6

Postacquisition Data Processing

Usually GPR reflection profiles that are viewed during or directly after being acquired in the field are obscured by what interpreters refer to as “noise,” “reverberations,” “interference,” “multiples,” “clutter,” “spikes,” and “snow.” Often reflection profiles can contain extraneous reflections such as air waves, multiple reflections, and point source reflection hyperbolas, which also make them difficult to interpret or process into usable maps. Raw field reflection profiles are also usually not collected with either accurate depth or horizontal scales, which must be placed into the reflection records after returning from the field. In almost every case, “raw” reflection data must be “cleaned up” and adjusted in some way prior to interpretation.

A large number of commercial, proprietary, and free GPR processing programs are available for this type of data processing. Many of the GPR processing techniques included in these programs have been partially borrowed and then modified from those used in the petroleum industry, which processes seismic reflection data, or other remote sensing applications that deal with complex image processing (Hatton et al. 1986; Malagodi et al. 1996; Milligan and Atkin 1993; Sheriff and Geldart 1985; Ulriksen 1992; Yilmaz 2001). In all cases, to process GPR reflections the original data must either have been recorded digitally or be analog data that have been digitized.

One should never attempt to use processing programs “off the shelf” without understanding the implications of each data manipulation technique. That is because many techniques were written for very specific objectives, and some or

Table 6.1. Common Postacquisition Processing Objectives and Methods

Processing Objective	*Methods to Be Used*
Correct vertical and horizontal scales in reflection profiles; average or smooth reflections along transects	Standard "rubber sheeting"; distance normalization and vertical exaggeration; trace stacking
Remove horizontal banding created by system noise and frequency interference	Background removal; vertical high-pass filters
Remove high-frequency noise ("snow")	Low-pass frequency filters; F-k filters
Remove multiple reflections	Deconvolution
Remove and compress point source hyperbolas to their sources; correct the orientation of steeply dipping layers	Migration

even all may not be applicable to one's archaeological or geological objectives. It is always dangerous to process data only in the hope that the final product will "look better," without understanding exactly what the processing step is doing to the original field recordings. A list of the common data processing techniques that can potentially be used for GPR data and their objectives is found in table 6.1.

As with most postacquisition processing, some steps should be performed in a certain order (Pedley and Hill 2003; Woodward et al. 2003). In table 6.1, these steps are listed in the approximate order that they should be attempted. For instance, reflection profiles should always be corrected spatially in the horizontal and vertical dimensions prior to initiating other steps. Background removal may then remove horizontal reflections in profiles but cause a decrease in the remaining amplitudes of some reflections, which then need to be increased with range gaining to be visible. Or background removal may eliminate many reflections leaving a good deal of "snow," which must then be removed with frequency filters. Once this step is performed, a third procedure, range gaining, may then may be necessary to enhance important reflections not otherwise visible. Any number of these types of incremental steps may be necessary, often in different orders of application.

SCALE CORRECTION AND THE CREATION OF REFLECTION PROFILES

The simplest processing procedure takes the individual reflection traces from each transect and places them in sequential order so that they may be viewed as a two-dimensional vertical profile through the ground. These can be printed in "wiggle trace" format, which shows the individual traces and their amplitudes, or in a gray scale interpolated image, where amplitudes of individual reflections vary in shades of gray (figure 6.1). In the same step, reflection profiles

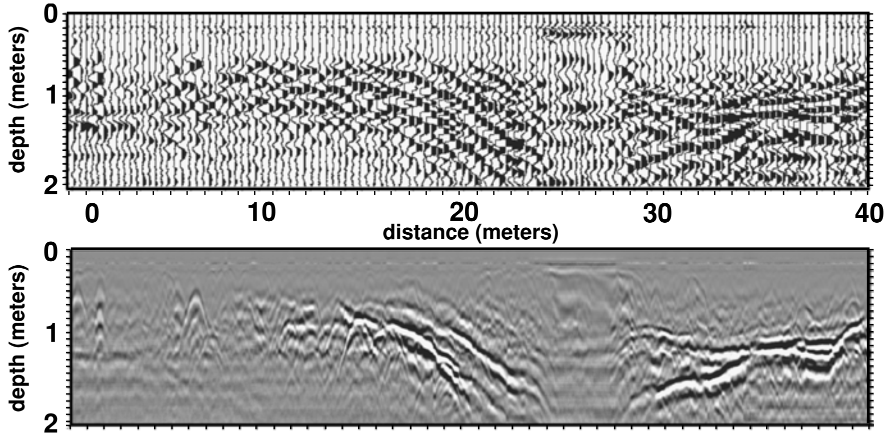

FIGURE 6.1
Wiggle Trace and Gray-Scale Reflection Profiles. Individual traces collected in a transect can be displayed in wiggle trace format (upper profile) or in a gray-scale image that tends to blend all reflection traces together for a smoother look (lower profile).

can be exaggerated in both the vertical or horizontal dimension to emphasize certain aspects of the stratigraphy or buried archaeological features. This exaggeration can often be accomplished with a mouse while profiles are visible on the computer screen, which will expand scales quickly until a desired look is achieved. A series of these fairly simple processing steps, once they have been determined, can then be applied to all reflection profiles within a grid automatically.

Standard reflection profiles can also be modified so that the relative amplitudes of reflections are assigned colors. In this way, significant reflections that may represent important interfaces in the ground are more readily visible to the human eye. Care must be taken in choosing a color palette, however, because sometimes many-colored reflection profiles can be "busy" and difficult to interpret (Leckebusch 2003; Milligan and Atkin 1993), and gray scale often is easier for the human brain to interpret than many complex colors.

If reflection data are collected in continuous mode, there will always be an unequal number of reflection traces between fiducial marks because of the inconsistencies in the antenna towing speed. Distance normalization commands will "rubber-sheet" reflection traces so that there is an equal spacing of traces between fiducial marks, creating a normalized horizontal scale on all reflection profiles. When data are collected in steps or with a survey wheel, the

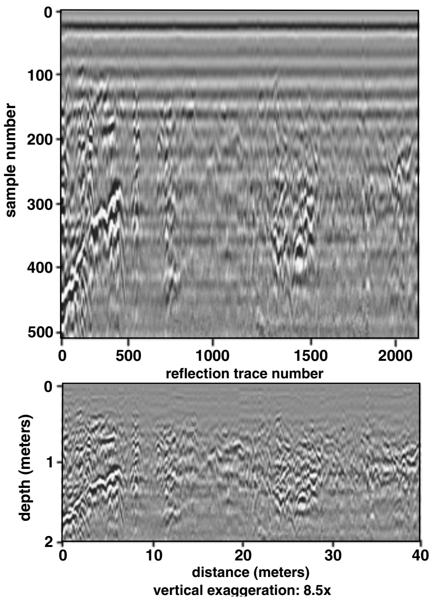

FIGURE 6.2
Raw Reflection Profile and Adjusted Profile. The upper profile contains only the raw reflections with no scale. They are measured in samples for the vertical dimension and reflection traces in the horizontal. The lower profile has been corrected for the time zero lag and adjusted in both the horizontal and vertical dimension to meters, with the vertical exaggeration noted.

placement of reflection traces in distance along transects is already normalized, but a horizontal and vertical scale must still be inserted to create the final product (figure 6.2).

During this process, it is always important to correct for the zero offset position that was set prior to data collection (figure 4.2). This is the offset in time between zero in the time window and the first reflection from the ground surface (often 1 or 2 nanoseconds). Its adjustment will place all reflections in the correct two-way travel time below the ground surface. If relative dielectric permittivity or the average velocity of the material through which radar energy is traveling is known from velocity tests, the arrival times of all reflections can then be adjusted to approximate depth in the ground. If velocities have not yet been determined, it is always good to leave the vertical scale in nanoseconds and adjust it later after velocity has been calculated.

If profiles were collected over uneven ground or exhibit other discontinuities due to velocity changes or surface vegetation differences, reflection traces can be easily stacked during this process. Stacking, which applies a running average and smoothes reflection data, will combine a certain number of traces (chosen at the discretion of the user) into one, in an arithmetic averaging process. This function is often performed during data collection in the field (chapter 4) but can also be performed at this time.

When data are collected over topographically complex areas, surface elevations must be compensated for so that all subsurface reflections can be adjusted to their correct positions in space (figure 3.8). If this is not done, the orientation and placement of subsurface features can never be known exactly, and often very strange interpretative results are created. Surface elevation correction of reflection profiles is a processing step that is a form of *static correction*, and it is often referred to as such in software commands. Besides topographic adjustments, static corrections can also adjust for changes caused by differences in antenna coupling or lateral velocity variations. When sites have a great deal of topographic relief—for instance, those conducted on the flanks of large mounds or hills and valley sides—there is no adequate way to perfectly adjust reflections in the ground (Lehmann and Green 2000). This is because the ray paths of radar waves in the ground are incredibly complex when antennas are tilted on a slope and the cone of energy transmission, and therefore the sources of reflections in the ground is always changing. There is no software yet developed that can adequately account for this type of transmission and reflection complexity; although some have attempted to do so.

REMOVE HORIZONTAL BANDING

The most common type of filtering that can be applied to any data set is the removal of horizontal banding that appears in most GPR reflection profiles (figure 6.3). Due to the “ringing” of some antennas, horizontal bands are recorded on most profiles (Leckebusch 2003; Shih and Doolittle 1984; Sternberg and McGill 1995). Often banding of this sort can be generated as “system noise,” which is inherent to any GPR unit and from nearby radio and other electromagnetic frequency interference. Horizontal bands in profiles can also be the product of reflections from surface objects that were the same distance away from the antenna during acquisition, such as the person pulling the antennas or a towing vehicle. However they are produced, banding often obscures important subsurface reflections that would otherwise be visible on profiles.

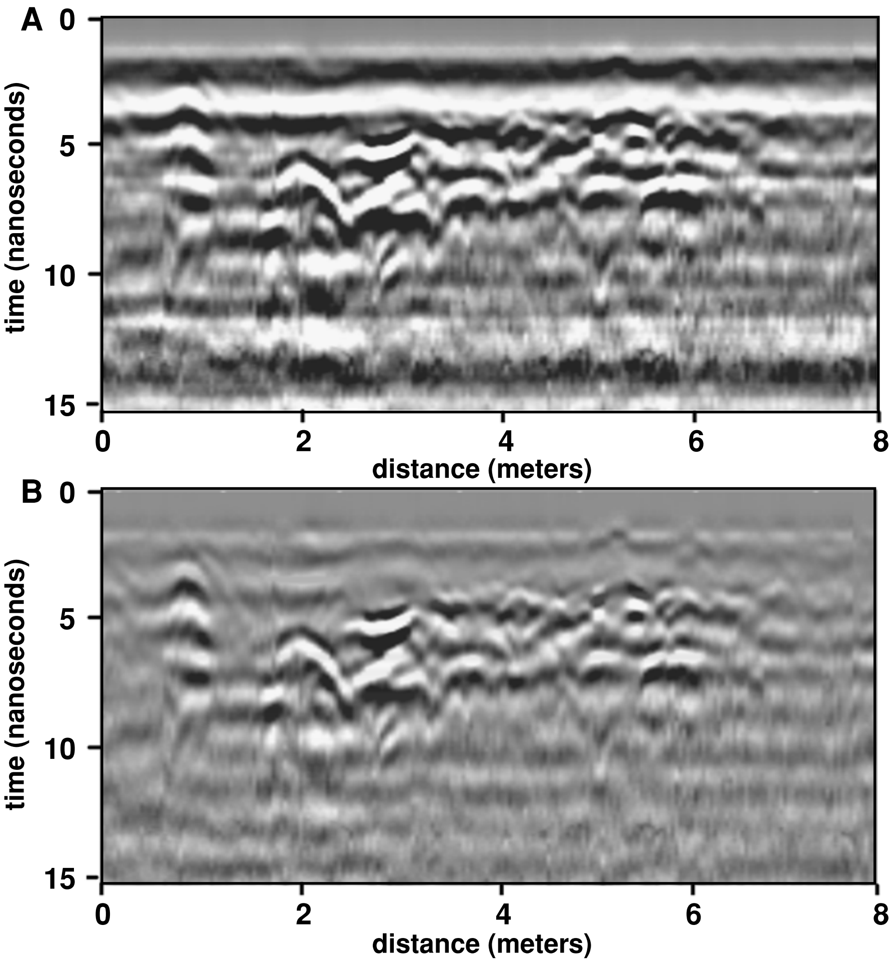

FIGURE 6.3
Background Removal Processing. The unprocessed reflection profile (A) has horizontal banding that obscures many important reflections. When this banding is removed (B), nonhorizontal reflections, especially in the upper 5 nanoseconds of the profile, become visible.

Most processing programs have the ability to remove these bands in a simple arithmetic process that sums all the amplitudes of reflections that were recorded at the same time along a reflection profile (or within a certain number of contiguous reflection traces) and divides by the number of traces summed. The resulting composite digital waveform, which is hopefully an average of all the background noise producing the horizontal banding, is then subtracted from the data set. These postfiltering background-removed profiles then will display only the nonhorizontal reflections, or those horizontal reflections that are short in length. Some processing programs can also remove a running average of any number of reflection traces desired in each reflection profile (Leckebusch 2003).

Great care must be taken when applying a background removing filter in areas where subsurface stratigraphy, or the features of interest, are horizontal, or nearly so. If this processing step were to be used on GPR profiles that have recorded horizontal reflections produced from horizontal buried interfaces, most, if not all, of those important reflections may be subtracted. Background removal should also only be applied on a digital reflection data set with a sufficient number of reflection traces. This is because background removal filters remove all the waves that occur at the same time, leaving only those that are more random. If too few reflection traces have been acquired in one profile over too short a distance, or if only a few traces are averaged to create the composite wave to be subtracted, the composite wave to be removed could be composed of all the important reflections in the profile (Leckebusch 2003). The averaging involved in removing the background would then remove most of the reflections from the ground, as well as the noise, leaving little reflection data of any sort.

Horizontal banding noise can also be removed with frequency filters, both high- and low-pass. Horizontal banding noise can also be caused by low-frequency interference that produces long-wavelength variations within reflection traces. It can be removed during data collection by applying the correct high-pass filters, as discussed in chapter 4, or, if the frequencies creating the noise can be isolated, removed during postacquisition filtering steps (Malagodi et al. 1996).

If all these processing steps will still not "clean up" reflection data, or if unusual conditions in the subsurface or a good deal of electromagnetic interference are encountered, additional steps may be necessary. The following techniques are not commonly used by most archaeologists, but in certain situations they can greatly improve data quality and clarity. In some drastic cases, a very large percentage of the original raw data must be removed in order to enhance the remaining reflections and produce quality results (Conyers and Cameron 1998).

REMOVAL OF HIGH-FREQUENCY NOISE

This process can get quite complex as there are a number of processing parameters that can be adjusted in order to enhance data quality. If there is a great deal of high-frequency interference from cell phones, pagers, radio transmitters, or other devices nearby, reflection profiles may contain so much "snow" and "banding" as to be uninterpretable. When this occurs. background removal, which is usually the first and simplest processing step, may still yield very poor reflection profiles. A number of filters in some processing programs attempt to remove the interfering frequencies with either *infinite impulse response* (IIR) or *finite impulse response* (FIR) filters. Both filtering processes remove certain frequencies with the difference being the number of reflection traces used in averaging and the type of averaging and interpolation algorithms used in the filtering process. In all cases, what is being done is a sophisticated method to remove specific high (and sometimes low) frequencies that might be contributing noise.

There are many experimental filtering techniques of this sort, originally developed for seismic data processing by the petroleum exploration industry, that have been applied to GPR reflection data (Lehmann et al. 1996; Maijala 1992; Milligan and Atkin 1993; Yu et al. 1996). Care must be taken when using these processing steps because there are some important differences between radar and seismic reflection data. The wide aperture of radar antennas, which transmit and receive reflections back from a large subsurface area in a cone of transmission, make any automatic application of seismic techniques sometimes difficult as their wave transmission properties are much different. Another difference is that radar energy slows down during its propagation in the ground, while seismic waves will increase their velocity with depth (Leckebusch 2003).

F-k filtering is one such technique borrowed from seismic processing where reflections recorded in time are transformed into frequency data using statistical transform programs (Maijala 1992). The outcome of this processing procedure is that high-angle reflections (possibly also point source reflection hyperbolas), which may be obscuring important horizontal data, are removed. This seismic data-processing technique has been misapplied to some archaeological GPR data and should only be used with caution.

REMOVAL OF MULTIPLE REFLECTIONS

Multiple reflections (often just called *multiples*) are caused when radar energy reflects back and forth between a buried object and the ground surface, or between subsurface layers. When each of the reflections from these objects or interfaces are received at the surface antenna and recorded, they are displayed in profile as repetitive horizontal reflections (figure 6.4), all of which are an equal distance apart (as measured in time). Often multiples of this sort can be confused with "real" reflections that might have been created from multiple stacked layers in the

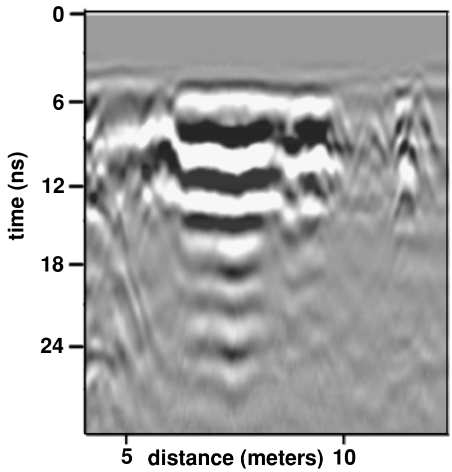

FIGURE 6.4
Multiple Reflections. These stacked multiples were generated from a horizontal surface with a high coefficient of reflectivity. Radar energy was reflected from the buried interface back to the ground surface, and then back into the ground, to be rereflected numerous times from both interfaces, creating the stacked reflections.

ground. Usually they can be differentiated because multiples are spaced at an equal interval in time as they are stacked on top of each other within reflection profiles. Sometimes multiples are also created by "ringing antennas" that are located within each other's near-field, and therefore reverberate, creating the same effect.

These unwanted multiple reflections often obscure important reflections that might have been recorded at the same time in the reflection traces, and if so, they must be removed. This process is called *deconvolution*, or more precisely *predictive deconvolution*, because the method attempts to predict the shape of the transmitted radar pulse from the surface antenna and how it will change as it moves in the ground. This processing technique is another step that has been modified for GPR data from seismic studies (Fisher et al. 1994; LaFleche et al. 1991; Maijala 1992; Malagodi et al. 1996; Neves et al. 1996; Rees and Glover 1992; Todoeschuck et al. 1992). It is based on the theory that as a radar pulse is transmitted into the ground portions of the electromagnetic wave will change form, or convolve. The purpose of this filter is to remove the portion of the recorded waves that have convolved during transmission in the ground. Deconvolution processing restores the reflected waves in a profile to their original pattern and presents the data with a "different look." The deconvolution technique can be used to identify and then remove multiple reflections, if they can be accurately predicted.

One of the problems with deconvolution processing is that restoring reflected waves to their original forms is mostly educated guesswork. It is usually difficult to determine how the original transmitted waves were shaped and any deconvolution process may be modifying the data in unreal ways. Although many GPR experts claim to understand what radar waves do in the ground, much about this processing technique still remains obscure. If deconvolution processing of radar data can be improved, it may yield important clues to understanding how the physical properties of the ground modify transmitted electromagnetic waves and help in all types of GPR data interpretation. Most attempted applications of this processing step have so far proved to be unsatisfactory (Maijala 1992; Rees and Glover 1992) or, at worst, have removed important reflections unintentionally.

MIGRATION

Standard GPR systems portray a distorted image of subsurface stratigraphy and features in the ground. This is caused both by the wide beam of radar propagation producing multiple ray paths as well as changes in the velocity, and therefore refraction of the transmitted beam with depth. Migration is a two-dimensional imaging process that has been used with success to eliminate some of these distortions caused in all reflection data collection procedures (Beres et al. 1999; Fisher et al. 1992; Fisher et al. 1994; Grasmueck 1994; Malagodi et al. 1996; Milligan and Atkin 1993; Young and Jingsheng 1994). The distortions that can be most readily corrected by migration are caused by the wide transmission beam of radar antennas that generate reflections from point sources, appearing as hyperbolas (figure 3.17). Before reflection profile data can be processed into two-dimensional maps and three-dimensional images, these hyperbolas often must be removed (Conyers et al. 2002).

Steeply dipping surfaces will also diffract radar energy during its transmission to and from a reflecting surface (Jol and Bristow 2003). Longer travel times that result from this diffraction will place reflections at incorrect depths or locations in the subsurface, distorting the size and geometry of some subsurface beds or features. The migration process can be used to spatially adjust for these kinds of distorted or hyperbolic reflections and "collapse" them back to the point of origin (figure 6.5).

The easiest migration method for hyperbola removal is accomplished by summing all the reflections along a hyperbola's arms and placing the resulting average at its apex. This must usually be done manually for all hyperbolas in a profile, which usually necessitates first identifying all of them, which can be a tedious process. A more sophisticated process called the *Kirchoff method* (Geophysical Survey Systems 2000) calculates the angle of incidence and the distance the reflecting feature is below the surface. It then applies velocities or velocity profiles (which often must be assumed) to the data and corrects the placement of reflections, also effectively collapsing all hyperbola arms back to their apexes. The same processing procedure can be used for steeply dipping beds, where the same type of geometric corrections can be made. There are three other migration algorithms used for migration called *Stolt*, *phase-shift*, and *finite-difference*. Tests conducted by Leckebusch (2003) showed no difference between them or with the Kirchoff method.

Migration is becoming a standard technique in most GPR processing programs, but it can be very time-consuming and also potentially distort many reflections incorrectly. It should therefore be employed for very specific types of data analysis, and only after one is sure of the origin of the distorted reflections, the velocity of materials in the ground, and the geometry of wave travel paths in the subsurface.

In addition to the more standard two-dimensional reflection profile migration, three-dimensional migration is possible (Grasmueck 1996; Leckebusch and Peikert 2001; Shrugge and Artman 2004). This method will collapse not only hyperbolic reflections that are generated "in-line" (along the direction antennas are moved in transects) but also reflections that are received from out of the plane of the antenna transect (from the sides).

In many cases, it may be better to view radar reflection profiles in an unmigrated format first because point source hyperbolas are many times capable of identifying subsurface anomalies that represent archaeological features of interest. If all the hyperbolas were collapsed back to the point of origin (assuming that migration processing techniques are being properly applied), point sources are often more difficult to recognize, possibly causing some important buried features or objects to go unrecognized when viewed in profile. The opposite could also be true if important reflections (other than those creating the hyperbolas) were generated within the axes of the point source hyperbolas. In this case, the migration of hyperbolas back to their point of origin might allow important but otherwise obscured reflections to become visible in reflection profiles.

INCREASE THE VISIBILITY OF SUBTLE REFLECTIONS

Low-amplitude reflections can always be enhanced so as to become visible in reflection profiles by increasing the range gains at certain recording times (depths

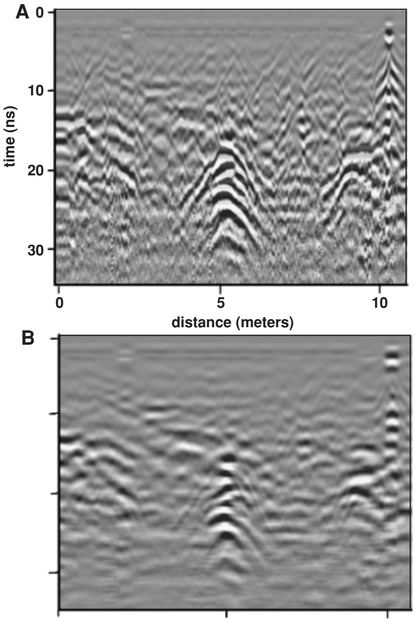

FIGURE 6.5
Reflection Migration. Reflection hyperbolas generated from the tops and sides of buried stone walls at Petra, Jordan (A), are migrated back to their origins (B), cleaning up the profile and leaving only the hyperbola apexes.

in the ground). Many processing programs have the ability to move a mouse along a gain curve, increasing the amplitudes at specified times for all reflection traces in a profile (figure 4.1). When the amplitudes of all reflections in a desired time window are increased, background removal filters must then be applied as a second processing step to remove resulting horizontal banding, which is also increased. This process can be repeated until otherwise invisible reflections are visible. The risk in this series of processing methods, as with all postacquisition processing, is that each step filters and potentially distorts the initial waveforms, making the final product potentially so distorted as to be unrecognizable.

Reflections generated from very subtle changes in the ground can also be enhanced with a processing step called a *Hilbert transform* (Sensors and Software 1999; Todoeschuck et al. 1992; Turner 1992; Yilmaz 1987). This step transforms the reflection amplitudes and their geometry in the ground into spatially distinct frequency and phase information. The phase of reflections (whether they are positive or negative deflections in the waveform from a mean) is often indicative of important changes in relative dielectric permittivity of materials at a reflecting interface. For instance, the phase of a reflected wave will often be different if generated at a void space (with an RDP of 1) than it would be for a harder or denser object (that might have a much greater RDP than the surrounding material). The phase change in amplitudes along a profile can therefore potentially tell the interpreter what type of material is generating the reflection. The same is true for frequency changes along a reflection of interest, as they indicate how the ground is "filtering" the radar energy during transmission and as it is reflected back to the surface.

DATA PROCESSING CONCLUSIONS

As a matter of course, all reflection profiles should be processed to normalize distance both horizontally and vertically. Background removal is also a very simple and important technique that should be attempted to determine if it can improve the visibility of important subsurface reflections. All but these simplest GPR data-processing steps can potentially distort reflection data out of recognition and should be used with caution. While very noisy or distorted data can often be corrected and filtered so as to be more usable, there is always a risk in "overprocessing." In the seismic processing business, some people have devoted their lives to postacquisition data processing and can often work wonders with poor-quality data. But they also make jokes among themselves about their ability to modify data to such a degree that they can produce almost any result desired by a client. The standard joke in the seismic data-processing laboratory is that if the reflection data do not produce the desired outcomes, just send them back to the data-processing experts, as they can produce whatever results one would like!

Although it is hoped that one would never become this intellectually confused within the data-processing web, the potential exists with the abundance of processing steps discussed here, few of which are really understood in their complexity by many GPR professionals, let alone the typical archeological user.