Geosciences Journal
Vol. 11, No. 1, p. 75 − 81, March 2007

Removal of ringing noise in GPR data by signal processing

Jung-Ho Kim
Seong-Jun Cho
Myeong-Jong Yi*
Engineering Geophysics Group, Korea Institute of Geoscience and Mineral Resources, 30 Gajeong-dong, Yuseong-gu, Daejeon, 305-350, Korea

ABSTRACT: Ringing is a common type of coherent noise in ground penetrating radar (GPR) data. When this kind of coherent noise is strong and is not properly removed, deeper structure may be completely masked. Ringing appears as nearly horizontal and periodic events, which are the most important features enabling us to remove the noise by signal processing. In this study, we have reviewed basic principles of various signal processing techniques to remove the ringing noise and compared their performances using field GPR data contaminated by severe ringing noise. The reviewed methods include background removal, f-k filtering, predictive deconvolution with filtering in wavenumber domain, and filtering by radon transform. Furthermore, it is shown that ringing can be successfully removed by the eigenimage filtering method, where GPR image is decomposed into eigenimages by singular value decomposition. This comparative analysis shows that the refined techniques are definitely more effective than the simple methods for the ringing noise removal with less distortion of GPR signals and each method has its own advantage as well as limitations. Moreover, preservation of the horizontally linear events from geological targets can be possible only through a kind of selective or local filtering such as the eigenimage filtering method.

Key words: GPR, ringing, signal processing, f-k filtering, deconvolution, eigenimage filtering

1. INTRODUCTION

Ground Penetrating Radar (GPR) is one of the most widely used geophysical methods to image the near surface area for geotechnical and environmental problems. In the application of GPR method, there are many cases where the acquired data are contaminated with ringing noise and it is hard to discriminate the reflection events from this noisy component. In the GPR image, ringing usually appears as horizontal and periodic events and is a common type of coherent noise. Although one of the most attractive merits of GPR method is to provide the subsurface image with very high resolution, one of the demerits of GPR technique may be the relatively shallower depth of investigation than other geophysical methods. When GPR data are contaminated by severe ringing, the depth of investigation may be even shallower because the strong ringing masks the weaker reflected signals from deep depths. Particularly in the case of 3-dimensional (3-D) survey, if we cannot effectively remove this noise from the 3-D data, the resultant horizontal sliced images below a certain depth may show only the footprint of antenna movement. Lots of signal processing techniques for removing this ringing noise have been studied and applied; simple subtraction of an average trace or background removal (Nobes, 1999), deterministic deconvolution (Xia et al., 2003), predictive deconvolution and filtering in wavenumber domain (Kim et al., 2005), domain filtering (Young and Sun, 1999), Radon transform (Nuzzo and Quarta, 2004), and so on. In this paper, these general processing techniques for removing ringing noise are reviewed and compared using field GPR data contaminated by severe ringing noise. In addition to these processing techniques, we will show that the eigenimage processing technique for extracting wavy feature of a GPR image (Cagnoli and Ulruch, 2001) also can be successfully used for the removal of ringing noise.

*Corresponding author: muse@kigam.re.kr

2. BACKGROUND REMOVAL TECHNIQUE

Figure 1 is an example of field GPR data severely contaminated by ringing noise. The image shows that ringing phenomenon appears as nearly horizontal events in the radargram. The field data in Figure 1 were acquired by the RAMAC/GPR system made by Mala Geoscience Co. with the shielded antenna having a central frequency of 250 MHz. Assuming that ringing is nearly consistent throughout the whole GPR section while reflected events are more random and less correlated, we can regard the average trace of the whole section as the trace containing ringing noise only. With this assumption, the horizontal appearance of ringing in the radargram enables us to remove the noise by the simple subtraction of an average trace. This processing method is often referred to as background removal. As shown in Figure 2a, the horizontal events were almost completely removed by subtracting an average trace. However, we can recognize that periodic characteristics are still present and dominant in the late time data, which means the incomplete removal of ringing noise.

We can generalize this approach by subtracting mean or median traces within moving trace intervals, i.e., residual mean or median filtering. The moving median or mean filtering technique can be used as an alternative to the back-

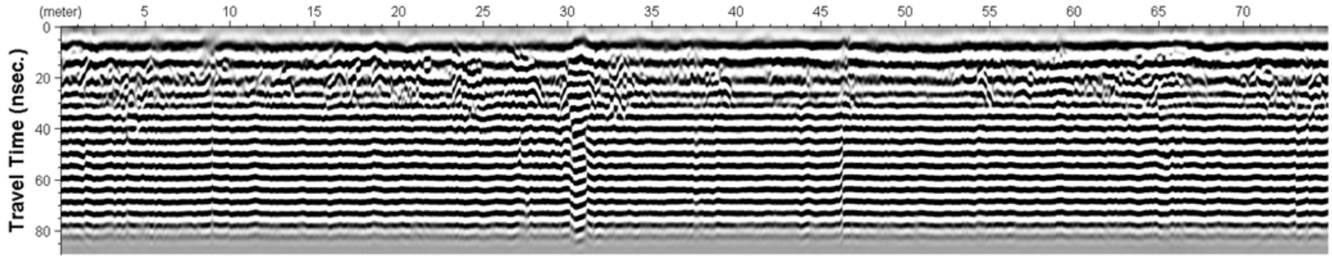

Fig. 1. Field data example showing very severe ringing noise. Applied data processing schemes are dc filtering, gain function for compensating spherical spreading and attenuation, band-pass filtering and normal move-out correction.

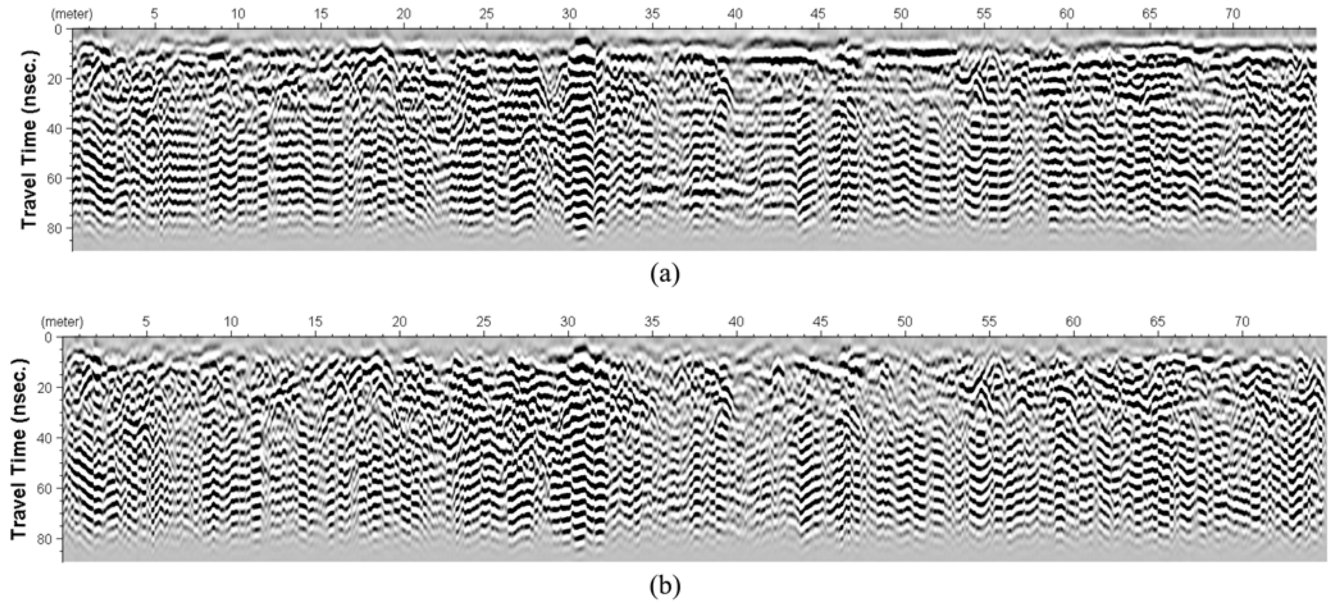

Fig. 2. Removal of ringing noise by simple subtraction of mean or median trace. An average trace of whole radar section was subtracted from the field data shown in Figure 1(a) and residual median filtering was applied to the same field data (b).

ground removal technique when the characteristics of ringing noise is changing over traces. The result of residual median filtering in Figure 2b, however, shows the nearly similar problem observed when the average of whole trace is subtracted. Moreover, we can easily notice that it is highly possible to eliminate signals having the horizontal or even gently dipping features.

3. FILTERING IN F-K DOMAIN

Ringing noise appearing as nearly horizontal events can be regarded as a component having infinite wavelength in wavenumber domain. As illustrated in Figure 3a, the most of the energy in the GPR image shown in Figure 1 is concentrated in the region having zero and near zero wavenumber (cycles/m), i.e., infinite and very long wavelength. Thus the ringing noise can be removed by filtering out the long wavelength components in the wavenumber domain. The filtered image, Figure 4a, seems to be slightly better than the result from subtraction of an average trace, Figure 2a, in the sense of more effective elimination of horizontal feature of the noise. However, the periodic characteristics are still dominant in the late time, which means that considerable amount of ringing noise are still remaining.

This behavior of filtering can be explained as follows. The ringing noise in Figure 1 shows not only perfectly horizontal appearance but also very monochromatic characteristics. The amplitude spectrum in frequency domain, Figure 3b, shows the monochromatic characteristics of the noise. Thus the ringing noise contained in the data of Figure 1 cannot be effectively removed by applying a band-pass filter in frequency or wavenumber domain only. Therefore, we can expect that ringing noise can be successfully eliminated by the filtering in frequency-wavenumber (f-k) domain or by the cascade application of the filters in frequency and wavenumber domains.

Figure 4c is the result of high-pass filtering in wavenumber domain after applying a band-reject frequency filter (Fig. 4b)

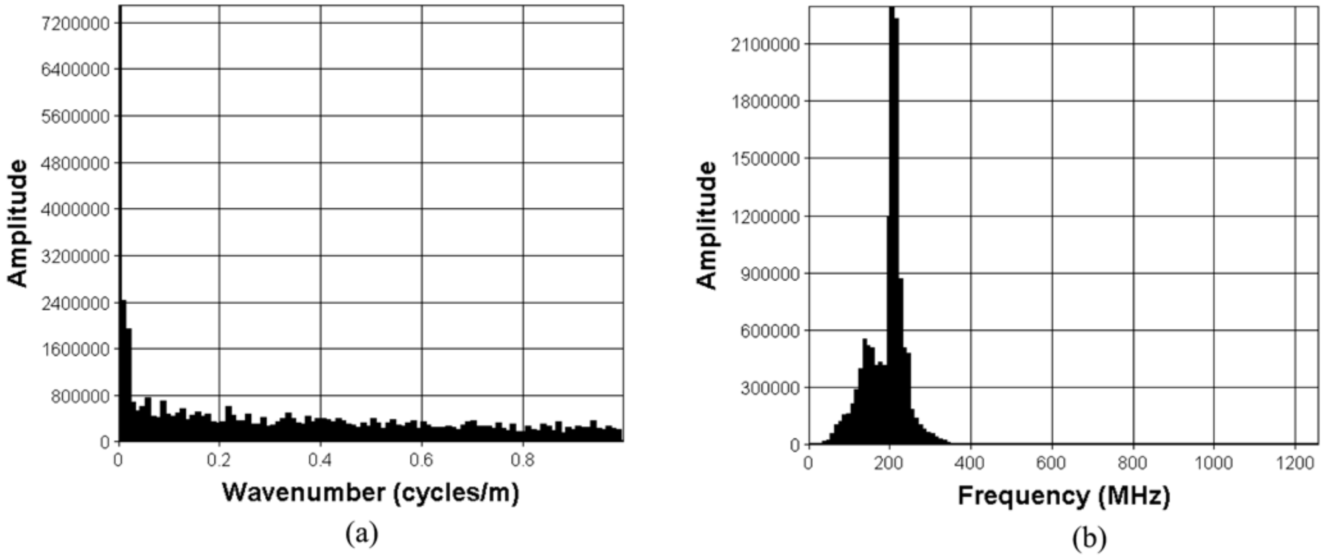

Fig. 3. Spectra in wavenumber domain (a), and frequency domain (b) of the field data shown in Figure 1.

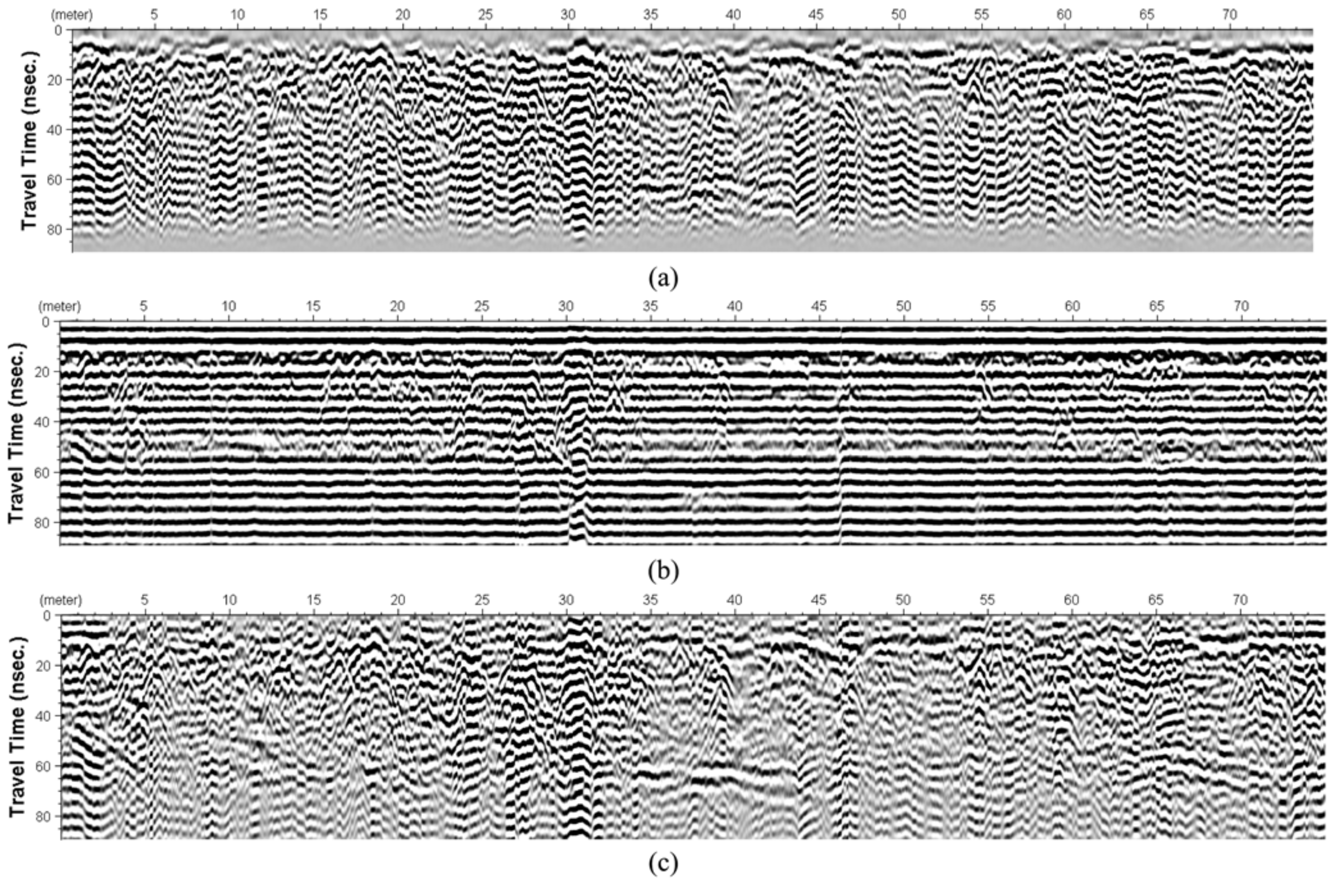

Fig. 4. Removal of ringing noise by filtering in frequency-wavenumber (f-k) domain. (a) shows the processed results of field data shown in Figure 1 by high-pass filtering in wavenumber domain, while (b) shows the result of band-reject filtering in frequency domain. (c) was obtained by applying the high-pass filter in wavenumber domain to the band-rejected radar image shown in (b).

with very narrow reject band nearly analogous to a notch filter. The processed image shows the effective removal of ringing, as compared with those of the simple processing schemes described in the previous section, even though ringing characteristics are still recognizable.

4. DECONVOLUTION WITH WAVENMUBER FILTERING

Deconvolution is a very useful signal processing technique to increase the resolution by making wavelet spiky and removing multiples and/or inter-bedded multiples which look like ringing. However, it would be impossible to completely remove ringing noise through applying only the deconvolution to the GPR data severely contaminated with ringing noise such as Figure 1, since ringing noise is quite different from the source wavelet. On the other hand, we can expect that the basic wavelets comprising GPR image would become uniform after applying deconvolution so that the monochromatic characteristics of GPR data with severe ringing would be reduced to some extent. Figure 5a is the image after applying predictive deconvolution. DC filter and gain function were applied before deconvolution processing, and band-pass filtering in frequency domain and normal move-out (NMO) correction were applied to the deconvolved result. Compared with the band-reject filtered image shown in Figure 4b, the monochromatic characteristics were more effectively reduced as illustrated in Figure 5a. To eliminate the horizontal features still remaining in the deconvolved image, we applied the high-pas filter in wavenumber domain to the section in Figure 5a. Figure 5b is the image after applying wavenumber domain filtering to the deconvolved data. The cascade application of predictive deconvolution and high-pass filtering in wavenumber domain can give the best result in the sense of removing ringing noise among various approaches discussed so far. This method, however, may generate processing artifacts and low signal-to-noise (S/N) ratio of GPR data may restrict the routine application of deconvolution.

5. FILTERING BY RADON TRANSFORM

In seismic exploration, processing techniques based on Radon transform have been used for a wide variety of purposes, such as velocity analysis, multiple suppression, wave separation, migration, and so on. Among the several variants of Radon transform methods, the linear Radon transform maps a straight line in a two-dimensional time-distance (t-x) plane into a point in intercept time-slope (τ-p) domain. Since the most dominant feature of ringing noise is horizontal appearance in GPR image and the horizontal appearance has zero slope, ringing noise will be mapped along the p=0 axis after linear Radon transform as illustrated in Fig.ure 6. Accordingly, we can easily remove the noise in τ-p domain by filtering out the data aligned along the p=0 axis. The f-k transform also maps ringing noise along the k=0 axis. The linear Radon transform, however, has an advantage over the f-k transform technique, since the intercept time τ of ringing noise in τ-p domain is same as the arrival time in the original t-x domain. Based on this advantage, Nuzzo and Quarta (2004) proposed the selective filtering method in τ-p domain to preserve the horizontal reflections other than ringing noise. In this comparative study, however, this method was not tested with the field data because basic idea is similar to f-k transform technique although selective or local filtering is possible in this method. Since our field GPR data contains severe ringing noise, it is very difficult to select the filtering region to preserve horizontal reflections.

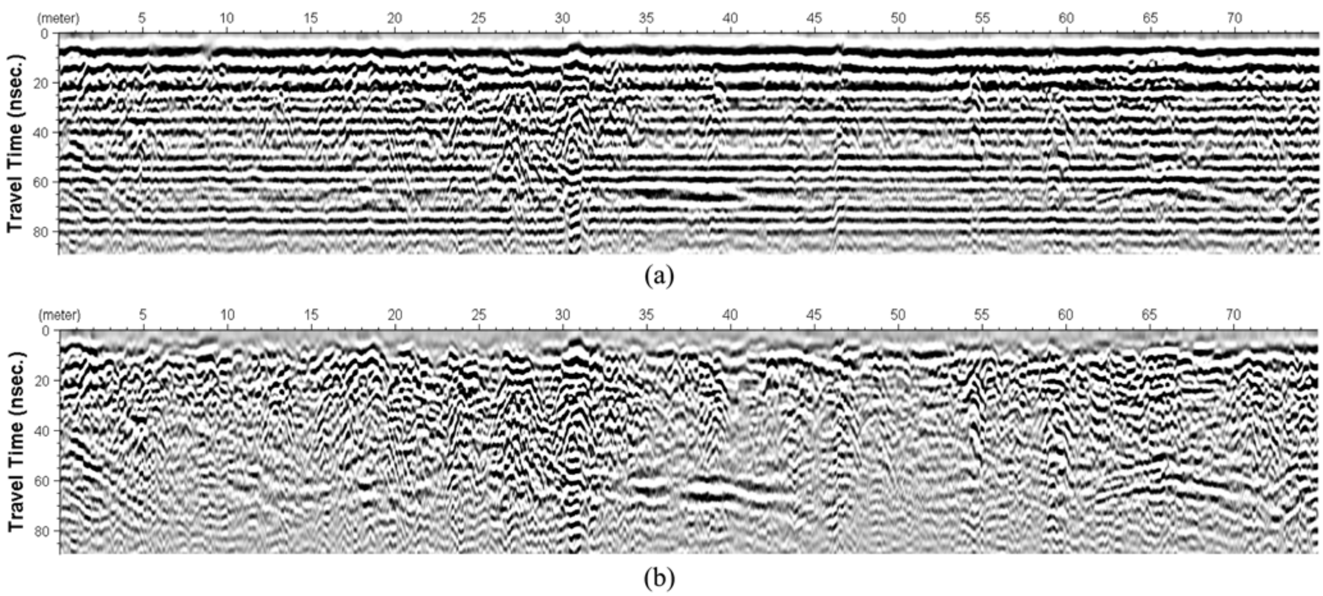

Fig. 5. Deconvolution of GPR data for the removal of ringing noise. Field data shown in Figure 1 was processed by predictive deconvolution (a) and the high-pass filtering in wavenumber domain was applied to the deconvolved section (b).

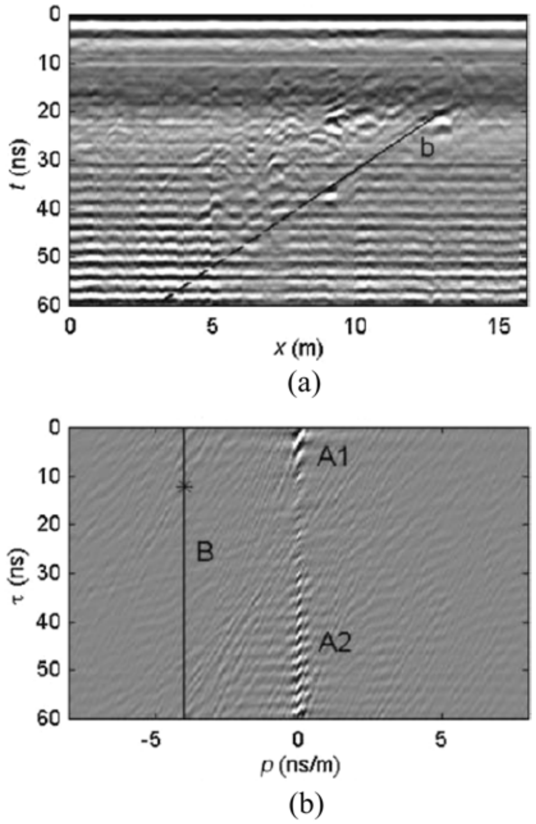

Fig. 6. Example of Radon transform of GPR data. Original data (a) and their radon transformed data (b) (after Nuzzo and Quarta (2004)). Reflection events along the line b map to the line B in the τ-p domain. A1 and A2 are the direct coupling and system ringing, respectively.

6. EIGENIMAGE FILTERING BY SVD

Gerlitz et al. (1993) adopted eigen filtering technique using singular value decomposition (SVD) to separate reflected waves from direct arrivals. Using the SVD method, we can decompose a GPR image into eigenimages and quantify how much a decomposed eigenimage correlates with the original GPR image. Based on this idea, Freire and Ulrych (1988) proposed an eigenimage filtering technique and Cagnoli and Ulrych (2001) used this approach to quantify the waviness of reflectors in GPR image. If GPR data are severely contaminated by ringing noise, the noise can be regarded as a component which is the most consistent and correlated with the contaminated GPR data. On the other hand, reflected events will be more random and less correlated components. Therefore, we can separate ringing noise and reflected events by using the eigenimage filtering technique, and consequently, we can remove the noise from the GPR data contaminated with the ringing noise.

Let $\mathbf{D}$ be a GPR data matrix which contains m traces and n data samples, i.e.,

$$\mathbf{D} = \{\mathbf{d}_1, \mathbf{d}_2, \ldots, \mathbf{d}_n\} \tag{1}$$

Note that a vector $\mathbf{d}_i$ is not the data along time axis, i.e., a trace, but along distance axis. The singular value decomposition of $\mathbf{D}$ is given by

$$\mathbf{D} = \mathbf{U}\mathbf{S}\mathbf{V}^T \tag{2}$$

where $\mathbf{U}$ and $\mathbf{V}$ are orthogonal matrices of m×m and n×n, respectively and $\mathbf{S}$ is m×n diagonal matrix of which diagonal element, s_i, is called as a singular value of the matrix $\mathbf{D}$. The column vector $\mathbf{u}_i$ of matrix $\mathbf{U}$ is normally called as a data space eigenvector. In this case, however, eigenvector in trace domain will be more suitable terminology since the original data matrix $\mathbf{D}$ spans in trace and time domain. From the same reason, the column vector $\mathbf{v}_i$ of the matrix $\mathbf{V}$ will be called as an eigenvector in time domain. Using these two eigenvectors and singular values, the above equation can be rewritten as

$$\mathbf{D} = \sum_{i=1}^{n} s_i \mathbf{u}_i \mathbf{v}_i = \sum_{i=1}^{n} s_i \mathbf{E}_i \tag{3}$$

The multiplication of two vectors $\mathbf{u}_i$ and $\mathbf{v}_i$ forms a m×n matrix $\mathbf{E}_i$ which can be regarded as a GPR image. The above equation implies that a GPR image can be decomposed into n different images and can be regarded as the weighted sum or linear combination of these images. Accordingly we can call this matrix $\mathbf{E}_i$ as an eigenimage (Cagnoli and Ulrych, 2001). Since $\mathbf{E}_i$ is originated from a single eigenvector in time domain, an eigenimage consists of the same trace but having different scale factor trace by trace. The singular values are ordered in decreasing magnitude, and the first eigenimage will contain the most common feature of the original image. As i increases, the contribution of the corresponding eigenimage to the given GPR image will decrease. Band-pass eigenimages are computed by rejecting highly correlated as well as highly uncorrelated parts of the original image, i.e.,

$$\mathbf{D}_{filtered} = \sum_{i=p}^{q} s_i \mathbf{E}_i \tag{4}$$

where, $1 < p \leq q < n$.

As illustrated in the band-pass eigenimage shown in Figure 7a, we can recognize that the filtering of eigenimages is also a good approach to remove ringing noise. The weighted summation of just two eigenimages of singular value index $i = 1$ and 2 can be regarded as the contribution of the ringing noise. Comparing the three filtered images of Figures 4c, 5b, and 7a, the reflection patterns are almost same and reflections from isolated bodies also shows nearly same appearances. However, we can also notice that there are slight discrep-

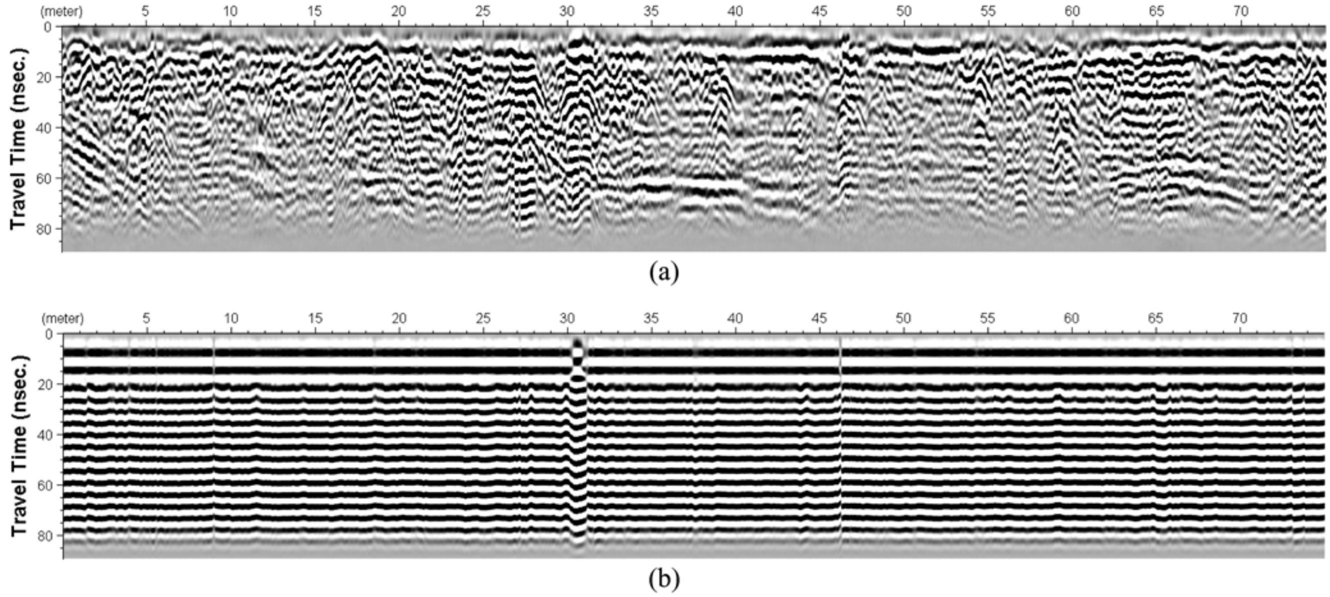

Fig. 7. Eigenimage filtering for the removal of ringing noise. (a) Band-pass eigenimage of Figure 1, where p=3 and q=80. (b) Low-pass eigenimage, where p=1 and q=2.

ancies among the three images processed by different approaches. Some of them may be due to processing artifacts. Compared with the result obtained by filtering in f-k domain and deconvolution with filtering in wavenumber domain, the processed image by eigenimage filtering looks slightly better from the point of the better continuity of reflectors, particularly in the very early time region and bottom reflections at 60 nsec with 32-45 m horizontal location.

7. CONCLUSIONS

The experiments discussed so far show that the refined techniques are definitely more effective than the simple processing approaches in removing ringing noise with less distortion of GPR signals although each method has its own advantages along with limitations. For example, the successive application of deconvolution and high-pass filter in wavenumber domain has a merit on the point that deconvolution can enhance the resolution of the processed data. Improper design of deconvolution operator, however, may generate processing artifacts and low signal-to-noise (S/N) ratio of GPR data may restrict the routine application of deconvolution.

The basic principles of all the processing techniques to remove ringing noise are based on the appearance of the noise in GPR image; the horizontal and periodic events. Because of this starting point of the processing algorithms, there is always high possibility to remove not only the ringing noise but also the horizontal and linear events having geological meanings such as groundwater table. These geologically meaningful reflectors can be preserved through selective or local filtering methods (Young and Sun, 1999; Cagnoli and Ulrych, 2001). These methods, however, cannot be systematically and routinely applied particularly to 3-D GPR data set because too heavy computation is required for the large data set. Supposing the case that the processing schemes to remove ringing noise are applied to the entire data set and are not locally nor selectively implemented, the eigenimage filtering may be a good approach with relatively less distortion of horizontal reflection events.

ACKNOWLEDGMENTS: This research was supported by the Basic Research Project of the Korea Institute of Geoscience and Mineral Resources (KIGAM) funded by the Ministry of Science and Technology of Korea.

REFERENCES

Cagnoli, B., and Ulrych, T.J., 2001, Singular value decomposition and wavy reflections in ground-penetrating radar images of base surge deposits. Journal of Applied Geophysics, 48, 175–182.

Freire, S.L.M., and Ulrych, T.J., 1988, Application of singular value decomposition to vertical seismic profiling. Geophysics, 53, 778–783.

Gerlitz, K., Knoll, D., Cross, G.M., Luzitano, R.D., and Knight, R., 1993, Processing ground penetrating radar data to improve resolution of near-surface targets. Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, edited by R.S. Bell, and C.M. Lepper, 2, 561–574, San Diego, USA, Apr. 1993.

Kim, J.-H., Yi, M.-J., Son, J.-S., Cho, S.-J., and Park, S.-G., 2005, Effective 3-D GPR survey and its application to the exploration of old remains. 2005 IEEE International Geoscience and Remote Sending Symposium Proceedings, 2005 IEEE IGARSS, Seoul, Korea, Jul. 2005.

Nobes, D. C., 1999, Geophysical surveys of burial sites: A case study of Oaro urupa. Geophysics, 64, 357–367.

Nuzzo, L. and Quarta, T., 2004, Improvement in GPR coherent noise attenuation using t-p and wavelet transforms. Geophysics, 69, 789–802.

Xia, J., Franseen, E. K., Miller, R. D., Weis, T. V., and Byrnes, A. P., 2003, Improving ground-penetrating radar data in sedimentary rocks using deterministic deconvolution. Journal of Applied Geophysics, 54, 15–33.

Young, R. A. and Sun, J., 1999, Revealing stratigraphy in ground-penetrating radar using domain filtering. Geophysics, 64, 435–442.

Manuscript received June 14, 2006
Manuscript accepted March 8, 2007