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gradient method can reduce the amount of computation greatly, and the restoration based on the piecewise random sampling are better than that of random sub-sampling.

**Keywords** Wavefield recovery, Curvelet transform, Compressed sensing, Zero-norm approximation, Inverse problems, Ill-posedness, Sparse optimization

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$l_p - l_q$ , $q \to 0$

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$$\min \| \boldsymbol{x} \|_0, \text{s.t.} \boldsymbol{A}\boldsymbol{x} = \boldsymbol{y}. \tag{12}$$

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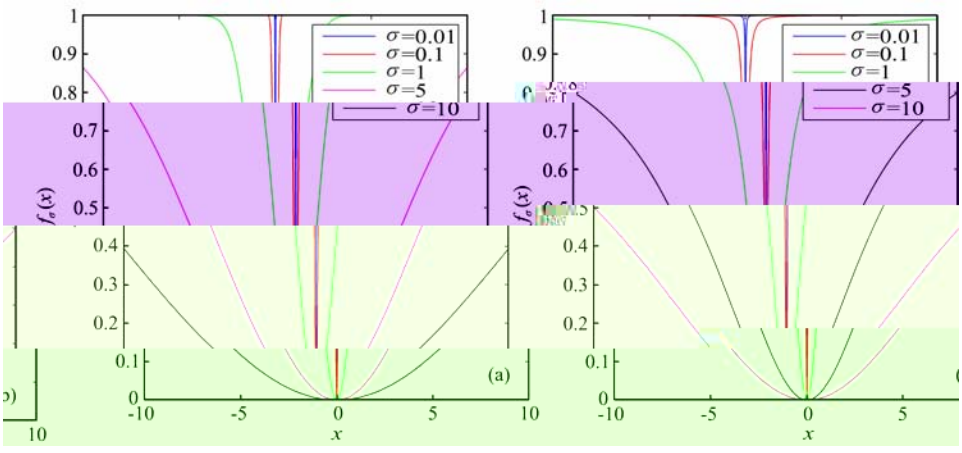
$f_\sigma(x)$: (1) $\sigma$,

$f_\sigma(x)$ $x$ ;

(2) $\sigma$ 0 , 0 :

$$\lim_{\sigma \to 0} f_\sigma(x) = \begin{cases} 0, & x = 0, \\ 1, & x \neq 0. \end{cases} \tag{13}$$

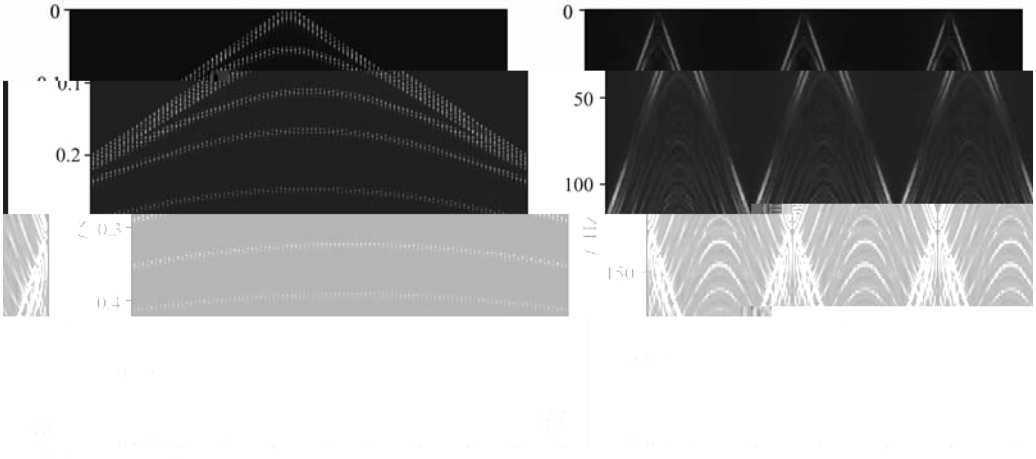
$$f_\sigma(x) = 1 - \exp(-x^2/2\sigma^2), \quad 1 \tag{14}$$




1 $f_\sigma(\boldsymbol{x}) = 1 - \exp(- x$

4 (a) (b)

Fig. 4 (a) The original data;(b) Frequency spectrum of (a)




5 (a) (b)

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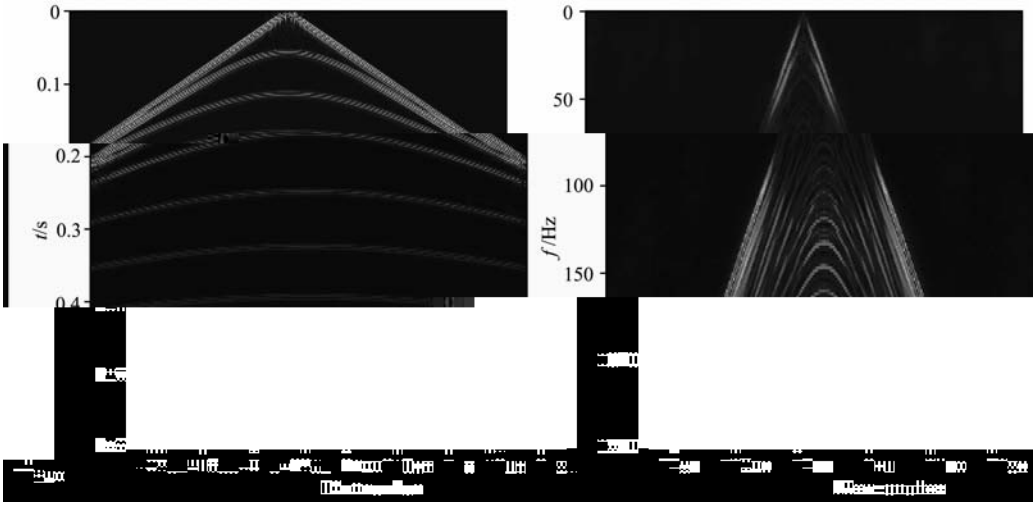
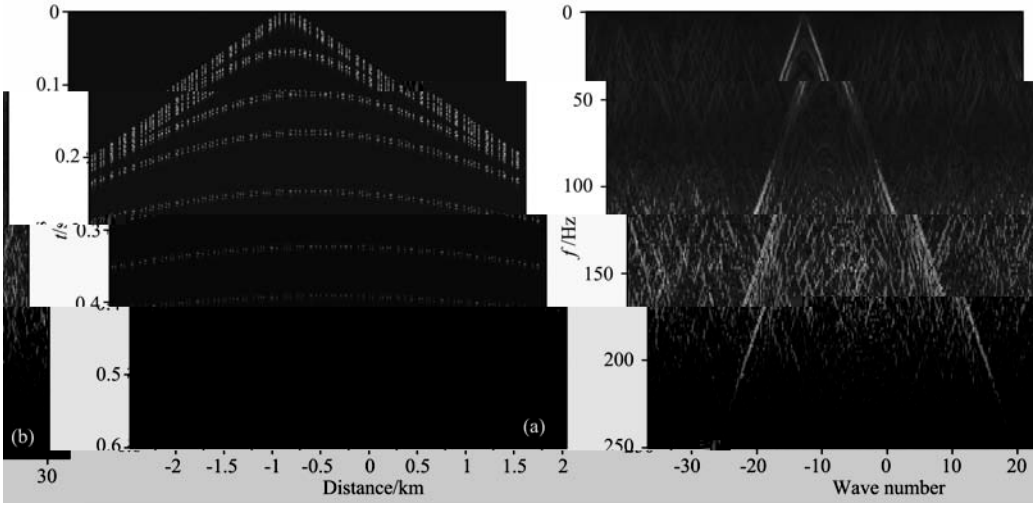



7 (a) (b)

Fig. 7 (a) Restoration of random sub-sampling; (b) Frequency spectrum of (a)

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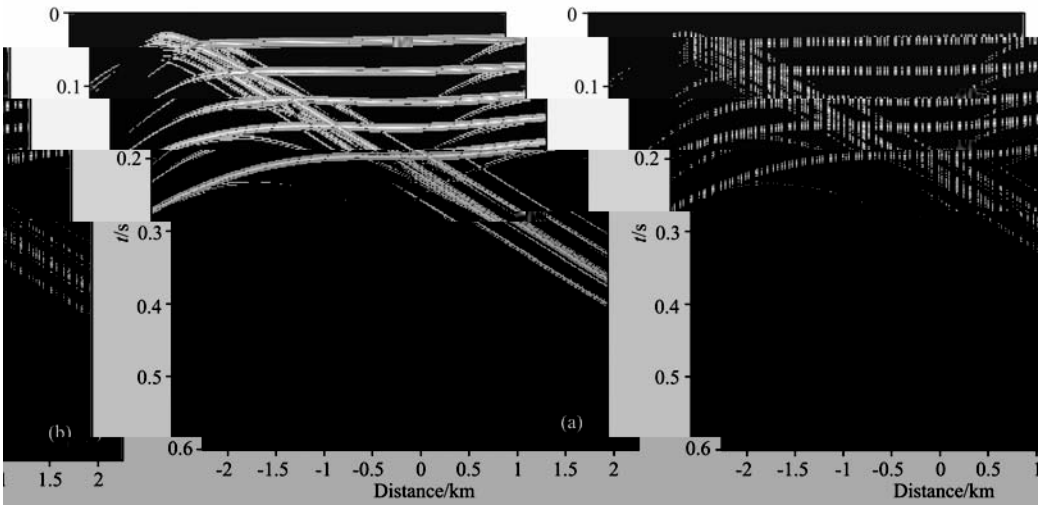
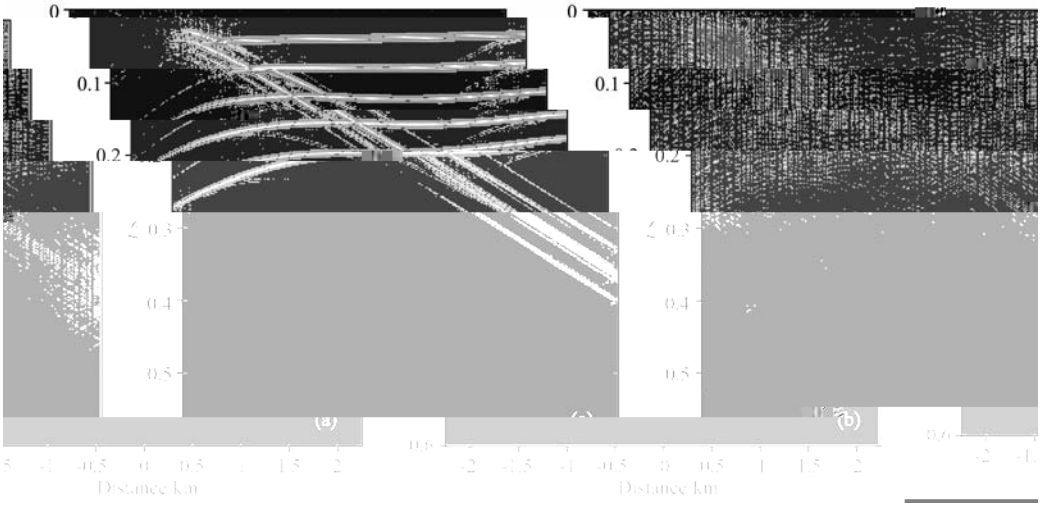


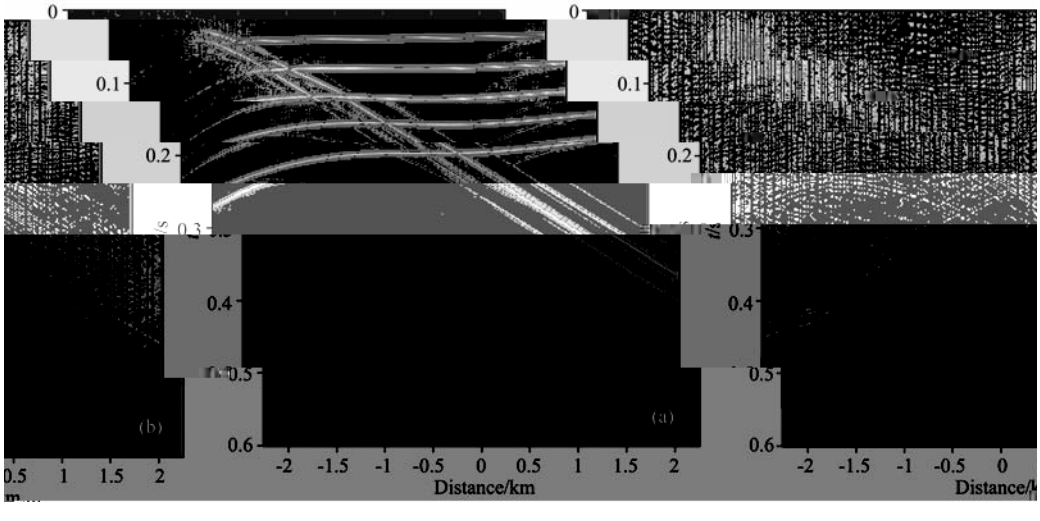

12 (a) (b)

Fig. 12 (a) The original data; (b) The sampled data



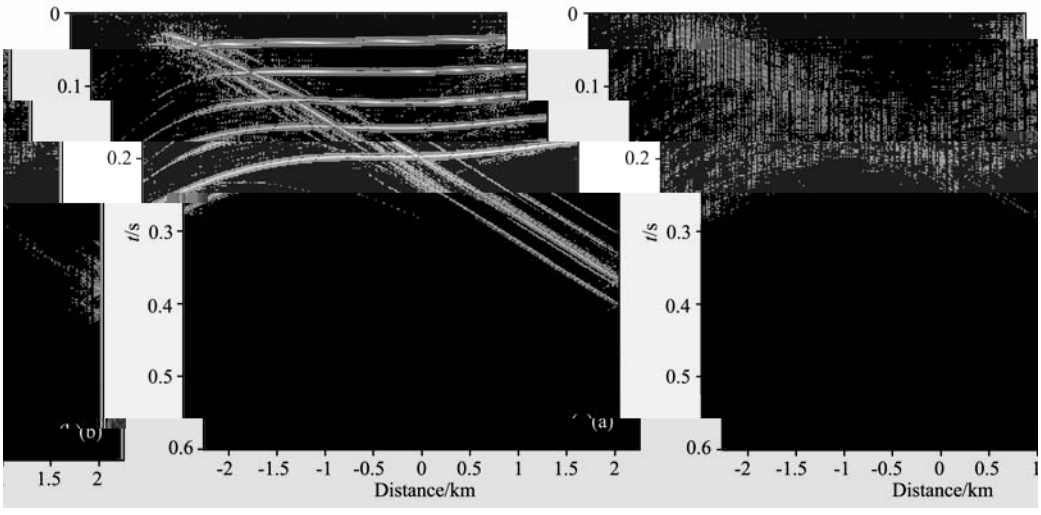

13 1 0 (a) (b)

Fig. 13 (a) Restoration of zero-norm approximate method based on case 1 function; (b) Difference between the original data and (a)



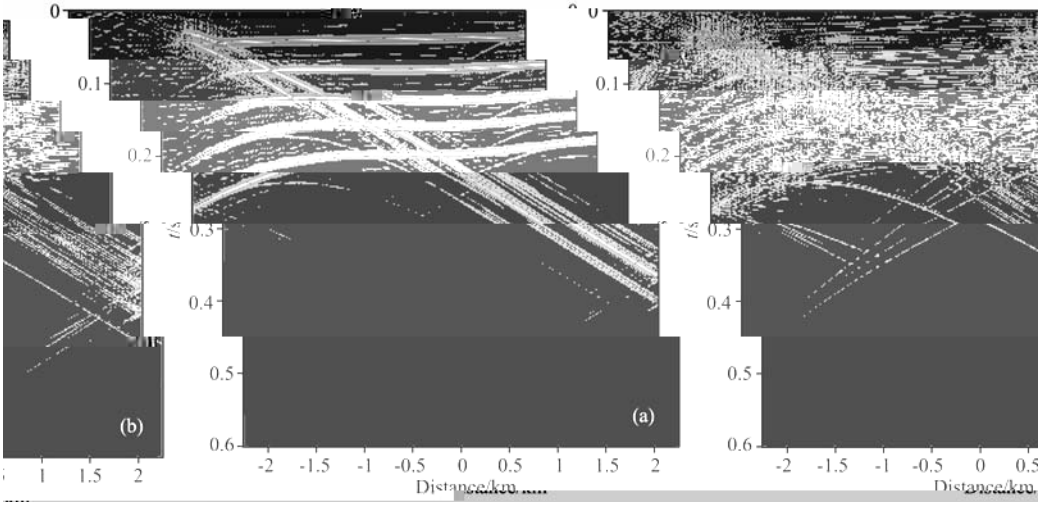

14 2 0 (a) (b)

Fig. 14 (a) Restoration of zero-norm approximate method based on case 2 function; (b) Difference between the original data and (a)




15 (IST) (a) (b)

Fig. 15 (a) Restoration of IST method; (b) Difference between the original data and (a)




16 (SPGL1) (a) (b)

Fig. 16 (a) Restoration of the SPGL1 method; (b) Difference between the original data and (a)

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**Table 1 The restoration results comparison of the above three methods**

| | | | /s |
|---|---|---|---|
| 0 : 1 | 0.0529 | 25.5282 | 306 |
| 0 : 2 | 0.0522 | 25.6524 | 318 |
| (IST) | 0.0571 | 24.8597 | 1326 |
| (SPGL1) | 0.0555 | 25.1210 | 1069 |

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