Computers & Geosciences 102 (2017) 12–21

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Research paper

Double-Sided Sliding-Paraboloid (DSSP): A new tool for preprocessing GPR data

Mohamed Rashed[a,b], Essam A. Rashed[c,*]

[a] Water Research Center, King Abdulaziz University, Jeddah, Saudi Arabia
[b] Geology Department, Faculty of Science, Suez Canal University, Ismailia 41522, Egypt
[c] Image Science Lab., Department of Mathematics, Faculty of Science, Suez Canal University, Ismailia 41522, Egypt

ARTICLE INFO

Keywords:
Rolling ball algorithm
Ground penetrating radar
Background noise

ABSTRACT

Background noise in Ground Penetrating Radar (GPR) data is a nagging problem that degrades the quality of GPR images and increases their ambiguity. There are several methods adopting different strategies to remove background noise. In this study, we present the Double-Sided Sliding-Paraboloid (DSSP) as a new background removal technique. Experiments conducted on field GPR data show that the proposed DSSP technique has several advantages over existing background removal techniques. DSSP removes background noise more efficiently while preserving first arrivals and other strong horizontal reflections. Moreover, DSSP introduces no artifacts to GPR data and corrects data for DC-shift and wow noise.

1. Introduction

Ground penetrating radar (GPR) has become one of the most increasingly used geophysical tools in the past few decades. Among the many reasons behind the wide spread of GPR applications are its capability to provide useful information about the shallow underground in relatively short time and the high-resolution images it provides. The steep decline in the cost of field instruments and the availability of open source freeware for processing GPR data have also contributed to the implementation of GPR tools in different fields. Another reason for the expansion in using GPR is that the collected data need minimal processing and GPR can be considered as semi-real-time investigation tool. Background noise is an irritating problem that reduces the quality of the subsurface images provided by GPR surveying.

Background noise is a coherent type of noise that appears as high amplitude low frequency horizontal bands obscuring reflections caused by targets of interest. The major part of background noise comes from antenna ringing. Ringing is caused by either impedance mismatch between the antenna and the ground or electronic design of the GPR antenna. Perfect impedance match between the antenna and the ground is practically impossible due to the variant nature of the ground from one site to another. Consequently, some of the transmitted energy is backscattered of the ground surface causing antenna ringing (Daniels et al., 2008). The internal electronic design of the antenna allows residual electric currents to reverberate between the tips of the transmitter antenna and the input feed. These currents are created by the remaining energy after the original pulse has traveled the full length of the antenna. Every time these currents travel between the tip of the antenna and the input feed, a secondary pulse is generated causing the transmitter to send several pulses that decay with time rather than sending a single clean pulse (Radzevicius et al., 2000).

The oldest and most commonly used background noise removal technique is the average trace or moving average trace subtraction (Nobes, 1999). However, there are many alternative processing techniques to attenuate background noise. These techniques include, but are not limited to, domain filtering (Young and Sun, 1999), eigenimage processing (Cagnoli and Ulrych, 2001), deterministic deconvolution (Xia et al., 2003), Radon transform (Nuzzo and Quarta, 2004), predictive deconvolution and filtering in the wavenumber domain (Kim et al., 2005), eigenimage filtering through singular value decomposition (Kim et al., 2007), multiresolution wavelet analysis (Jeng et al., 2009), fuzzy weighted background calculation (Sezgin, 2011), alternative seismic stacking techniques (Rashed, 2013), background matrix subtraction (Rashed and Harbi, 2014), and directional total variation minimization (Rashed, 2015).

In this study, we propose a new procedure for background noise removal called Double-Sided Sliding-Paraboloid (DSSP). DSSP is based on the rolling-ball background subtraction algorithm that was originally designed to treat medical images with variable background contrast (Sternberg, 1983). The proposed DSSP procedure employs a sliding paraboloid instead of the rolling ball. The paraboloid is slide on

* Corresponding author.
E-mail address: erashed@science.suez.edu.eg (E.A. Rashed).

http://dx.doi.org/10.1016/j.cageo.2017.02.005
Received 24 September 2016; Accepted 4 February 2017
Available online 06 February 2017

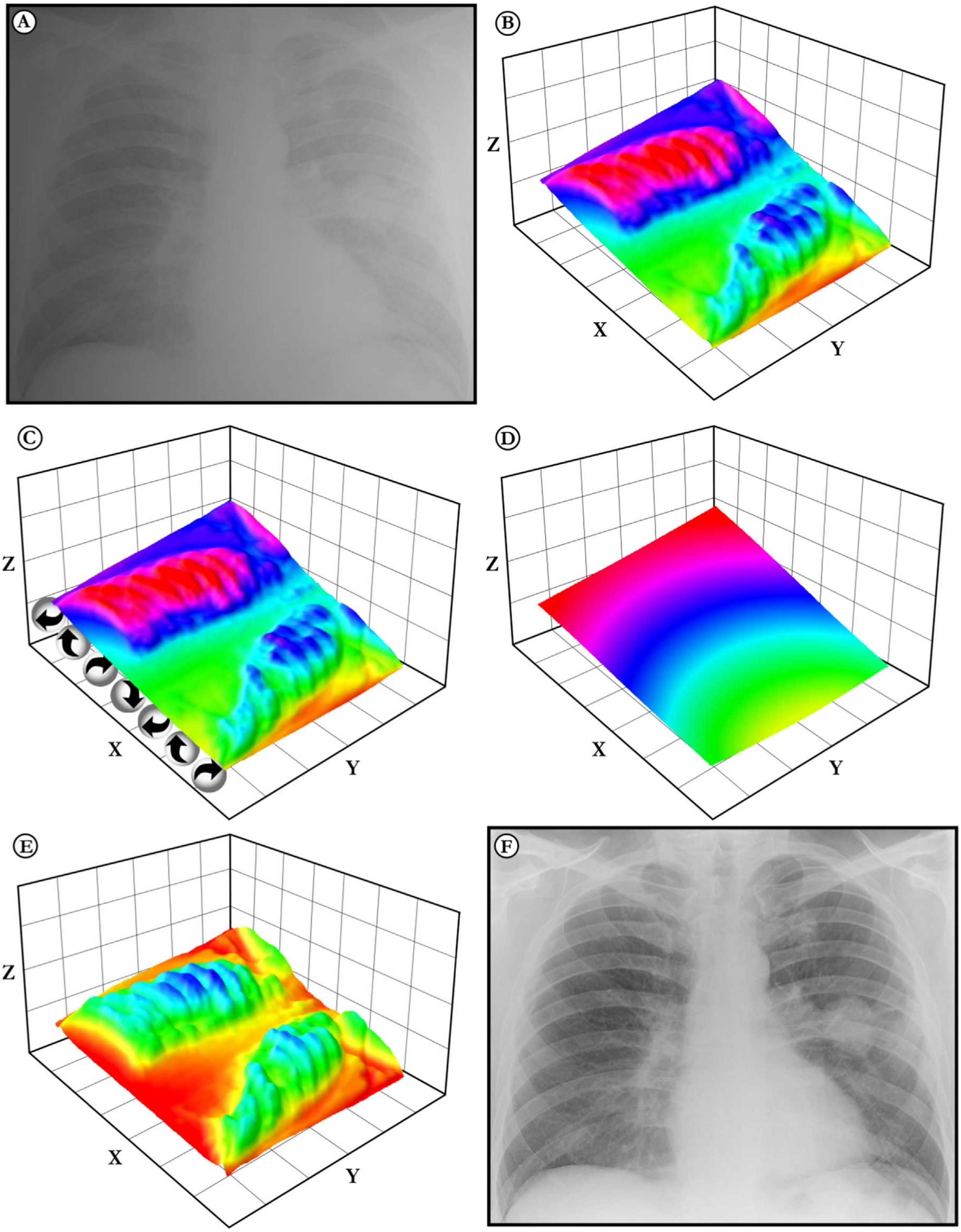

Fig. 1. Basic principles of the rolling ball background subtraction algorithm. (A) Original image, (B) 3D surface of the image, (C) rolling ball, (D) calculated background, (E) corrected 3D surface, and (F) corrected image.

both sides of the GPR section and the two resultant backgrounds are subtracted from the original GPR section. The end result of this simple procedure removes background noise swiftly and efficiently. Moreover, DSSP procedure corrects GPR data for DC-offset and attenuates wow noise.

2. DSSP algorithm

The rolling ball background subtraction algorithm is an old image processing technique that is used to correct medical images with uneven background brightness (Sternberg, 1983). This old procedure, however, is still successfully used in the field of medical image processing till today (Rizk et al., 2014; Wyttenbach et al., 2015; Akbarizadeh and Moghaddam, 2016). A recently published study shows the capability of such a technique to process geophysical data collected using frequency domain electromagnetic instruments (Rashed, 2016).

The concept behind the rolling ball background subtraction proce-

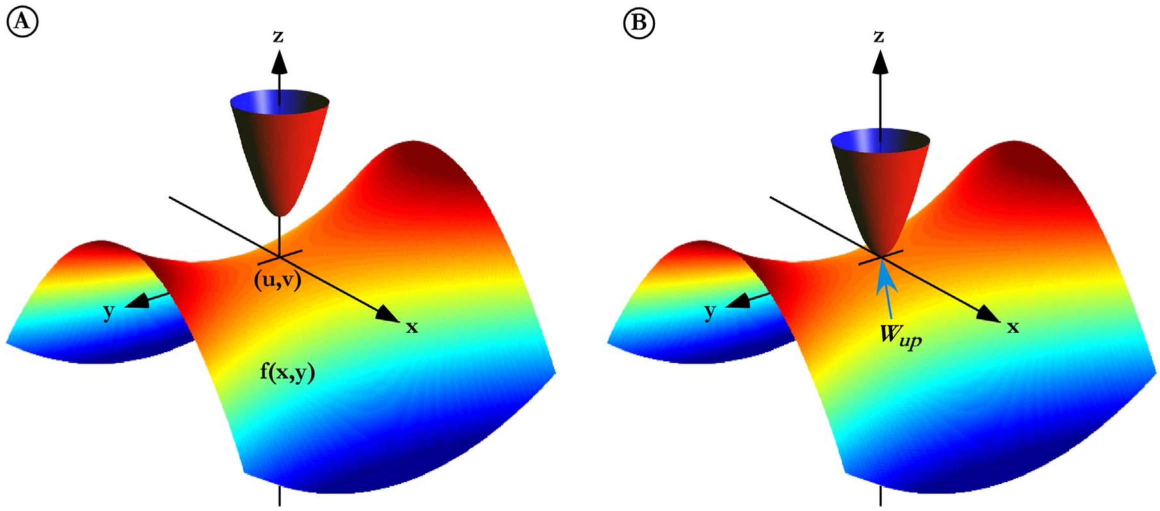

Fig. 2. Finding tangent point(s) between the paraboloid given by Eq. (2) and image surface f(x, y) at arbitrary pixel (u, v). (A) Initial state with paraboloid motion direction towards the surface, and (B) the solution point w_{up}.

dure is rather simple. When an image has non-uniform background brightness, as the one shown in Fig. 1A, it is difficult to see features of interest. The image is plotted as a 3D surface with the Z value representing the intensity of the image (Fig. 1B). A 3D ball of a user-defined radius is then rolled underneath the plotted 3D surface so that it touches the surface in one or more points as it rolls (Fig. 1C). The tangent points of the rolling ball to the surface are interpolated to form another 3D surface that represents the background (Fig. 1D). This background surface is then subtracted from the image surface, creating a corrected surface with even background brightness (Fig. 1E). When the corrected data are replotted with the same plotting parameters of the original image, the resultant image has a uniform background and many of the features masked on the original image are seen in a better way on the treated image (Fig. 1F).

The radius of the rolling ball controls the objects to be preserved and those to be filtered out. Smaller ball radius usually yields better results but it is risky. If the ball is small enough to fit completely inside a feature of interest, this feature would be considered as background and eliminated by the process, and hence the use of sliding paraboloid, a special case the rolling ball. A paraboloid is a special type of quadric surface. There are two types of paraboloid that are; elliptic and hyperbolic paraboloid. Elliptic paraboloid is a paraboloid that can be put into a position such that its sections parallel to one coordinate plane are ellipses, while its sections parallel to the other two coordinate planes are parabolas. Elliptic paraboloid is represented by the following equation:

$$\frac{z}{c}=\frac{x^2}{a^2}+\frac{y^2}{b^2} \tag{1}$$

where a and b are constants that dictate the level of curvature in the xz and yz planes, respectively and the sign of the constant c dictates the upward/downward orientation of the paraboloid. When a equals b, an elliptic paraboloid becomes a paraboloid of revolution. Paraboloid of revolution, a surface obtained by revolving a parabola around its axis, is used in the proposed algorithm.

The elliptic paraboloid presented in Eq. (1) is assumed to be located around the universal center point of Cartesian grid. To consider a sliding paraboloid in the 3D space, we reformulate Eq. (1) as:

$$\frac{z-w}{c}=\frac{(x-u)^2}{a^2}+\frac{(y-v)^2}{b^2} \tag{2}$$

where (u, v, w) indicate the paraboloid representation point in the 3D space. The formulation in Eq. (2) can be used to create parametric motion of the paraboloid in 3D space. For example, increasing the value of w moves the paraboloid up and vice-versa. Considering the 2D image as a parametric surface defined as:

$$z=f(x,\ y) \tag{3}$$

where z is the intensity value. The target here is to find the tangent points during the process of moving the paraboloid object in the up-down direction. We are interested only on the tangent point(s), where the paraboloid cannot be pushed any further against the surface. At an arbitrary image pixel (u, v), the points w_{up} and w_{down} can be found through the following equations:

$$w_{up}=\max_{l_{min}\le l\le l_{max}}\left\{l:\ l=f(x,\ y)-c\left(\frac{(x-u)^2}{a^2}+\frac{(y-v)^2}{b^2}\right)\right\} \tag{4}$$

$$w_{down}=\min_{l_{min}\le l\le l_{max}}\left\{l:\ l=f(x,\ y)+c\left(\frac{(x-u)^2}{a^2}+\frac{(y-v)^2}{b^2}\right)\right\} \tag{5}$$

where w_{up} (w_{down}) is the z-coordinate value of the point where the paraboloid is tangent to the image from the top (bottom) and l_{min} (l_{max}) is the minimum (maximum) image intensity value. The tangent point (x, y, z) is then marked as a background pixel value. This process is explained in Fig. 2 corresponding to up-down direction. This process is repeated until all the surface area of the 3D image is covered (Fig. 2).

In the proposed DSSP method, we consider the paraboloid of revolution (i.e. a=b), so Eq. (1) can be written in the following formulae:

$$z=t(x^2+y^2), \tag{6}$$

where $t=\frac{c}{a^2}$. This means we have only a single parameter t that should be selected carefully for background estimation. On one hand, if t is relatively large, the paraboloid will be presented in a thin shape that may fall entirely inside a feature of interest. Therefore, this feature will be incorrectly classified as background and removed by the proposed algorithm. On the other hand, if t is relatively small, the paraboloid will be presented as flat disk and several background features are likely to be missed accordingly. A balance between too large and too small values should be adjusted based on the amplitude and frequency of both signal and noise in the data under processing. Therefore, t is a data-defendant parameter. A quick examination of the 3D surface of the data under processing usually leads to the selection of the appropriate values of this parameter. However, the parameter selection process involves some fine tuning to reach the most satisfactory results. A pseudo code of the DSSP algorithm is provided as a Supplementary material to this article.

In the following section, we discuss the concept of the proposed

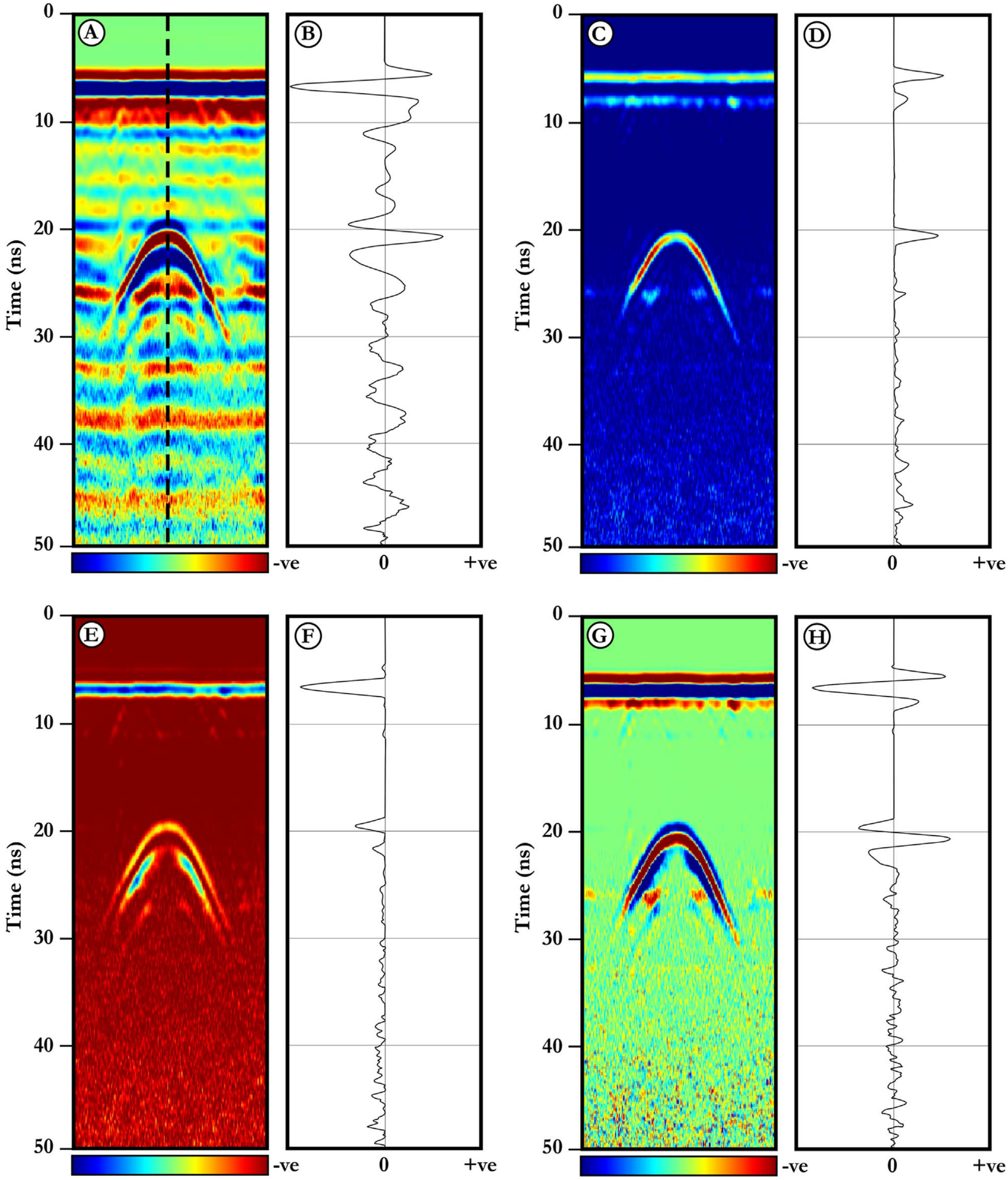

Fig. 3. Procedures of applying the double-sided sliding-paraboloid (DSSP) algorithm to field GPR data. (A) Original GPR section, (B) original scan, (C) left-side DSSP image, (D) left-side (DSSP) scan, (E) right-side DSSP image, (F) right-side (DSSP) scan, (G) DSSP filtered GPR section, and (H) DSSP filtered scan.

DSSP background removal algorithm and explain the reasons for using the sliding paraboloid instead of the rolling ball. Fig. 3(A) shows a part of a real field GPR section that has a beautiful hyperbola in addition to background noise. The section also shows the direct wave arrivals at 7 ns (ns) and a strong horizontal reflection at 26 ns. Fig. 3(B) shows a single scan of these data, marked with dashed black line in Fig. 3(A). Now, assume a paraboloid, with appropriate radius of curvature at the apex, sliding along the left side of the scan with the tangent points interpolated to form the half background scan. When this half background scan is subtracted from the original scan it creates the scan shown in Fig. 3(D). Extending this process to the 2D image shown in Fig. 3(A) creates the image shown in Fig. 3(C). It can be clearly seen that all background noise, in addition to the negative wings of anomalies are filtered out.

When the same paraboloid slides along the right side of the original scan and the resultant scan is subtracted from the original scan it

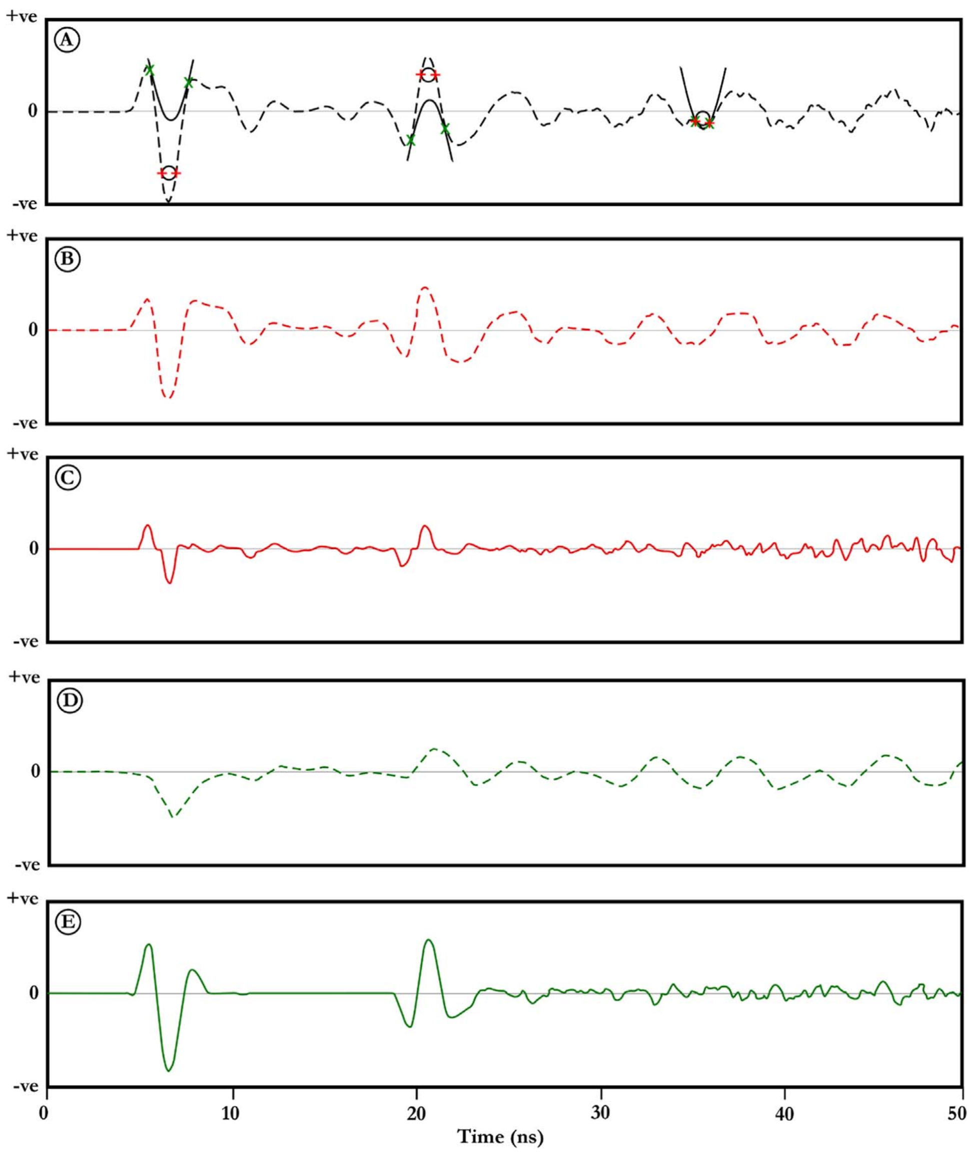

Fig. 4. Comparison between the efficiency of the rolling ball and the sliding paraboloid in removing background noise from GPR data. (A) Tangent points of circle and parabola with the original scan at different positions, (B) background estimated using rolling circle, (C) Scan filtered using rolling circle, (D) background estimated using DSSP, and (E) Scan filtered using DSSP.

creates the scan shown in Fig. 3(F). Extending this procedure to the 2D image produces the image shown in Fig. 3(E). Summing the 2 resultant scans in Figs. 3(D) and 3(F) forms a scan with no background noise (Fig. 3H). Likewise, summing the images in Figs. 3(C) and 3(E) generates the GPR section shown in Fig. 3(G).

The net result of the proposed DSSP algorithm shows several interesting details. First, the background noise is efficiently filtered out exposing features concealed in the original section, such as the high frequency jitter in the late times of the GPR section. Second, the strong direct wave arrival, usually filtered out by other background removal techniques, is conveniently preserved. Third, the edges of the hyperbola are not smoothed, a phenomenon that occur as a side effect of most known background removal techniques. Fourth, no artifacts are created by the filtering process near the right and left edges of the section. These artifacts are usually caused by padding the image or using variable scan number in calculating the background noise near the start and end of the GPR section. Last but not least, the strong horizontal reflection at 26 ns is partially preserved. Almost all other background removal tools eliminate horizontal and semi-horizontal features of interest along with the background noise.

There are several reasons for using the sliding paraboloid instead of the rolling ball in the proposed DSSP background removal algorithm. The main reason the sliding paraboloid provides better results than the rolling ball is that paraboloid has infinite lateral extension. This infinite lateral extension, combined by the unique geometry of the paraboloid, minimizes the risk of full fit within a feature of interest, and hence filtering it out. Moreover, a paraboloid with the same radius of curvature at the apex as a ball touches the high-frequency high-amplitude features, such as reflections and direct waves, at points closer to zero than the ball (Fig. 4A). Thus the rolling ball filters out a large portion of features of interest leaving only low amplitude traces of these features. On the other hand, the sliding paraboloid allows for larger portion of features of interest to be preserved. As for the low frequency low amplitude background or ringing noise, both the sliding paraboloid and the rolling ball yield almost similar results.

Another advantage of the sliding paraboloid is that is doesn't need downsizing the image before implementation, a common practice in rolling ball algorithm to reduce computation time. Instead, a virtual paraboloid is used by implementing parabolas at different directions and not a real paraboloid to reduce computation time. This procedure yields exactly the same results in much less time.

Fig. 4(A) shows the same scan shown in Fig. 3(B) with a circle and a

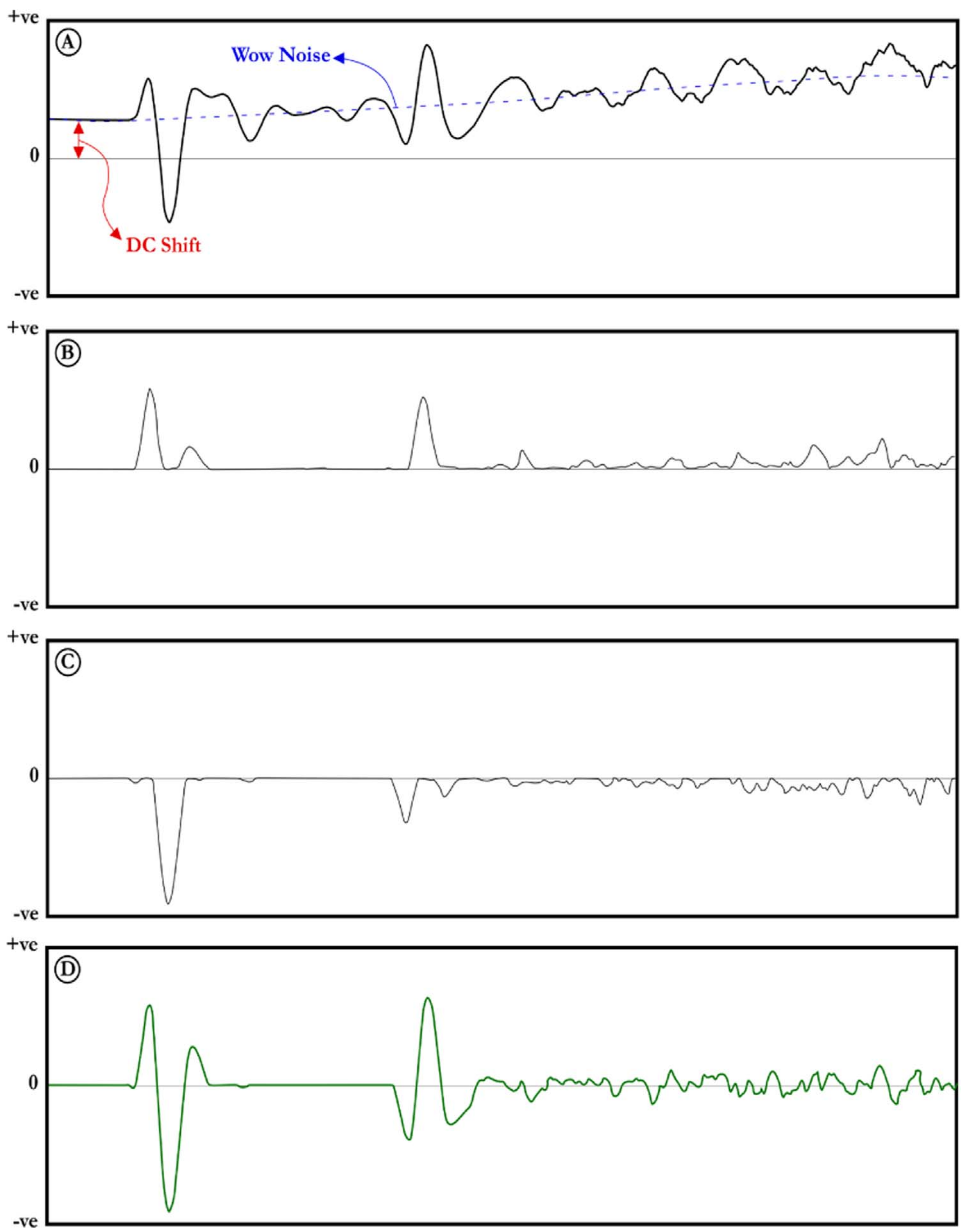

Fig. 5. Effect of DSSP background removal algorithm on DC-shift and wow noise. (A) Original scan with DC shift and wow noise, (B) DSSP result on the upper side, (C) DSSP result on the lower side, and (D) final DSSP result.

parabola of the same radius at 3 different positions. The tangent points of the circle are marked by red + sign while those of the parabola are marked by green × sign. At the first position, representing a negative peak of the direct wave at 7 ns, the circle falls deep into the beak leaving only a small portion to be mapped while the rest is filtered out as a background. The parabola touches the peak at points larger than zero preserving the entire peak. The same can be seen at the second position with the positive peak of the hyperbola at 21 ns. At the third position, representing low frequency background noise at 36 ns, both the circle and parabola touch the scan at similar tangent points.

The background scan interpolated using the double-sided rolling circle is presented on Fig. 4(B) and its background subtraction result is shown on Fig. 4(C). While the background scan created using the double-sided sliding parabola is shown on Fig. 4(D) and the subtraction output on Fig. 4(E). The difference is quite clear suggesting that the DSSP filters out as much background noise as the double sided rolling ball, while preserving all features of interest in a much better way.

Another great advantage of the DSSP background removal algorithm is that it treats GPR data from DC shift and wow noise. In other words, if data under processing are going to be treated for background removal using the proposed DSSP algorithm, there is no need to apply pre-processing steps such as DC shift and dewowing. DC shift is a constant departure of the entire registered GPR trace from the zero amplitude baseline position that is mainly caused by inherent limitations of the electronics which deal with microwave pulses (Fig. 5A). Sometimes DC shift is so small that it can be negligible but large DC shift usually causes masking of late weak reflections. The traditional way to deal with DC shift is to calculate the mean value of amplitudes before first arrival for each trace independently and then subtract this value from all samples within this trace (Szymczyk and Szymczyk, 2012).

On the other hand, wow noise or signal saturation is a low frequency noise (less than 1 MHz) that is caused by signal saturation due to the high amplitude early wave arrivals, induction caused by the close proximity of the GPR transmitter and receiver antennas, and

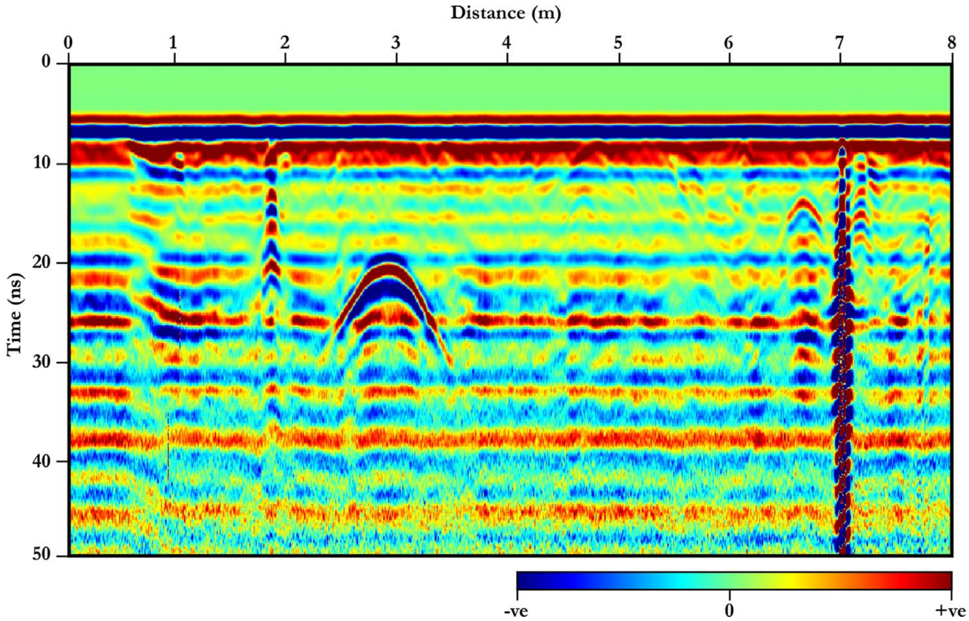

Fig. 6. GPR section used for comparing the proposed DSSP technique to other background removal techniques.

limited dynamic range of the GPR instrument (Fig. 5A). Removing this kind of noise, or dewowing, is usually achieved through applying a low-cut filtering in the frequency domain (Gerlitz et al., 1993).

Fig. 5(A) shows the same scan shown in Fig. 3(B) before applying DC shift correction and dewowing. The scan shows clear constant departure from zero and also a low frequency bowing towards the positive side of the scan. Figs. 5(B) and 5(C) show the results of background removal using the sliding paraboloid on both sides of the original scan, respectively, while Fig. 5(D) shows the summation of these 2 scans. Obviously, the DSSP algorithm does not only remove background noise effectively, but also removes both DC offset and wow noise.

3. Application to field data

A new processing algorithm is valued by how much enhancement it brings to real field data compared to the most common processing techniques and the state-of-the-art techniques. In this section, the DSSP background removal algorithm is applied to a field GPR section shown in Fig. 6 and the results are compared to those of the mean scan subtraction, which is the most commonly used background removal technique, and to the results of two of the state-of-the-art techniques namely; background matrix subtraction technique (Rashed and Harbi, 2014) and directional total variation minimization technique (Rashed, 2015).

The mean scan subtraction or moving mean scan subtraction is the most commonly used background removal method. In this procedure, a mean scan is formed by averaging all or some of the scans of a GPR section. This mean scan is subtracted from each scan in the GPR section (Nobes, 1999). The background matrix subtraction (BMS) forms a complete background matrix through an iterated process of exclusion and weighting. This matrix is then subtracted from the GPR data to remove background noise (Rashed and Harbi, 2014). Directional total variation minimization (DTVM) uses the natural characteristics of the background noise, which is consistency within the same depth, to suppress GPR signals and enhance background noise. The background noise is then subtracted from the original GPR data to attenuate background noise (Rashed, 2015).

The GPR section used in the comparison is a part of a survey collected over an area with a variety of buried utilities in southern Jeddah City, Saudi Arabia. The data are collected using a GSSI SIR-3000 system with a 400 MHz antenna. Time mode is used to collect the data with 100 scans per second and a transmit rate of 100 kHz. No gain function or frequency filters are applied during data acquisition and time range is set to 50 ns (Fig. 6).

This GPR shown in Fig. 6 section shows a number of different size hyperbolas caused by metallic and nonmetallic utilities buried at different depths in addition to relatively strong background noise. The section shows two major disturbances near the left edge of the section, at 0.5 m, and in the middle of the section, at 4.5 m. These disturbances are caused by the edges of a trench housing a large concrete pipe, causing the large hyperbola at 3 m, and a power cable, causing the ringing shallower hyperbola near 2 m. Another hyperbola is located at 6.5 m, while the chain-like feature at 7 m marks the location of a very shallow small metallic object. Another small hyperbola appears to the right of this feature at 7.2 m (Fig. 6).

The section also shows a strong horizontal reflection that extends along the section at time of 26 ns. This reflection marks an interface between lose sand and a solidified sandstone layer, that has been verified in field. The GPR section is characterized by relatively strong background noise that contaminates the entire section with variable amplitudes and appears as horizontal bands running along the section (Fig. 6). The results of applying the mean scan subtraction and DSSP background removal techniques are displayed on Fig. 7. While the result of background matrix subtraction and directional total variation minimization techniques are displayed in Fig. 8.

The section shown on Fig. 7(A) presents the results of applying the most commonly used mean scan subtraction background removal technique with window width of 101 scans, representing about 1 m. One can easily notice the zigzag-like artifacts overwhelming the entire section (Fig. 7A). These artifacts are caused by the irregular nature of the background noise. Another issue with this section is the smoothing of all hyperbolic features and the smeared high-amplitude artifacts on both sides of each hyperbola, which is a common side effect of the averaging process of the mean subtraction technique. The left edge of the trench also leaves remarkably high amplitude artifacts overwhelming the area between 0 and 1 m. It is also obvious that the first arrivals are completely eliminated and that the horizontal reflection at 26 ns is totally filtered out (Fig. 7A). Another noticeable phenomenon is the smeared high amplitude artifacts surrounding the chain-like feature near the right edge of the section.

On the other hand, the section treated using the proposed DSSP

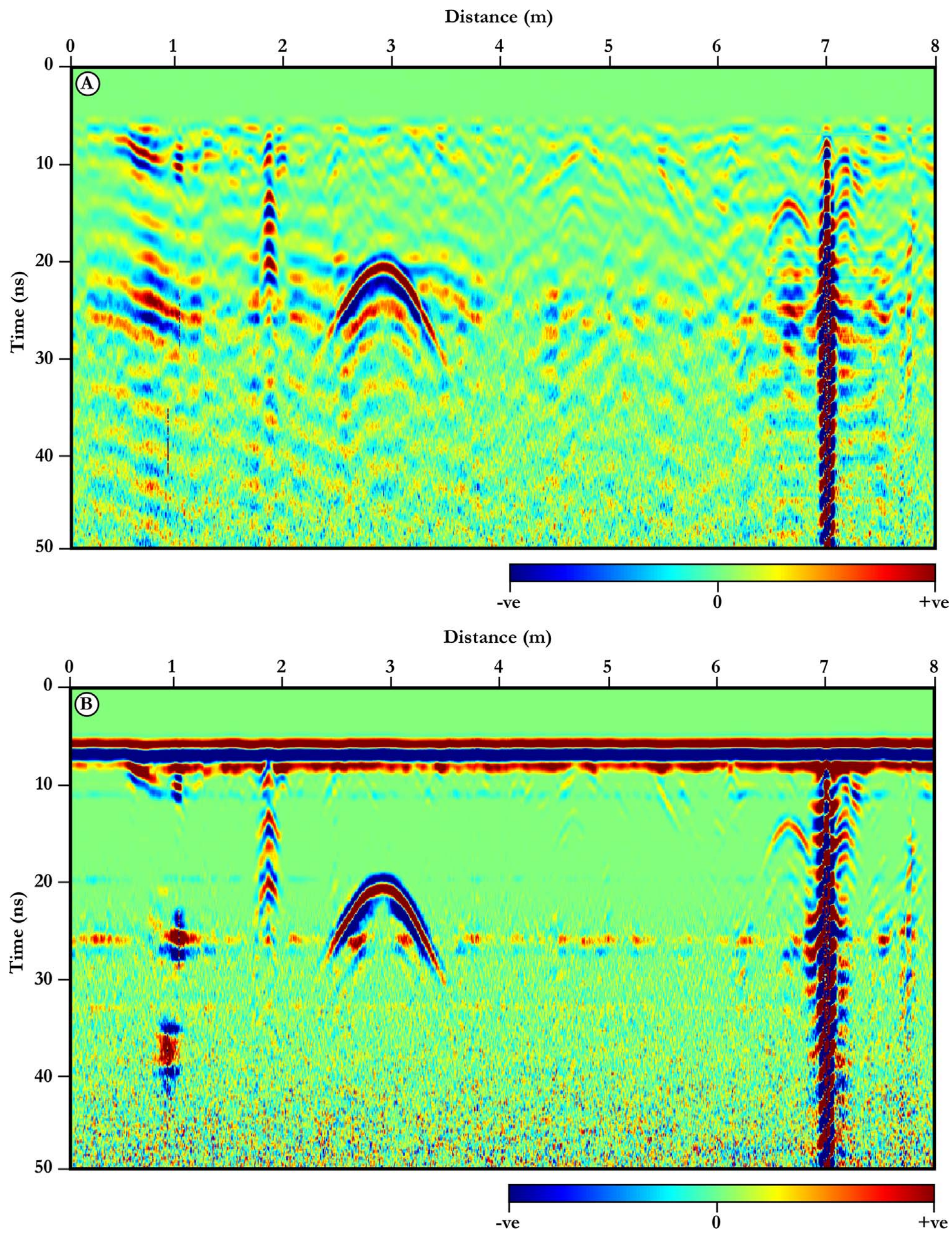

Fig. 7. The results of applying the mean scan subtraction technique (A) and the DSSP technique (B) to GPR section shown on Fig. 6.

technique maintains full integrity. Hyperbolic features have much sharper edges and higher amplitudes on this section (Fig. 7B). Both the first arrivals and the horizontal reflection at 26 ns are preserved. In addition, the left edge of the trench has minimal effect on the treated section. The background noise is completely removed so that the high frequency noise at later times appears clearly on this section.

The same section treated using the background matrix subtraction and the directional total variation minimization techniques are displayed on Figs. 8(A) and 8(B), respectively. Both show better background removal efficiency and preservation of features of interest than the mean scan subtraction. However, none of these 2 methods yields results comparable to the proposed DSSP background removal technique.

The background matrix subtraction technique is successful in treating the GPR section without smoothing the edges of the hyperbolic features. Hyperbolas have higher amplitudes than those on the section treated with the conventional mean scan subtraction technique. The section treated using the background matrix subtraction technique has less smearing on the sides of hyperbolas and zigzag artifacts are of lower amplitude than those on the section treated using the mean scan subtraction technique. However, both the horizontal reflection and the first arrivals are filtered out and the quality of the resultant section is way less than that resulted from the proposed DSSP technique (Fig. 8B).

The section treated using the directional total variation minimization technique is slightly better than that treated using the background matrix subtraction technique. It is less affected by the high amplitude noise burst at 1 m, especially at times 25 and 37 ns. The section shows less smearing effect on both wings of the large hyperbola. However, residual background noise can be clearly seen on this section, despite of the 200 iterations used to process this section (Fig. 8B).

In conclusion, the three background removal methods that are used in this study to evaluate the performance of the proposed DSSP method result in slightly different outputs. The mean scan subtraction tool has resulted in the worst results with strong artifacts, smoothing of hyperbolic edges and loss in their amplitudes, and filtering out of the

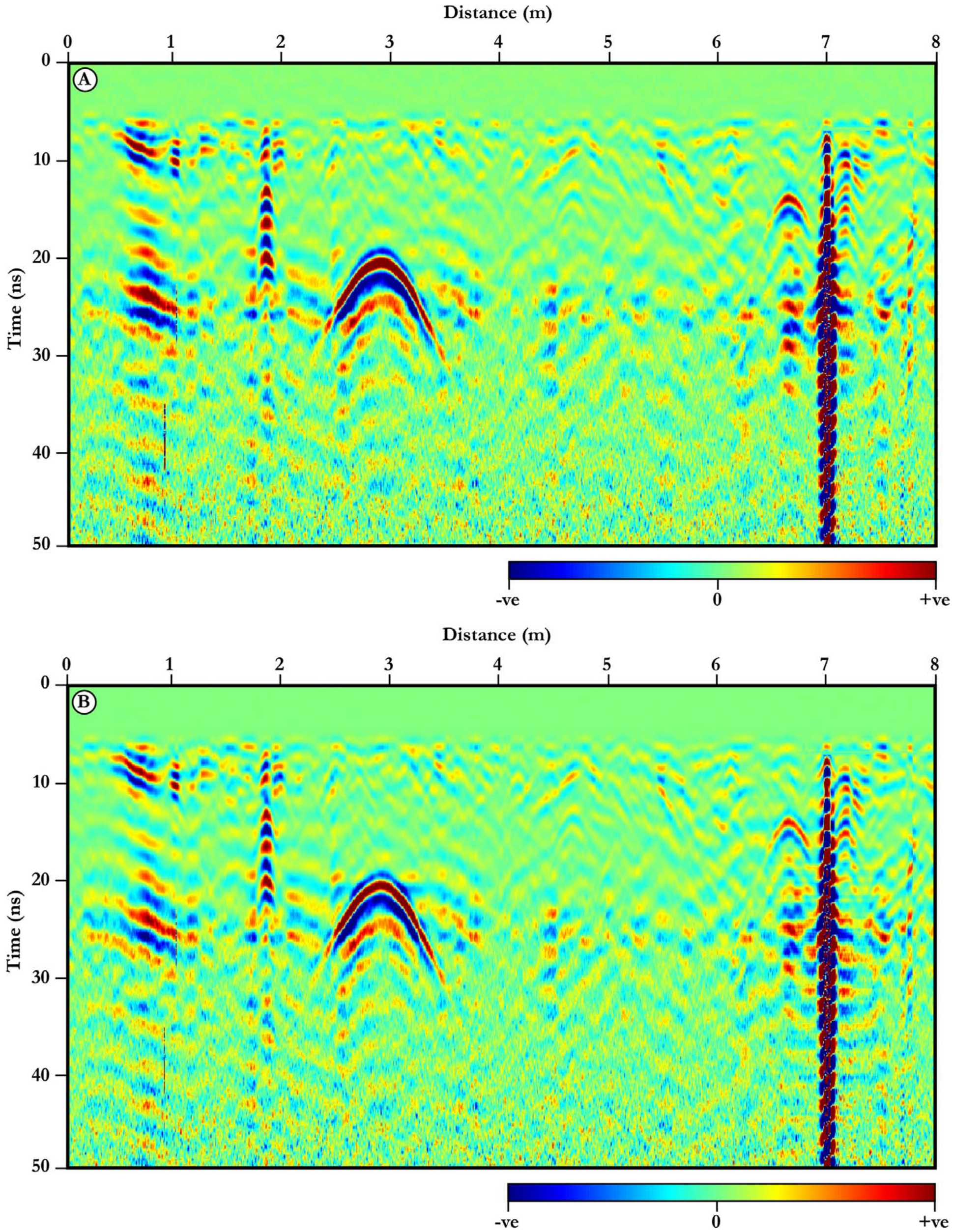

Fig. 8. The results of applying the BMS technique (A) and the DTVM technique (B) to GPR section shown on Fig. 6.

first arrival and horizontal reflection. The background matrix subtraction and directional total variation minimization techniques yield slightly better results. However, both results have residual background noise and the first wave arrivals and horizontal reflection are completely filtered out. On the other hand, the result of the proposed DSSP technique is way better than the three methods in terms of preserving all features of interest and completely removing the background noise.

4. Discussion and conclusions

Preprocessing is a routine procedure in GPR data analysis. Preprocessing involves correcting data for DC shift, dewowing, background noise removal, and attenuation compensation. DC shift correction is a simple procedure of subtracting an average value of the amplitudes before first arrival from each trace. Likewise, dewowing is achieved via a simple procedure of low-cut filtering. Background noise, however, is a relatively problematic issue due to the variant amplitude and irregular banding of the background noise. Consequently, a variety of techniques employing different approaches have been introduced during the past couple of decades to remove or attenuate background noise in GPR data.

Background removal techniques, known till today, have some serious drawbacks. These drawbacks include the inconveniently imminent removal of the first wave arrivals, vital for zero time adjustment. Similarly, horizontal features are filtered out along with the background noise. Another drawback is the artifacts introduced by these algorithms, especially near the start and the end of the GPR section due to the use of data padding or the variant number of traces used to calculate background noise near the edges of the section. Reduction in amplitudes and smoothing of the edges of features of interest, such as hyperbolic and dipping features, is another harmful side effect of almost all background noise removal techniques.

This study presents the double-sided sliding-paraboloid (DSSP) as an effective alternative procedure for background noise removal. The DSSP procedure is based on the well-known rolling ball algorithm, original intended to correct medical images with uneven brightness.

The DSSP procedure is quite simple. A virtual paraboloid of revolution, of user defined radius at the apex, slides on both sides of a 3D surface of the GPR section resulting in 2 background surfaces. Each of these background surfaces is subtracted from the original GPR section and the 2 resultant outputs are summed to generate a background noise-free GPR section.

Tests conducted using field GPR data show that the DSSP procedure is superior to both the most commonly used and the most recently published background removal methods. The DSSP procedure does not only remove background noise more effectively but also preserves the amplitudes and the sharp edges of features of interest in a remarkably better way. Another big advantage of the DSSP procedure is that it does not introduce artifacts, commonly introduced by other background removal methods to GPR data. Moreover, the DSSP procedure preserves both the first wave arrivals and the strong horizontal reflection, usually filtered out by other background removal methods. In addition, the DSSP procedure automatically corrects GPR data for DC shift and wow noise interference. These usually require the application of 2 independent processes to correct for when using other background removal algorithms.

In conclusion, the proposed DSSP background removal procedure removes background noise more effectively, preserves features of interest more intact, introduces no artifacts to data, and needs no DC shift correction or dewowing before implementation. These give the DSSP procedure several advantages over other background noise removal tools known till present.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2017.02.005.

References

Akbarizadeh, G., Moghaddam, A., 2016. Detection of lung nodules in CT scans based on unsupervised feature learning and fuzzy inference. J. Med. Imag. Health Inf. 6, 477–483.

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

Daniels, J., Ehsani, M., Allred, B., 2008. Ground penetrating radar methods (Handbook of Agricultural Geophysics, 7). CRC Press, 129–145.

Gerlitz, K., Knoll, M., Cross, G., Luzitano, R., Knight, R., 1993. Processing ground penetrating radar data to improve resolution of near-surface targets. Proceeding of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, San Diego, USA. SAGEEP, 561–575.

Jeng, Y., Lin, C., Li, Y., Chen, C., Huang, H., 2009. Application of multiresolution analysis in removing ground penetrating radar noise. Front.+Innov.-2009 CSPG CSEG CWLS Conv., 416–419.

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

Kim, J., Cho, S., Yi, M., 2007. Removal of ringing noise in GPR data by signal processing. Geosci. J. 11, 75–81.

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

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

Radzevicius, S., Guy, E., Daniels, J., 2000. Pitfalls in GPR data interpretation: differentiating stratigraphy and buried objects from periodic antenna and target effects. Geophys. Res. Let. 27, 3393–3396.

Rashed, E., 2015. GPR background removal using a directional total variation minimisation approach. J. Geophys. Eng. 12, 897–908.

Rashed, M., 2013. Application of alternative seismic stacking techniques to ringing noise removal from GPR data. Surf. Geophys. 11, 465–472.

Rashed, M., 2016. Rolling ball algorithm as a multitask filter for terrain conductivity measurements. J. Appl. Geophys. 132, 17–24.

Rashed, M., Harbi, H., 2014. Background matrix subtraction (BMS): a novel background removal algorithm for GPR data. J. Appl. Geophys. 106, 154–163.

Rizk, A., Paul, G., Incardona, P., Bugarski, M., Mansouri, M., Niemann, A., Ziegler, U., Berger, P., Sbalzarini, I.F., 2014. Segmentation and quantification of subcellular structures in fluorescence microscopy images using Squassh. Nat. Protoc. 9, 586–596.

Sezgin, M., 2011. Simultaneous buried object detection and imaging technique utilizing fuzzy weighted background calculation and target energy moments on ground penetrating radar data. EURASIP J. Adv. Sign. Process. 55, 1–12.

Szymczyk, M., Szymczyk, P., 2012. Preprocessing of GPR data. Image Process. Commun. 18, 83–90.

Sternberg, S., 1983. Biomedical image processing. IEEE Comput. 16, 22–34.

Wyttenbach, T., Bleiholder, C., Anderson, S.E., Bowers, M.T., 2015. A new algorithm to characterize the degree of concaveness of a molecular surface relevant in ion mobility spectrometry. Mol. Phys. 113, 2344–2349.

Xia, J., Franseen, E., Miller, R., Weis, T., Byrnes, A., 2003. Improving ground-penetrating radar data in sedimentary rocks using deterministic deconvolution. J. Appl. Geophys. 54, 15–33.

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