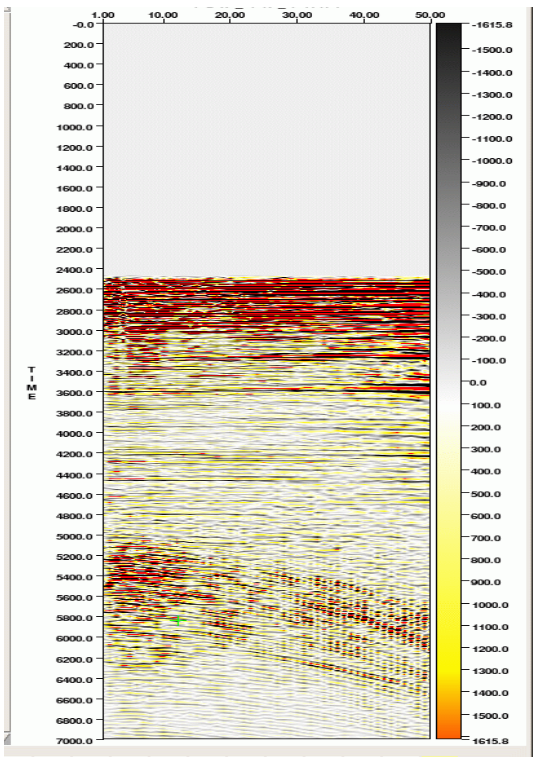

Figure 2. NMO-corrected CMP gather from field data

To implement the forward transform, we utilized the method of [19], with modifications.

In the first step, we carried out frequency analysis of the data around the multiple area in the $t-h$ domain to determine the frequency range of the multiples. The frequency spectrum (Figure 3) shows maximum of 75Hz is optimum for the transformation.

To optimally transform the data in the Radon space where the primaries are well separated from the multiples, an optimum range of moveout ($q-$trace) values is necessary, and the challenge is how to choose the maximum and minimum value of q. To obtain this, we measured the multiple time at the near and reference offsets of 350m and 5,350m respectively, and determined

$\Delta t = t_f - t_n$ along the parabola that defines the multiple, where t_f and t_n are multiple time at reference and near offsets, respectively. This was done in the $t-h$ domain; Δt of approximately 800ms was obtained and the value was fairly constant for all the multiples in the data, measured at different locations in the area. The maximum moveout, Λt_{max}, was therefore set to be 1,500ms, about $2*\Delta t$ while a minimum moveout value, Λt_{min} of -500ms was used to accommodate primary reflections that may have been over corrected during NMO correction as a result of irregularities in NMO velocity, giving a q range of -500ms to 1500ms.

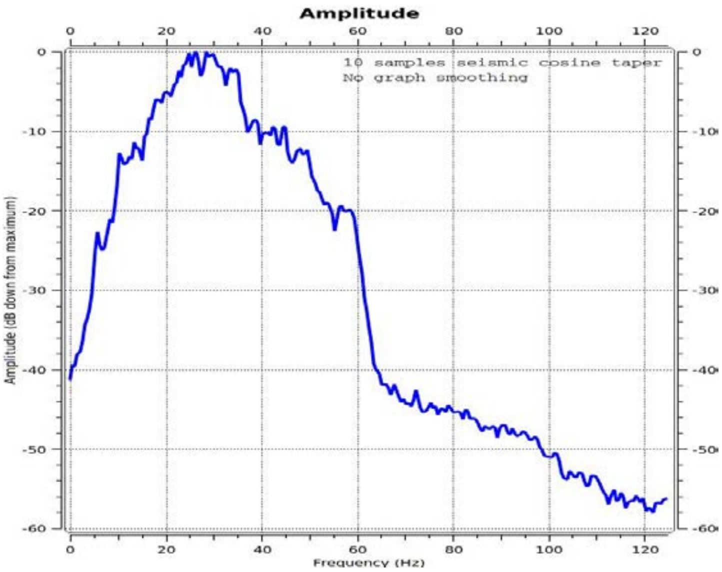

Figure 3. Frequency spectrum around multiple area in input data

The range of q values for optimum transformation in the radon space having been obtained, the next challenge was determination of the sampling or increment of the $q-$traces between the minimum and maximum values. This is essentially the number of parabolas which the data would be decomposed into in the radon domain to cause a good separation between the primaries and multiples.

In our approach, we performed a series of forward Radon transforms with different sampling values while keeping the range of $q-$traces obtained above constant and at constant frequency of 1Hz to 75Hz. In order to avoid generating streaks on the output, we started by setting the sampling equal to 50, the nominal fold of the data, and increased by 1.5 the fold. We observed that as the increment increases, more detail and resolution is seen in the Radon space, but beyond a particular sampling, no significant improvement is seem in the multiple model generated. The Radon transform parameters derived are shown in Table 2.

Table 2. Optimum parabolic Radon transform parameters derived

Number of Parabolas	175
Reference Offset	5350 m
P-Range	-500 to 1500 ms
Maximum frequency	75Hz

5. Results and Discussion

The Radon transformation of the CMP gather (Figure 2) is shown in Figure 4.

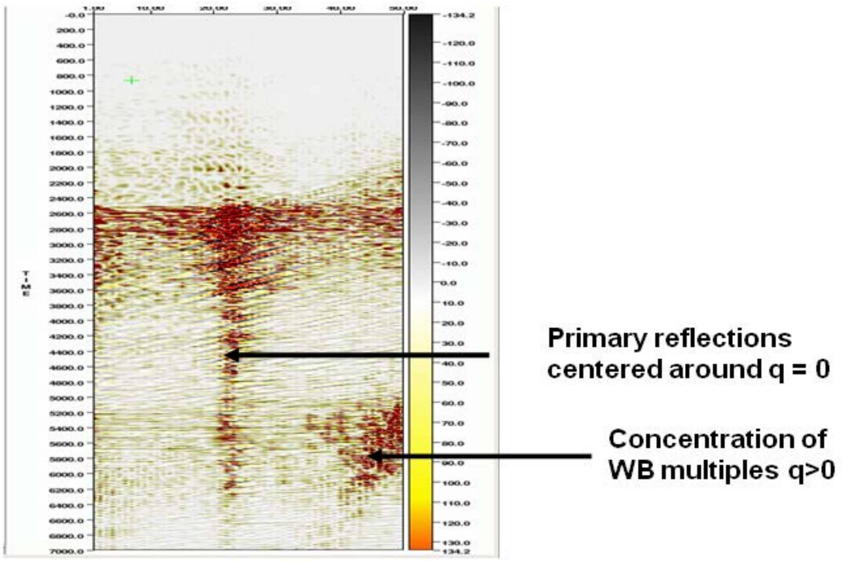

Figure 4. Radon transform of CMP gather

The primary events show up at almost zero residual moveout in the Radon space while the water bottom multiple events show up in the positive residual moveout. It is therefore easy to separate the multiple model from the primaries by picking a mute in the Radon space as shown in Figure 5.

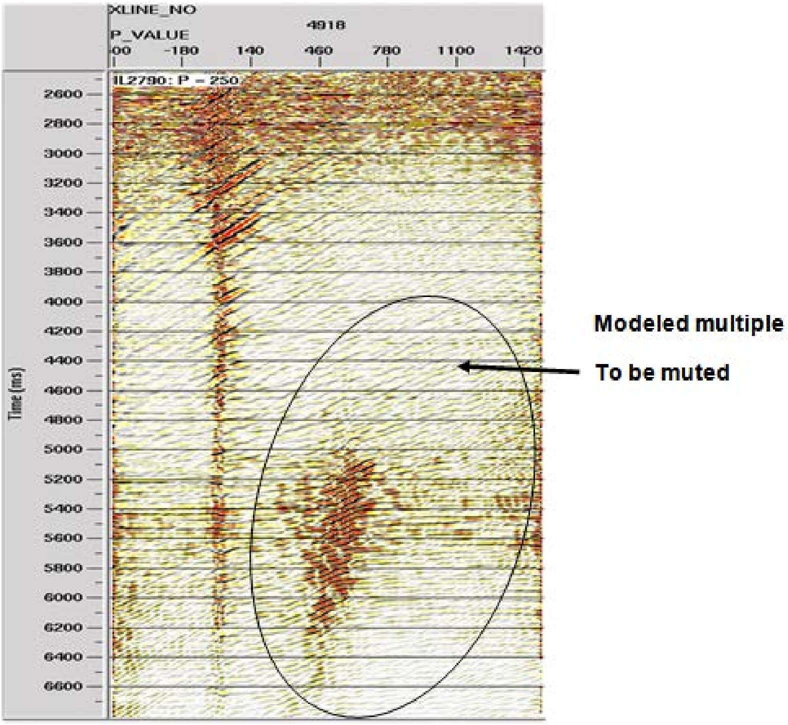

Figure 5. CMP gather in Radon space with mute

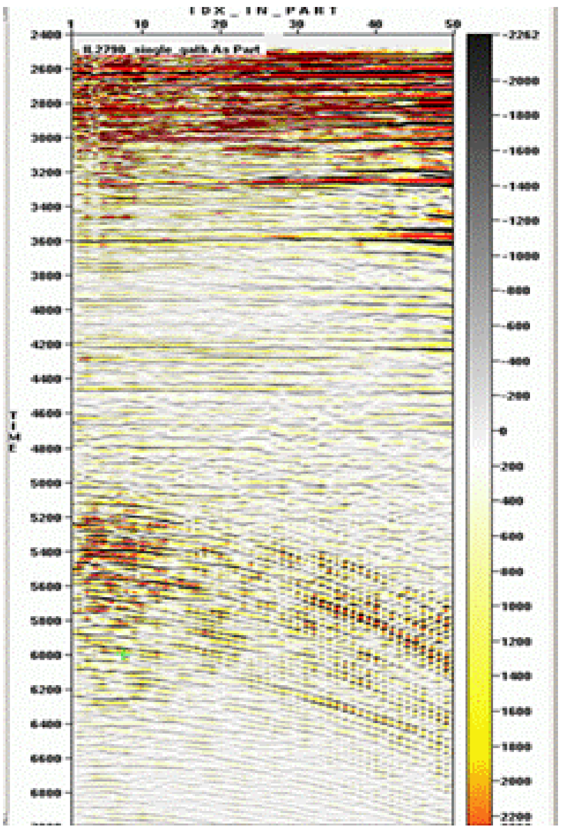

Figure 6 a: Input CMP gather

Application of the mute in the radon space would lead to the removal of primary events in the shallow. As a result, in our approach to the multiple elimination, we output the modeled radon gathers and transformed back to the t-h domain where we did a subtraction of the multiple model from the primaries by application of the mute. To ensure that shallow events were unaffected by the subtraction and to preserve amplitudes in the shallow, we applied the mute effective from twice the water bottom time.

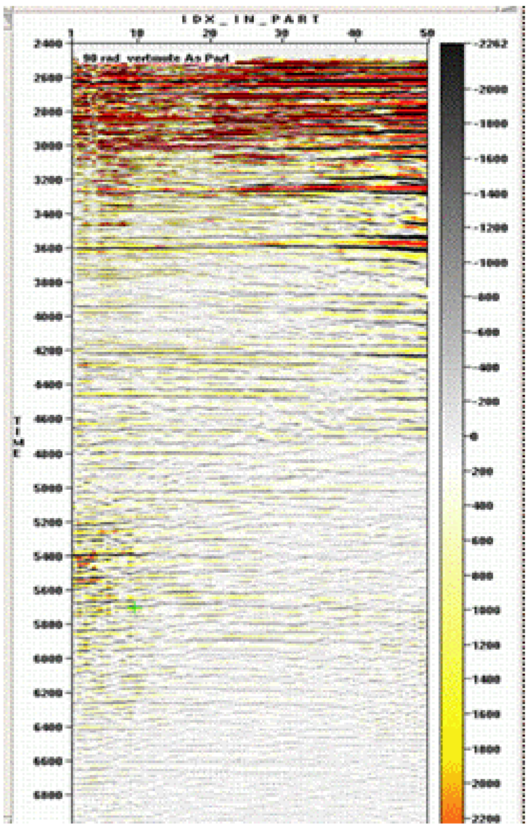

Figure 6 b. Multiple-eliminated CMP gather

Figure 6a shows a zoomed display of the NMO-corrected input CMP gather while Figure 6b shows the result of application of the Radon filtering. The results show that the parabolic Radon algorithm is able to eliminate water bottom multiples from the data effectively, especially at far offsets.

The results could be better if NMO velocities and the radon filtering parameters are optimum. There are remnants of the multiples at the near offset and this is consistent with the results of [11] and [12]. The underlying model for the Radon demultiple is based on the assumption that the model can be represented by parabolas of various curvatures centred at the zero offset [20] With a decrease in the differential moveout along a parabola, the effectiveness of the Radon filter in attenuating multiples become difficult. Therefore, the remnant of the multiples seen at the near offset after the radon demultiple is expected due to a decrease in the moveout differential at the near offset [1,12]. This is also the case with peg-leg multiples of the water bottom. The level of multiple attenuation using the method should greatly increase confidence in structural interpretation when the gathers are stacked, as they would give better stacking response and reveal structures more representative of the subsurface. On the other hand, the near offset limitation of the method is irrelevant if the objective is special studies involving reservoir/AVO analysis for which the near offsets are normally muted while creating angle gathers for such studies. However, [21] opine that applying a proper bulk shift to the CMP gathers and picking NMO velocities for flattening the gathers prior to the parabolic radon transform could remove the drawback of the method in complex areas. Application of the bulk shift is thought to cause a reduction in the velocity field, making the trajectory of the NMO corrected gathers to become parabolic and result in proper focusing of primaries and multiples in radon space, causing the near offset to be stable.

6. Conclusion

We successfully attenuated water bottom multiples from seismic data obtained from offshore Niger Delta by deriving a special parabolic Radon filter and applying it to the input. Our approach derives a model of the multiples in the radon space and subtracts the model from the input in the offset-time domain while preserving reflection amplitudes in the shallow section. This is particularly important as the target was to attenuate the water bottom multiples which occur in the deep section. The method has difficulty in completely attenuating multiples in the near offsets due to a decrease in moveout differential at the near offsets. The effectiveness of the method for multiple attenuation can be improved by the use of an optimum NMO velocity for NMO correction of the CMP gathers and a careful selection of the Radon transform parameters.

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