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Angle based curvelet transform method for ground roll removal

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Abstract: A recently proposed curvelet transform is a multi-scale multi-direction transform which provides sparse representation of two dimensional signals with smooth curve linear discontinuity. In seismic processing, several methods were proposed based on curvelet transform to eliminate coherent noises such as ground roll from seismic data. All of these methods either are none self-operating or need initial estimation for solutions. We introduce a new method for ground roll removal using curvelet transform that is self-operating and don't need initial estimation. In this method we separate data in each scale according their angles to three different categories: angles which mainly contain body wave, angles that both contain ground roll and body waves, angle which mainly contain ground roll. Using different thresholding scheme for these three categories, ground roll can be removed from seismic data.

Key words: Curvelet transform, Morphological Component Analysis (MCA), seismic, Ground roll.

INTRODUCTION

Successful removal of noise without impairing the information contained in the reflections is an important task of seismic data processing. Ground-roll is a kind of coherent noise that makes a serious problem in most land seismic datasets because they not only obscure the recognition of useful reflections, but also conspire against the success of other important processing steps such as deconvolution.

The amplitude of ground-roll is higher than the body waves; therefore, its overlap with the body waves can conceal the reflected seismic events. However, the ground roll has low frequency content and group velocity compared to the body waves. Also it has large dip and appears almost in vertical direction in contrast with reflection layers that have short dip and appear almost in horizontal direction. These distinctive characters make ground roll distinguishable from other kinds of data, particularly body waves.

Conventional approaches to ground-roll elimination include low-cut frequency filtering, which relies on ground-roll's lower frequency content and moveout filtering, which exploits the characteristic linear moveout of ground-roll for its discrimination and suppression (Harlan, W., *et al*., 1984). Low-cut frequency filtering, therefore, is a good choice for suppressing only those frequencies in the ground-roll that is clearly below the lowest useful signal frequencies. Thus, at best, its action at enhancing the signal to ground-roll amplitude is incomplete (Treitel, S., *et al*., 1967). moveout filtering introduces undesired artifacts such as spatial correlation of background noise, loss of fault clarity, and a Gibb's phenomenon associated with the cutoff moveouts of the filter (Yilmaz, O., 2001). By introducing and development of wavelet transforms, new techniques were proposed (Corso, G., *et al*., 2003; Leite, F.E., *et al*., 2008). In these methods data is decomposed into wavelet space then according to an elimination schemes part of signal in different scales is removed. The main idea behind elimination schemes is that ground roll is concentrated in a range of scales, thus the amplitude of those scale should be attenuate.

Recently Curvelet transform are employed in many tasks of seismic data processing. It provides very efficient tool for local analysis of seismic data (Herrmann and Hennenfent, 2008; Naghizadeh and Sacchi, 2010). Curvelet is a local decomposition of data based on the dip and frequency content. Yarham and Herrmann (2008) used sparse representation of curvelet coefficients for Ground-roll elimination. Lately, Wang *et al.* (2009) used a combination of interferometric prediction with L1/L2 norm curvelet subtraction to subtract the ground roll waves.

The directional characteristic of the curvelet transform allows an optimal identification and further removing of the Ground Roll of the seismic image. Using this curvelet feature we present here an angle base ground roll removal technique, in contrast to a partial attenuation. That means, instead of attenuating frequencies (or scales) where the Ground Roll is mainly present, we attenuate ground roll according curvelet's scales and angle.

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The paper is organized as follows. In Section 2, we briefly introduce the basics of curvelet transform theory. In Section 3, we present in some detail our filtering methodology for Ground Roll removing using curvelet transform. In Section 4 we apply the denoising technique to a seismic data contaminated by Ground Roll noise. Finally, in Section 5, we show the main results and discuss the article in a broad context.

Curvelet Transform:

The curvelet transform is a local and directional decomposition of an image (data) into harmonic scales. The curvelet transform aims to find the contribution from each point of data in the t-x domain to isolated directional windows in the f-k domain. In this article we use the discrete curvelet transform (Candes, E., *et al*., 2006)

Curvelets are in essence *anisotropic* extensions to wavelets that have better directional selectivity than wavelets. In the wave number domain, the length and width of the support of a curvelet satisfy the parabolic scaling relation

$$length = width^2 \tag{1}$$

because of this anisotropic scaling, curvelets become line-like in the limit of infinite frequency. Note that in the spatial domain, the parabolic scaling relation is $width = length^2$.

Curvelets are constructed through the following sequence of operations. First, the spectral domain is band-pass filtered into dyadic concentric squares or subbands; this means that the length of two neighboring squares differ by a factor of 2. Each subband is indexed by a scale index *j*. Subsequently, each subband is subdivided into angular wedges or shears (
Fig. **1**).

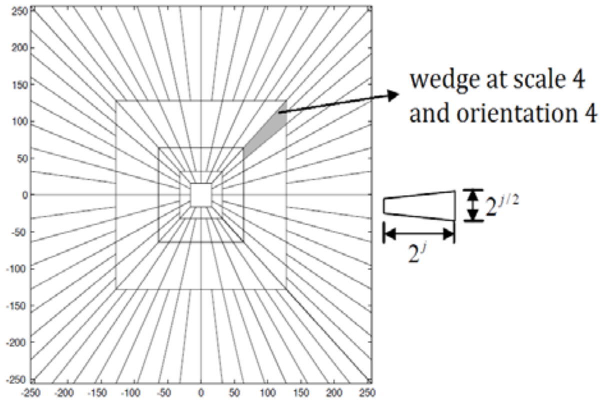


Fig. 1: The basic digital Cartesian tiling (Sumana, I. j., 2008)

The location of each wedge within a subband is identified by a rotational index *l* (
Fig. **3**)

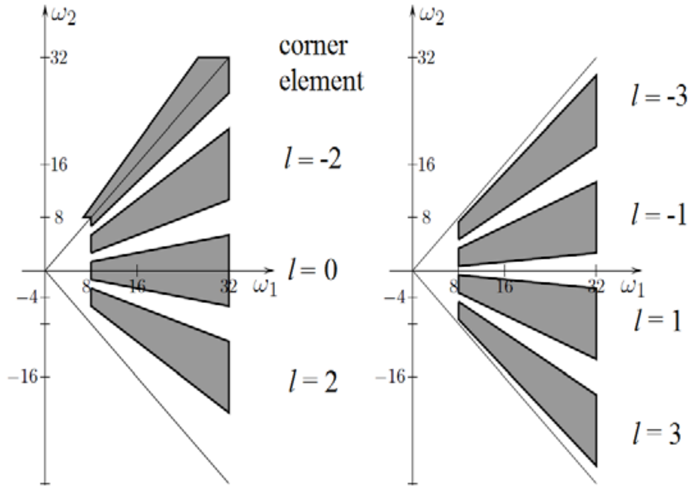


Fig. 2: supports in scale 4 for $l = -3, \dots, 3$, and one corner element (Naghizadeh, M., 2010).

The number of wedges in each subband is determined by the scale index j of the subband and is proportional to $2^{\lceil j/2 \rceil}$, where the notation $\lceil p \rceil$ denotes the upper integer part of p. This means that the number of wedges in a subband increases only every other scale. This way, the parabolic scaling relation is satisfied. The subband filtering gives curvelets their band-limited nature -just as with wavelets-, whereas the subdivision of these subbands into angular wedges provides them with orientation. At the coarsest scale no angular subdivision is done.

To facilitate translation of curvelets in the spatial domain, each wedge in the frequency domain is multiplied by a 2D orthonormal Fourier basis for the rectangle that just covers the support that contains the support that contains the wedge. With special choice of window functions, an example of Curvelet basis and its support are illustrated in

Fig. **3** (Ma, J. and G. Plonka, 2010).

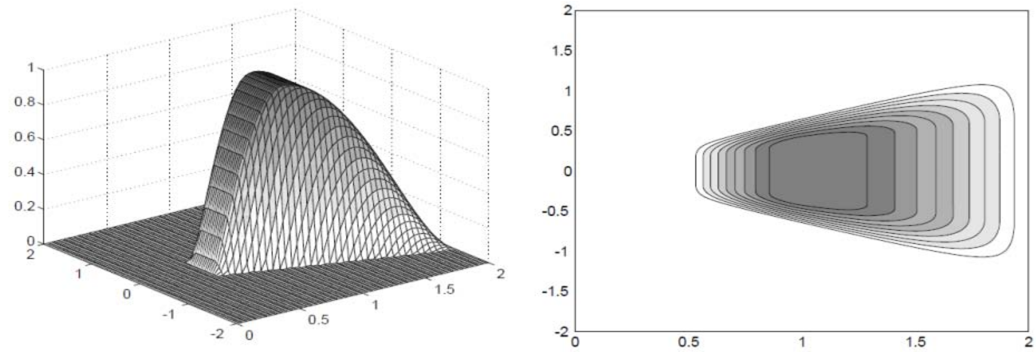


Fig. 3: An example of Curvelet basic and its support (Ma, J. and G. Plonka, 2010).

According to the discrete Fourier transform, this basis has the fewest members if the area of this rectangle is minimal, as a result the product of both sampling intervals in space is largest. Therefore, the orientation of this rectangle rotates with the angular wedge, and the spatial tiling associated with the local Fourier basis is oriented along the central direction of the angular wedge; that is, the spatial tiling associated with each angular wedge depends on the particular orientation of the wedge. The translation is indexed by k_1 and k_2 -in two dimensions-. Curvelets are therefore identified by all four indices (j, l, k_1, k_2): j determines their frequency content, l determines their main orientation, while k_1 and k_2 determine their location on the associated spatial grid.

The basic curvelet elements are obtained by parabolic dilatation, rotations and translations of a specific function $\phi_{j,l,k}$. The curvelet mother function ϕ_j $L^2(R^2)$ is defined in the Fourier domain by:

$$\hat{\phi}_j(\omega) = 2^{-3j/4} W_j(\omega) V_j(\omega) \tag{2}$$

where where W and V are the Cartesian equivalent of "radial window" and "angular window,". These two functions are smooth, non-negative and real-value, with Wtaking positive real arguments. W and V restricts the support $\hat{\phi}_j$ to a polar wedge that explain before and $\omega = (\omega_1, \omega_2)$ is frequency domain variable in Cartesian coordinate. The family of curvelet $\phi_{j,l,k}$ is defined in the Fourier domain at scale j, orientation $\theta_{j,l}$ and position $b_k^{(j,l)}$are then

$$\hat{\phi}_{j,l,k}(\omega) = e^{-i\langle b_k^{(j,l)},\omega\rangle} \hat{\phi}_{j,0,0}\left(S_{\theta_{j,l}}^{-1}(\omega)\right) \tag{3}$$

where $b_k^{(j,l)} = S_{\theta_{j,l}}^{-T}(k_1 . 2^{-j}, k_2 . 2^{\lfloor -\frac{j}{2} \rfloor})$ and S_θ is the shear matrix,

$$S_\theta = \begin{pmatrix} 1 & 0 \\ -\tan\theta & 1 \end{pmatrix}$$

and $\tan\theta_l = l \,.\, 2^{-\lfloor j/2 \rfloor}, l = -2^{\lfloor j/2 \rfloor}, \dots, 2^{\lfloor j/2 \rfloor} - 1$ are set of equispaced slopes angles. function f ∈ L^2 (R^2) will be representable by a curvelet series

$$c(j,l,k) := \langle f, \phi_{j,l,k} \rangle = \sum_{0 \le x_1, x_1 < n} f[x_1, x_1] \overline{\phi_{j,l,k}[x_1, x_1]}. \tag{4}$$

In this equation the coefficients cj,l,k are interpreted as the decomposition of f into a basis of curvelet functions $\phi_{j,l,k}$.

Curvelet Angles Base Method:

In this section, we describe in some detail the Curvelet Angle Base Method. This technique consists of three main steps: (1) decomposition of the signal in the curvelet space, (2) classification of angles in each scale into three categories, (3) define thresholding algorithm for each category and removing of the Ground Roll coefficients in the curvelet space, and (4) reconstruction of the signal after noise extraction. First we apply this method to synthetic seismic data and then examine it for real data.

Classifying Angles for synthetic data:

Ground roll, as was mentioned before, appears mainly in few angle in each scale. Therefore angles in each scale can be classified in three categories. In first category of those angles that contain major coefficient of ground roll in contrast with third category of those angles that mainly contain body waves. Between these two different categories, we introduce second category that belong to those angles that both contain ground roll and body waves and there is no dominant sign that is related to ground roll or body waves. In curvelet's domain, usually the angles before and after those angles who specified in first category are choosed for second category.

Thresholding schemes:

In this section, iterative variable thresholding algorithm is proposed. This algorithm is an instance of original method Morphological Component Analysis which is designed to separates two different signal components [10]. Suppose R as reflectors component and GR as ground rolls. Reconstruct all categories separately and use reconstruction of categories 1 and 3 as weight matrices. Start iteration and calculate curvelet transform of reflectors R and ground rolls GR using variable thresholding value in each iteration. This algorithm is shown inTable 2 (Note that A represent as analysis Curvelet operator and A^T as Synthesize Curvelet operator).

Table 1: Curvelet Angle Base Method for ground rolls removal.

```
Initialize:
TD                                              {total data}
$b_1, b_2$                                      {reconstruction of categories 1 and 3}
Choose:
$R = b_1$                                       {Reflectors}
$GR = b_2$                                      {Ground Roll}
L                                               {maximum number of iteration}
$\lambda_1, \lambda_2$ ,                        {initial thresholding values}
$l = 0$ ;                                       {iteration number}
$w_1 := C_1 |A^T b_2|$                          {Set reflectors weights},
$w_2 := C_2 |A^T b_1|$                          {Set ground roll weights}
$x_1 = A^T R$ , $x_2 = A^T GR$                  {initial curvelet coefficient}

while $l \leq L$ do
        $l = l + 1$;
        $r_1 = TD - GR$;                        {Calculate residual}

        REFLECTORS
        $x_1 = x_1 + A^T(r_1 - Ax_1)$;          {Descent update}
        If $(s,j) \epsilon\ category$ 1 Set $x_{1_{s,j}} = 0$ ,
        If $(s,j) \epsilon\ category$ 2
        $x_{1_{s,j}} = sgn(x_1).\max(0, |x_1| - |\lambda_{1,l} w_1|)$;        {soft thresholding}
        If $(s,j) \epsilon\ category$ 3
        $x_{1_{s,j}} = sgn(x_1).\max(0, |x_1| - |0.1\ \lambda_{1,l}|)$;       {soft thresholding}
        $\boldsymbol{\lambda_{1,l+1}} \xleftarrow{update\ \lambda_1\ such\ that\ \lambda_{1,l+1} < \lambda_{1,l}} \boldsymbol{\lambda_{1,l}}$        {update thresholding value}

        $R = Ax_1$;                             {Synthesizing}
        $r_2 = TD - R$;                         {Calculate residual}

        GROUND ROLL
        $x_2 = x_2 + A^T(r_2 - Ax_2)$;          {Descent update}
        If $(s,j) \epsilon\ category$ 1
        $x_{2_{s,j}} = sgn(x_2).\max(0, |x_2| - |0.1\ \lambda_{2,l}|)$;       {soft thresholding}
        If $(s,j) \epsilon\ category$ 2
        $x_{1_{s,j}} = sgn(x_2).\max(0, |x_2| - |\lambda_{2,l} w_{21}|)$;     {soft thresholding}
        If $(s,j) \epsilon\ category$ 3 Set $x_{2_{s,j}} = 0$
        $\boldsymbol{\lambda_{2,l+1}} \xleftarrow{update\ \lambda_2\ such\ that\ \lambda_{2,l+1} < \lambda_{2,l}} \boldsymbol{\lambda_{2,l}}$        {update thresholding value}

        $GR = Ax_2$;                            {Synthesizing}

  end while
```

```
end
```

The important steps of algorithm that was presented in Table 1 are thresholding values update. The formulas which are employed for updating λ_1 and λ_2 should be descended while the number of iteration raises. The rate of descending is also important and should be different for ground roll and body waves.

Simulation:

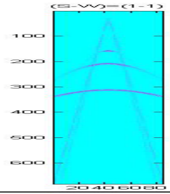
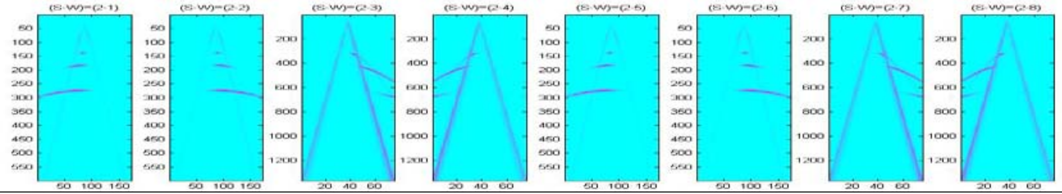
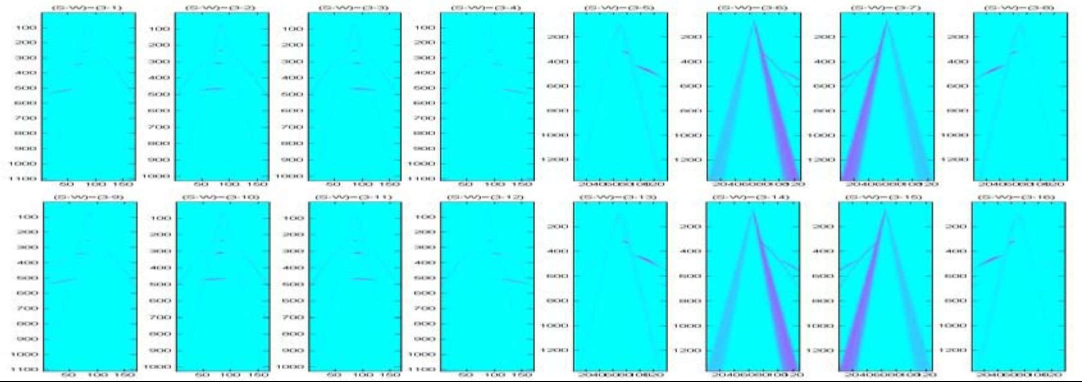
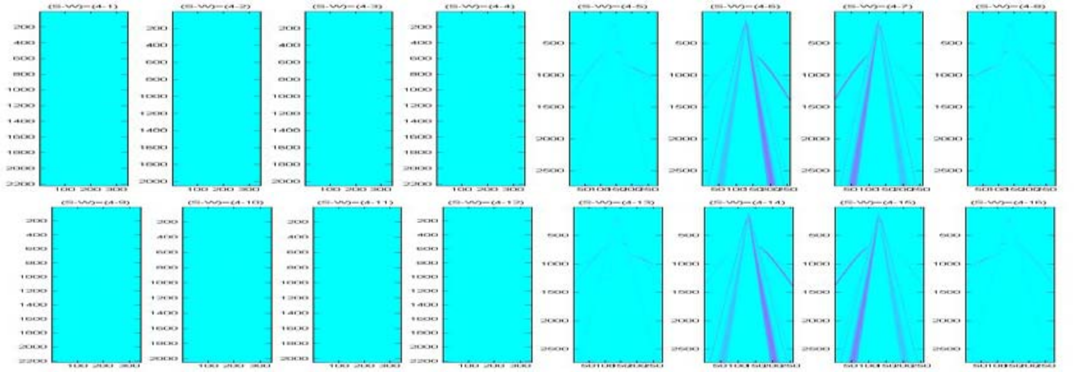
The method that described in previous section has been applied to two kinds of data, Synthetic data (Fig. **4**) and real data (

Fig. **7**), to verify that the scheme has a good performance for ground roll removal.

Result Of Application The Method On Synthetic Data:

In order to classify the angles of curvelet transform we should survey all them in every scale. Here all angles of curvelet transform in four scales for synthetic data are illustrated in Table 2. As it can be seen ground roll are dominant in few angle in each scale.

Table 2: Synthetic seismic data in different scales and angles of curvelet domain.

Scales	Angles
1	
2	
3	
4	

Also the size of figures in Table 2 is small but ground roll can be detected in few of them. According to Table 2 , different categories are specified. Three categories are summarized in Table 3.

Table 3: Angles Categories.

No.	categories	Scale 1	Scale 2	Scale 3	Scale 4	Scale 5	Scale 6
1	angle mainly contain ground roll	-	3,4,7,8	6,7,14,15	6,7,14,15	12,13,28,29	12,13,28,29
2	angles contain ground roll and body waves	1	1,2,5,6	5,8,13,16	5,8,13,16	11,14,27,30	11,14,27,30
3	angles mainly contain body wave	-	-	Others	Others	Others	Others

Initial value that we use for synthetic data are represented in Table 4.

Table 4: constant and formulas for synthetic data.

Variable	value
Number of iterations	50
Initial thresholding values $\boldsymbol{\lambda_1}$	0.1
Initial thresholding values $\boldsymbol{\lambda_2}$	0.35
Weight constant C_1	0.24
Weight constant C_2	0.16
Update thresholding formula for $\boldsymbol{\lambda_{1,l}}$	$\lambda_{1,l} = \frac{4}{4+l}\lambda_1$
Update thresholding formula for $\boldsymbol{\lambda_{2,l}}$	$\lambda_{2,l} = \frac{9}{9+l}\lambda_2$

Ground roll of synthetic seismic data was eliminated with thresholding algorithm based on three different categories. Result are shown in

Fig**. 5** and
Fig. **6**.

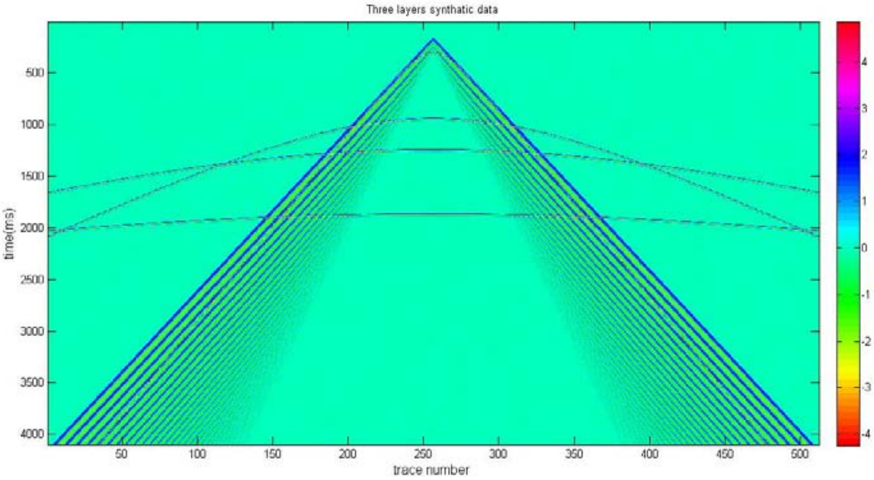


Fig. 4: Three layers synthetic data

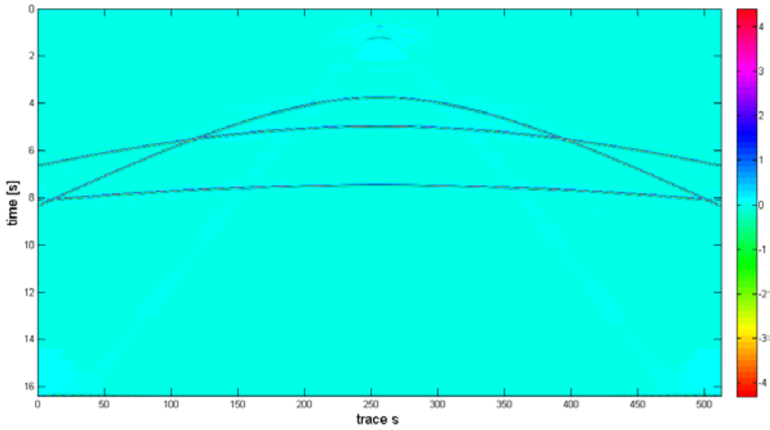


Fig. 5: Reflectors reconstructed by curvelet angle base ground roll removal.

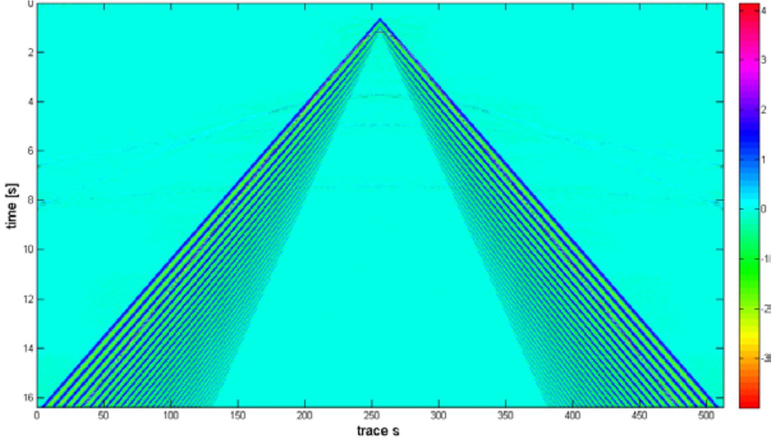


Fig. 6: Ground roll.

Result Of Application The Method On Real Data:

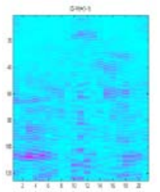
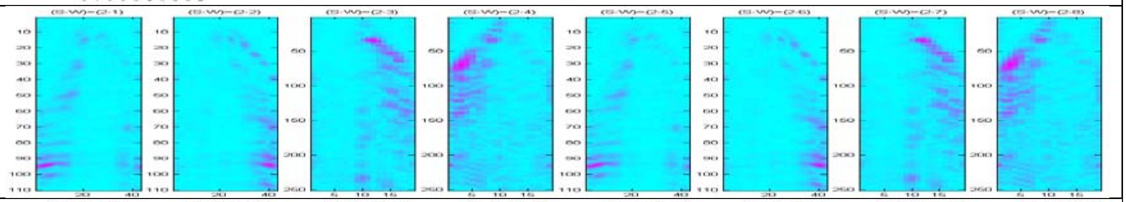
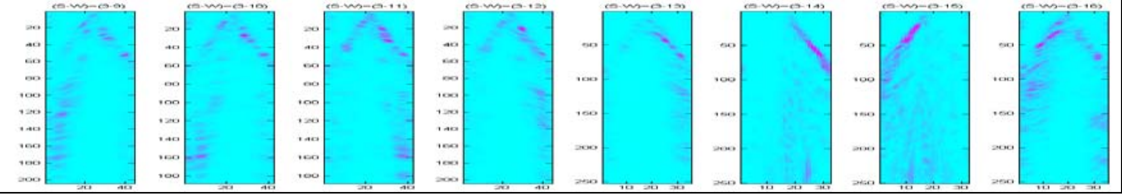
Again, we repeat all step of curvelet angle base method for real data. All angles of curvelet transform in four scales for real data are illustrated in **Error! Reference source not found.**. Also signal components separation in curvelet domain for real data is not obvious as for synthetic data but still it can be seen that ground roll are dominant in few angle in each scale.

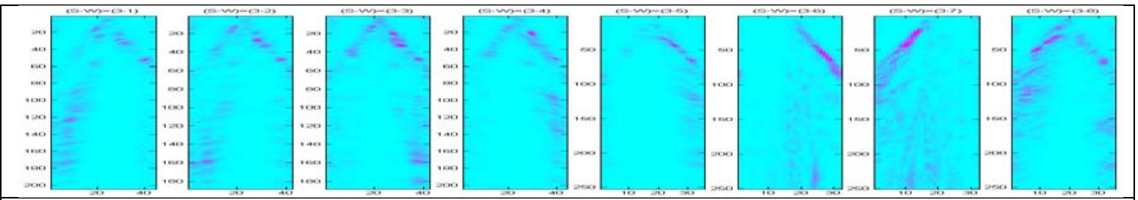
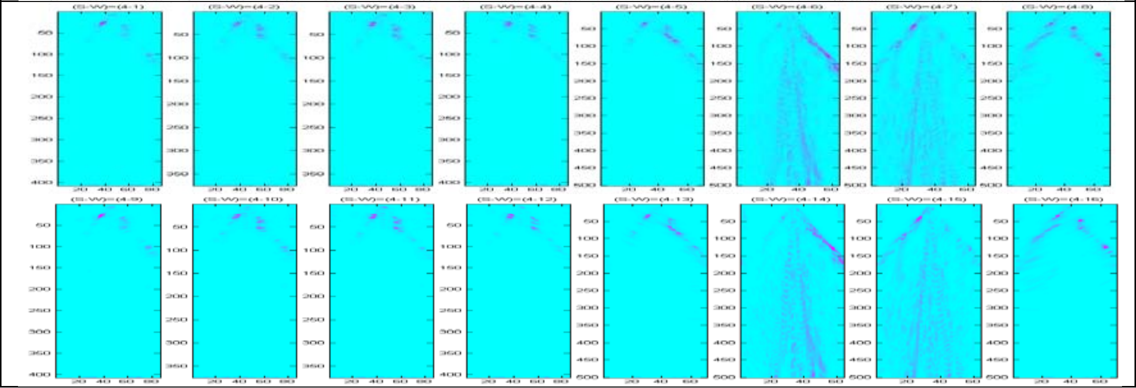
With compare Table 2 and **Error! Reference source not found.** It is seen that same categories of synthetic data can be use again here. Three categories are summarized in Table 5: Angles Categories.

Table 5: Angles Categories.

No.	categories	Scale 1	Scale 2	Scale 3	Scale 4	Scale 5	Scale 6
1	angle mainly contain ground roll	-	3,4,7,8	6,7,14,15	6,7,14,15	12,13,28,29	12,13,28,29
2	angles contain ground roll and body waves	1	1,2,5,6	5,8,13,16	5,8,13,16	11,14,27,30	11,14,27,30
3	angles mainly contain body wave	-	-	Others	Others	Others	Others

Table 6: Real seismic data in different scales and angles of curvelet domain.

scale s	Angles
1	
2	
3	

	
4	

Initial value that we use for real data are represented in Table 4.

Table 7: constants and formulas for real data.

Variable	value
Number of iterations	200
Initial thresholding values $\boldsymbol{\lambda_1}$	0.2
Initial thresholding values $\boldsymbol{\lambda_2}$	0.4
Weight constant C_1	0.2
Weight constant C_2	0.12
Update thresholding formula for $\boldsymbol{\lambda_{1,l}}$	$\lambda_{1,l} = \frac{15}{15+l}\lambda_1$
Update thresholding formula for $\boldsymbol{\lambda_{2,l}}$	$\lambda_{2,l} = \frac{35}{35+l}\lambda_2$

Original real data is illustrated in

Fig. **7**. Results obtained from applied curvelet angle base ground roll removal to real data are shown in Fig. **8** and

Fig. **9**.

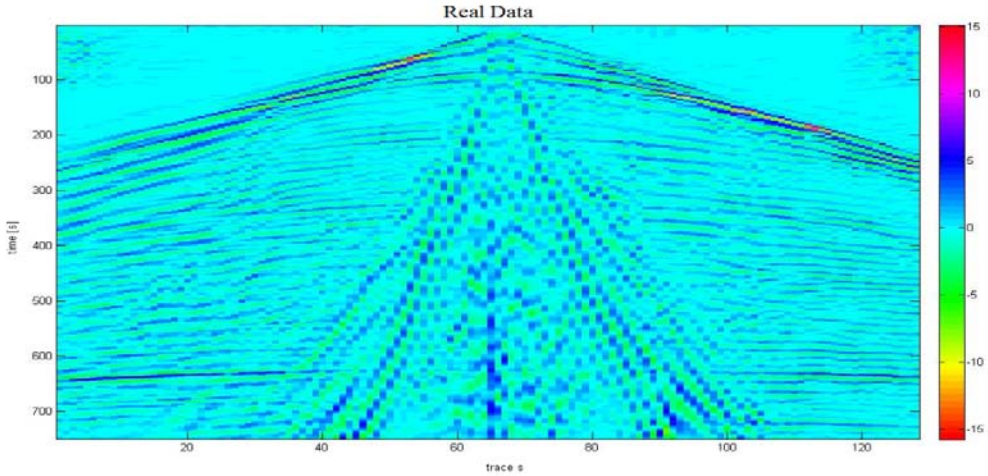


Fig. 7: Real seismic data containing both body wave and GR.

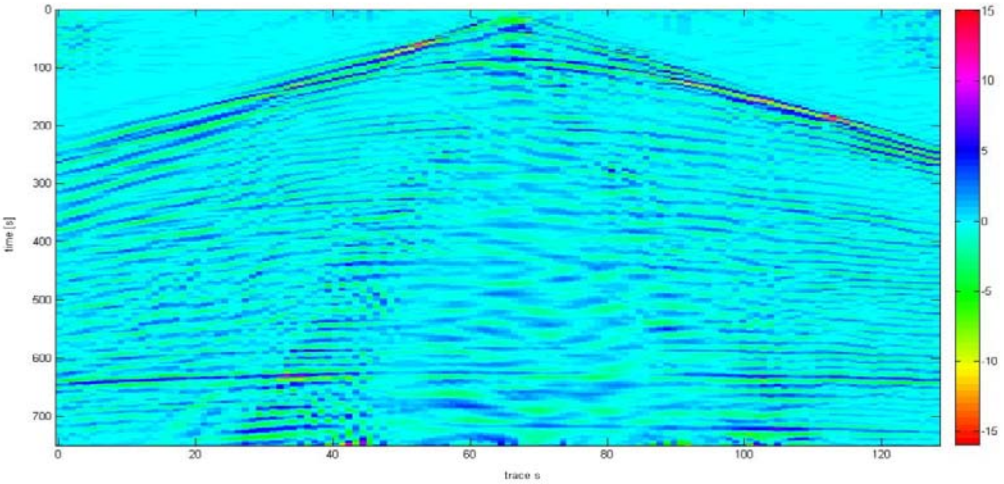


Fig. 8: Reflectors reconstructed by curvelet angle base ground roll removal.

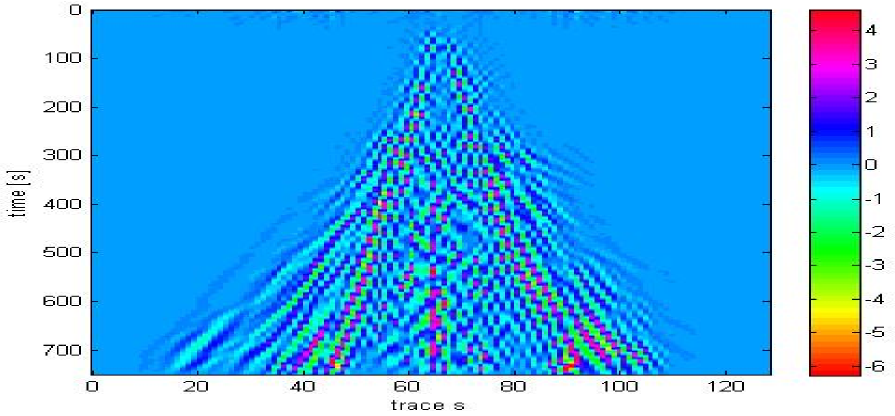


Fig. 9: Ground roll of curvelet angle base ground roll removal.

In the case of real data, we can compare results of this method with result of f-k transform (f-k transform is conventional method for ground roll removal). In

Fig. **10** and

Fig. **11** the results obtained from f-k transform are shown.

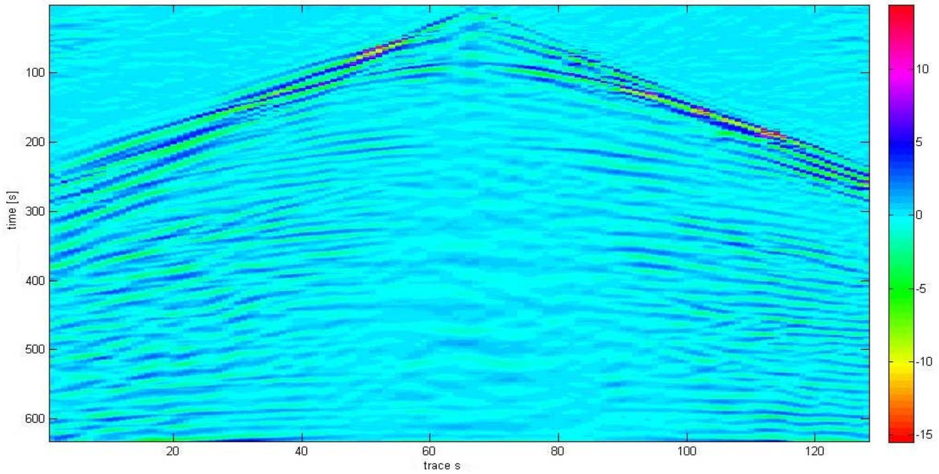


Fig. 10: Reconstructed reflections using f-k transform.

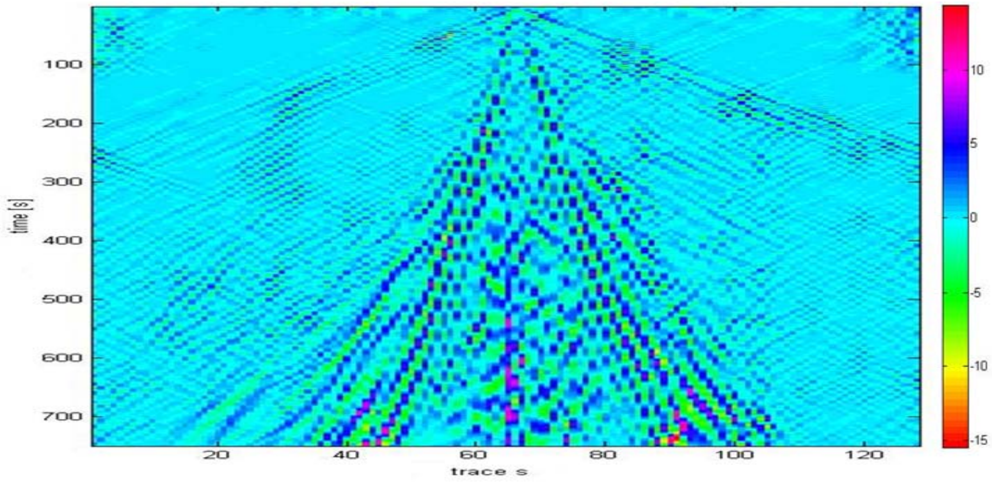


Fig. 11: Ground roll removed with f-k transform.

As it can be seen from continuity of reflector layers curvelet angle base ground roll removal method is better than f-k method and area which ground roll is removed from it is more clear. In addition, our method is self-operating and don't need to human experts instead of f-k method that heavily depend on human experts.

Conclusions:

In these work, a new method, curvelet angle base ground roll removal, for seismic ground roll removal has been presented. First synthetic data was used in which ground roll and reflectors are distinguishable. Curvelet angle base ground roll removal can remove ground roll from seismic data almost perfect. At last the method was applied to real data. Result was compared with f-k transform ground roll removal method to validate the performance. This comparison shows that our method results are better.

As a future work, in this method and any method that use curvelet for ground roll removal, curvelet can be replaced by other directional methods like contourlet and seislet. Also this method can be tuned for other kinds of seismic coherent noise.

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