

...  $\mathbf{fi}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

Ab  $\mathbf{z}$  ac  $\mathbf{z}$

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...

Ke d : Ac  $\mathbf{z}$  c aye e a  $\mathbf{z}$  de ,F  $\mathbf{z}$  d ffe e ce e  $\mathbf{z}$ ,d e e a  $\mathbf{z}$  e e y

\*  $\mathbf{f}$  ...  $\mathbf{ff}$  ...  $\mathbf{f}$  ...



...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...

## 2. P e y M e t d f D e p e r t e F D C e f f i c e p e S a r a S a c e

...  $f_{i+1} = f(x) + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

$$\frac{\partial f}{\partial x} = \frac{1}{\Delta x} \sum_{n=-N}^N c_n (f_n - f_{-n}),$$

...  $f_n = f(x + n\Delta x)$  ...  $c_n f_n - n k_x \Delta x$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

$$k_x \Delta x = \sum_{n=-N}^N c_n (n k_x \Delta x),$$

...  $k_x$  ...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

$$\frac{\partial f}{\partial x} = \frac{1}{\Delta x} [c f + \sum_{n=-N}^N c_n (f_{-n} + f_n)]$$

...  $c_n f_n - n k_x \Delta x$  ...  $f_{i+1} = f_i + \Delta f_i$  ...

...  $f_{i+1} = f_i + \Delta f_i$  ...  $f_{i+1} - f_i = \Delta f_i$  ...

$$-(k_x \Delta x) = c + \sum_{n=-N}^N c_n (nk_x \Delta x)$$

...  $k_x$  ...  $f$  ...  
 ...  $f$  ...  $f$  ...  $k_x \Delta x$  ...  $f$   
 fi ...  $f$  ...  $f$  ...  $f(x)$  ...  
 ... ffi ... fi  
 f ... f ...  
 ... f ...  
 ... fi ... f ... ff

$$c_n = -\frac{1}{n} (n\pi) w_n^N, n = \pm 1, \pm 2, \dots, \pm N,$$

$$c = -\sum_{n=-N}^N (c_{-n} + c_n),$$

...  $w_n^N = \frac{C_N^{N+n}}{C_N^N}$  ... ffi ...  $C_m^l = \frac{m!}{l!(m-l)!}$  ...  $m \geq l$  ...  
 ... ffi ...  $w_n^N$  ...  
 $w_n^{N+M}$  ... ffi ... f

$$c_n = -\frac{1}{n} (n\pi) w_n^{N+M}, n = \pm 1, \pm 2, \dots, \pm N,$$

...  $M$  ... fi ...  
 ... f ...

### 3 Ne Međ d f Deđ đ e FD C effie đ

#### 3.1 D e - e ađ - e e y FD e ađ : fi đ de ,ađ,ye 1D ca e

... f ...  
 ... ffi ... f ... f ...  
 ... f

where  $r = k_u \Delta x / \pi$  and  $\mathbf{f} = [f_1, \dots, f_N]^T$ .

For a given  $\Delta x$ , the upper limit of the wavenumber is  $k_u = \pi / \Delta x$ . The corresponding upper limit of the frequency is  $f_u = v / \Delta x$ . The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi = f / (v / \Delta x)$ .

$$r = \frac{k_u \Delta x}{\pi} = \frac{f}{v / \Delta x},$$

where  $f$  is the frequency of the wave. The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi$ . The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi$ .

The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi$ . The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi$ .

**Remark 1** With our approach, if we consider a too high upper limit for the wavenumber for a given scheme order and grid spacing, large numerical dispersion will appear at low frequencies; while if we consider a too small upper limit for the wavenumber, large numerical dispersion will appear at high frequencies. Percentage of  $k_u \Delta x$  to  $\pi$  is given by  $f / (v / \Delta x)$ .

where  $N$  is the number of grid points. The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi$ .

$$\begin{bmatrix} (k_x(1)\Delta x) & (k_x(2)\Delta x) & \cdots & (Nk_x(1)\Delta x) \\ \vdots & \vdots & \vdots & \vdots \\ (k_x(N)\Delta x) & (k_x(N)\Delta x) & \cdots & (Nk_x(N)\Delta x) \end{bmatrix} \begin{bmatrix} c \\ \vdots \\ c_N \end{bmatrix} = \begin{bmatrix} k_x(1)\Delta x \\ \vdots \\ k_x(N)\Delta x \end{bmatrix},$$

where  $k_x(n)\Delta x$ ,  $n = 1, \dots, N$  is the wavenumber of the wave. The ratio of the upper limit of the wavenumber to the upper limit of the frequency is  $r = k_u \Delta x / \pi$ .

### 3.2 Diferenciales finitos en el tiempo: ecuación de onda 1D con

condiciones de contorno de Dirichlet homogéneas. El problema de valores en los límites para la ecuación de onda unidimensional con condiciones de contorno de Dirichlet homogéneas se puede escribir como:

El problema de valores en los límites se puede escribir como:

$$\begin{bmatrix} -k_x(0)\Delta x & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & \cdots & -k_x(N)\Delta x \end{bmatrix} \begin{bmatrix} c \\ \vdots \\ c_N \end{bmatrix} = \begin{bmatrix} -[k_x(0)\Delta x] \\ \vdots \\ -[k_x(N)\Delta x] \end{bmatrix}.$$

El problema de valores en los límites se puede escribir como:

### 3.3 Diferenciales finitos en el tiempo: ecuación de onda 1D con condiciones de contorno de Dirichlet homogéneas

El problema de valores en los límites se puede escribir como:

$$\frac{\partial p}{\partial x} + \frac{\partial p}{\partial z} = v \frac{\partial p}{\partial t},$$

El problema de valores en los límites se puede escribir como:

El problema de valores en los límites se puede escribir como:

$$\begin{cases} \frac{\partial p}{\partial x} \approx \frac{\delta p}{\delta x} = \frac{1}{h} (c p_{,1} + \sum_{m=2}^N c_m (p_{,-m} + p_{,m})), \\ \frac{\partial p}{\partial z} \approx \frac{\delta p}{\delta z} = \frac{1}{h} (c p_{,1} + \sum_{m=2}^N c_m (p_{,-m} + p_{,m})), \end{cases}$$

El problema de valores en los límites se puede escribir como:

El problema de valores en los límites se puede escribir como:

El problema de valores en los límites se puede escribir como:

$$-k h \approx c + \sum_{m=2}^N c_m (\cos(mkh - \theta) + \cos(mkh + \theta)).$$

...  $\mathbf{f}_i$  ...  $\mathbf{f}_N$  ...  $\mathbf{f}_{N+1}$  ...  $\mathbf{f}_M$  ...

$$\sum_{\theta^-}^{\pi} \begin{bmatrix} a_{k,l}^h & \cdots & a_{k,l,N}^h \\ \vdots & \vdots & \vdots \\ a_{k_{N+1},l}^h & \cdots & a_{k_{N+1},l,M}^h \end{bmatrix} \begin{bmatrix} c \\ \vdots \\ c_N \end{bmatrix} = - \sum_{\theta^-}^{\pi} \begin{bmatrix} -k(\cdot) h \\ \vdots \\ -k(N+1) h \end{bmatrix},$$

...  $\mathbf{f}_i$  ...  $a_{k_l m}^h = (mk_x h) + (mk_z h)$  ...  $k_l$  ...  $i = 1, \dots, N+1$  ...  $\mathbf{f}_{k_l}$  ...  $l=x, z$  ...  $k_x = k$  ...  $\theta = \frac{j\pi}{M}$  ...  $\mathbf{f}$  ...  $\mathbf{f}_i$  ...

### 3.4 D e - e a $\tau$ - e e $\tau$ FD e a $\tau$ f $\tau$ e $\tau$ ee-d e a ac - $\tau$ c a $\tau$ e e a $\tau$

...  $\mathbf{f}$  ...  $\mathbf{f}_i$  ...  $\mathbf{f}_N$  ...  $\mathbf{f}_{N+1}$  ...  $\mathbf{f}_M$  ...

$$\frac{\partial p}{\partial x} + \frac{\partial p}{\partial y} + \frac{\partial p}{\partial z} = \frac{\partial p}{\partial t},$$

...  $p = p(x, y, z, t)$  ...  $\mathbf{f}$  ...  $\mathbf{f}_i$  ...  $\mathbf{f}_N$  ...  $\mathbf{f}_{N+1}$  ...  $\mathbf{f}_M$  ...

$$\begin{cases} \frac{\partial p}{\partial x} \approx \frac{\delta p}{\delta x} = \frac{1}{h} (c p_{i,j,k} + \sum_{m=-N}^N c_m (p_{i-m,j,k} + p_{i+m,j,k})), \\ \frac{\partial p}{\partial y} \approx \frac{\delta p}{\delta y} = \frac{1}{h} (c p_{i,j,k} + \sum_{m=-N}^N c_m (p_{i,j-k+m} + p_{i,j+m})), \\ \frac{\partial p}{\partial z} \approx \frac{\delta p}{\delta z} = \frac{1}{h} (c p_{i,j,k} + \sum_{m=-N}^N c_m (p_{i,j,-k+m} + p_{i,j,m})), \end{cases}$$

...  $c_i \mathbf{f}$  ...  $\mathbf{f}_i$  ...  $\mathbf{f}_N$  ...  $p_{m,n,l}^j = p(x+mh, y+nh, z+lh, t+j\tau)$  ...  $\tau$  ...  $m$  ...  $\mathbf{f}$  ...

...  $\mathbf{f}$  ...  $\mathbf{f}_i$  ...  $\mathbf{f}_N$  ...  $\mathbf{f}_{N+1}$  ...  $\mathbf{f}_M$  ...

$$-k h \approx c + \sum_{m=1}^N c_m ( (m k h \theta \phi) + (m k h \theta \phi) + (m k h \theta) ),$$

$$k = \sqrt{k_x^2 + k_y^2 + k_z} \theta$$

$$a_{k_l m}^h = (m k_x h) + (m k_y h) + (m k_z h), \quad (m = 1, \dots, N)$$

$$\sum_{\phi=0}^{\pi} \sum_{\theta=0}^{\pi} \begin{bmatrix} / & a_{k_{,l}}^h & \dots & a_{k_{,l},N}^h \\ \vdots & \vdots & \vdots & \vdots \\ / & a_{k_{N+,l}}^h & \dots & a_{k_{N+,l},N}^h \end{bmatrix} \begin{bmatrix} c \\ \vdots \\ c_N \end{bmatrix} = - \sum_{\phi=0}^{\pi} \sum_{\theta=0}^{\pi} \begin{bmatrix} -k(\cdot) h \\ \vdots \\ -k(N+) h \end{bmatrix}$$

### 3.5 S y r e e a e a r

$$\mathbf{f} \quad \mathbf{f} \quad \mathbf{f}$$



...  $f_i$  ...  $ff$  ...

...  $f$  ...  $A$  ...  $ff$  ...  
 ...  $f$  ...  
 ...  $f$  ...  $f$  ...  $f$  ...  $A$  ... (A)

...  $O(\dots)$   $f$  ...  $ff$  ...  $N=$  ,  $f$   $N=$  ... (A)

...  $f$  ...  $f$  ...  $ff$  ...  
 ...  $f$  ...  $f$  ...  $ff$  ...  
 (A) ...  $f$   $O(\dots)$   $f$   $N=$  , ...  $f$   $N=$  ... (A) ...  $f$   $O(\dots)$  -

...  $f$  ...  $f$  ...  
 ...  $ff$  ...

#### 4 N e c a d e e a a

...  $ff$  ...  $f$  ...  $f$  ...

$$E = \sum_{n=1}^N c_n (nk_x \Delta x) - k_x \Delta x$$

$$E = -[c + \sum_{n=1}^N c_n (nk_x \Delta x)] - (k_x \Delta x)$$

...  $f$  ...  $f$  ...  $ff$  ...  
 ...  $fE$  ...  $E$  ...  $f$  ...

...  $f$  ...  $f$  ...  $ff$  ...  
 ...  $f$  ...  $ff$  ...  $f$  ...  $r$  ...  $f$  ...

...  $f$  ...  $ff$  ...  $f$  ...  $N$  ...  
 ...  $f$  ...  $\times$  ...

...  $kh$  ...  $[\dots, \pi]$  ...  
 ...  $f$  ...  $f$  ...  $kh$  ...  $f$  ...

...  $kh$  ...  
 ...  $f$  ...  $ff$  ...

... ..

... ..  $kh \in [\dots, \pi]$  ...

... ..  $\mathbf{f}$  ... ..  $\mathbf{ff}$  ...

... ..  $kh \in \dots$  ...

... ..  $\mathbf{fkh}$  ...

... ..  $\mathbf{fi}$  ...

... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{ff}$  ...

... ..  $N >$  ...

... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..  $\mathbf{ff}$  ...

... ..  $\mathbf{f}$  ... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{ff}$  ...

... ..  $\mathbf{ffi}$  ...

... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..

... ..

$$E = -[c + \sum_{n=1}^N c_n (nk - (\theta)h) + \sum_{n=1}^N c_n (nk - (\theta)h)] - (kh) .$$

... ..  $\mathbf{fE}$  ... ..  $\mathbf{f}$  ... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..

... ..  $N =$  ... ..  $\mathbf{f}$  ... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..

... ..  $\mathbf{f}$  ... ..  $\mathbf{f}$  ... ..

... ..  $\mathbf{ff}$  ... ..  $\mathbf{ff}$  ... ..

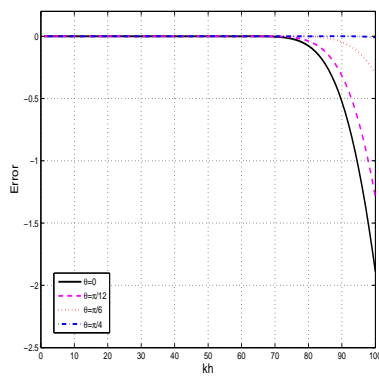
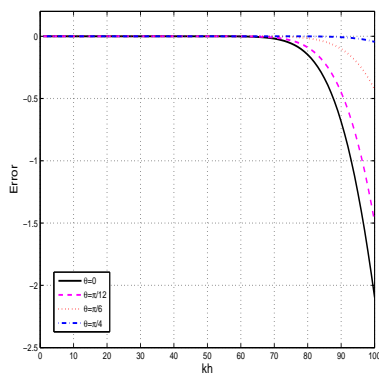
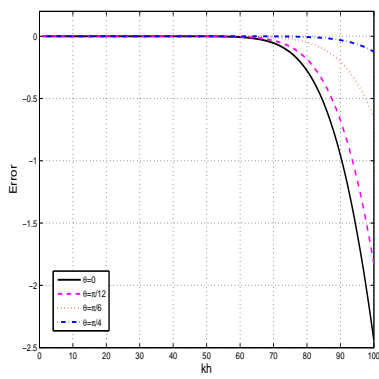
... ..  $\mathbf{ff}$  ... ..  $\mathbf{ff}$  ... ..

... ..





...  $f_i$  ...  $f_f$  ...



...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

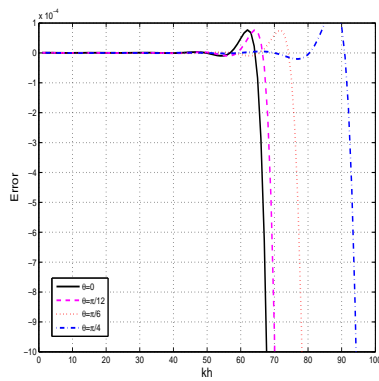
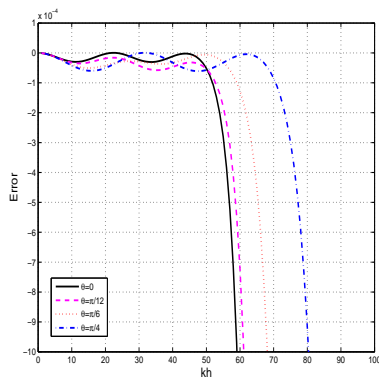
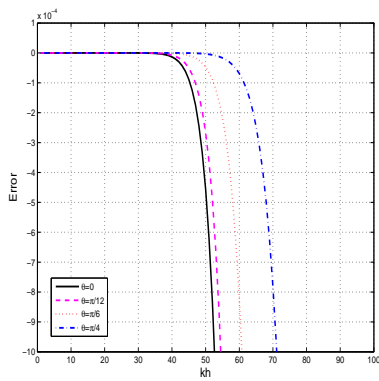
...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_{kh}$  ...



...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

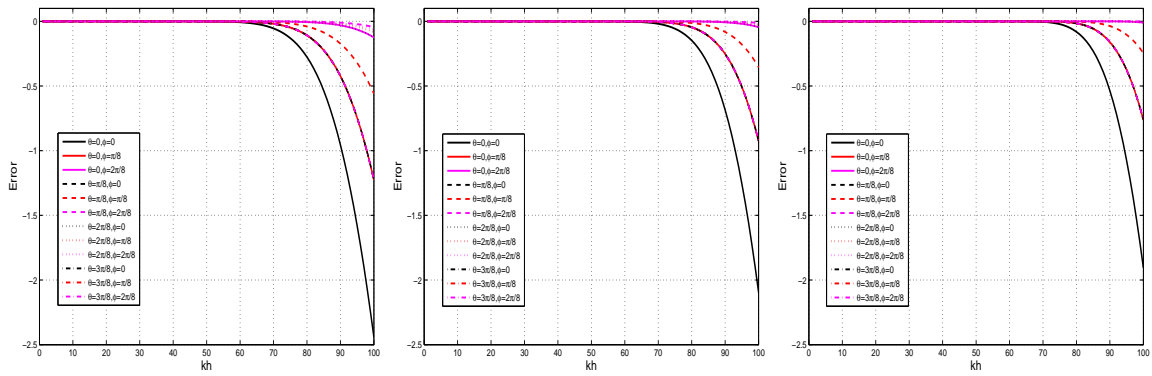
...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_i$  ...

...  $f_{kh}$  ...



$\mathbf{f} = \mathbf{f}(\mathbf{x}, \mathbf{y}, z, t)$

$\mathbf{f} = \mathbf{f}(\mathbf{x}, \mathbf{y}, z, t)$

$$E = -c - \sum_{m=1}^N c_m (mkh \theta \phi) + (mkh \theta \phi) + (mkh \theta) - kh$$

$\mathbf{f} E$

$N = \mathbf{f} \mathbf{f}$

$\mathbf{f} \times \mathbf{f} = \mathbf{f} \times \mathbf{f}$

$\mathbf{f} \times kh$

$\mathbf{f} \mathbf{f}$







Figure 6:  $\rho$  and  $\mathbf{ff}$  contours

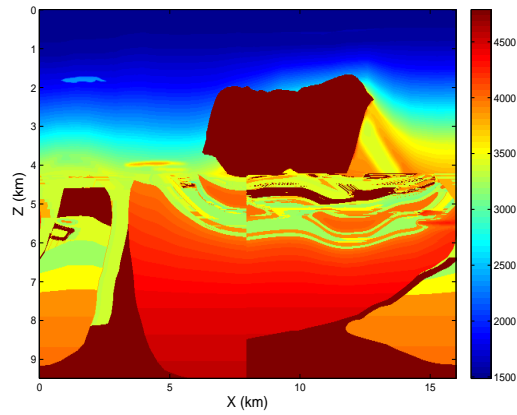


Figure 6:  $\rho$  and  $\mathbf{ff}$  contours

Figure 7:  $\mathbf{f}$  contours.  $t_{\text{max}} = 1000$  s.  $\mathbf{f}$  contours are shown in the  $(X, Z)$  plane. The contours are labeled with values: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100.

## 6 C c

Figure 8:  $\mathbf{f}$  contours.  $t_{\text{max}} = 1000$  s.  $\mathbf{f}$  contours are shown in the  $(X, Z)$  plane. The contours are labeled with values: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100.

Figure 9:  $\mathbf{f}$  contours.  $t_{\text{max}} = 1000$  s.  $\mathbf{f}$  contours are shown in the  $(X, Z)$  plane. The contours are labeled with values: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100.

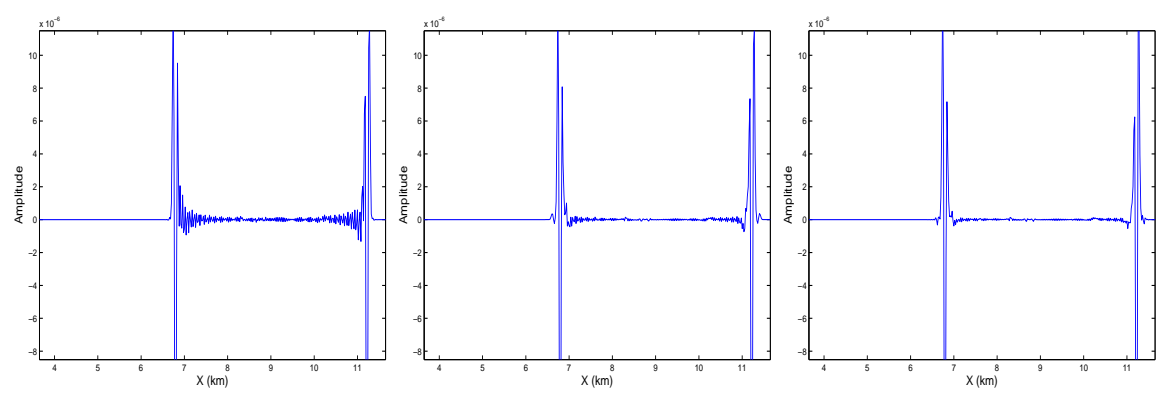
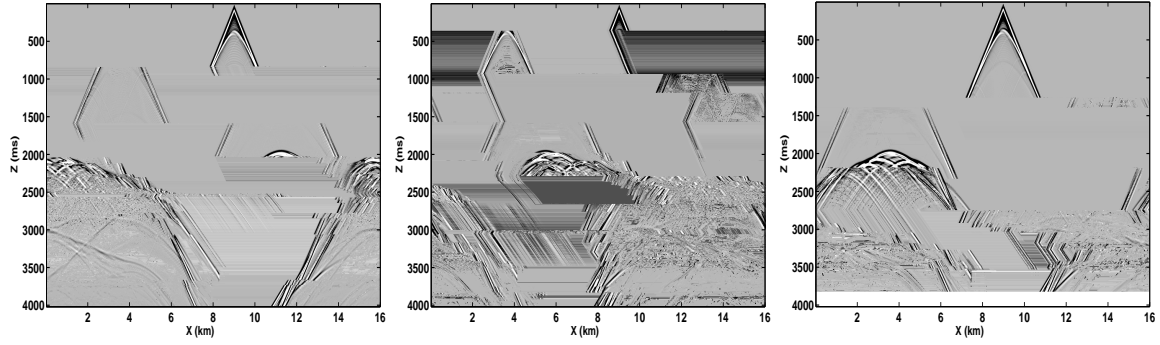


Figure 1.  $f_1$  and  $f_2$  versus  $r$ .

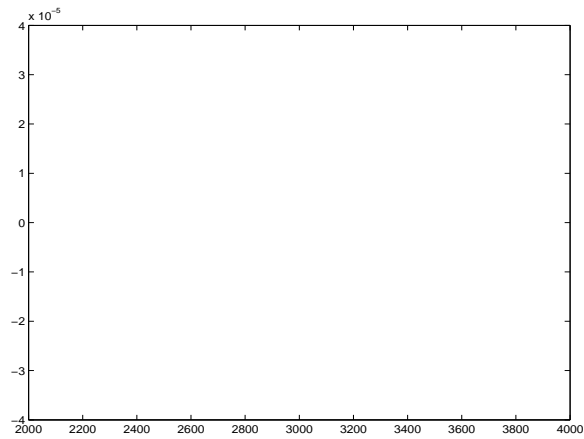


Figure 2.  $f_1$  and  $f_2$  versus  $r$ . The plot area is currently blank.

## Accepted Article

Figure 3.  $f_1$  and  $f_2$  versus  $r$ . The plot area is currently blank.

## Reference

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