4

Ground-Penetrating Radar Equipment and Acquisition Software

GPR SYSTEMS

A number of different manufacturers of GPR units are typically used in archaeological surveys. The most commonly used units in North America are manufactured by Geophysical Survey Systems Incorporated (GSSI), located in North Salem, New Hampshire, and Sensors and Software Inc. of Mississauga, Ontario, Canada. GPR manufacturers in Europe and Japan also market multiuse GPR systems with excellent archaeological applications. Most of the systems produced for general-purpose GPR surveys employ antennas that transmit pulsed radar energy of one center frequency. Sensors and Software antennas were originally developed to be moved in steps, recording data at specified intervals along transects in grids, but recent models can operate in both continuous and survey wheel acquisition mode.

All GPR systems on the market have the ability to collect data along transects using some kind of survey wheel that measures distance and spaces reflection traces equally along transects (figure 3.5). Some survey wheels roll along the ground surface, and their revolutions and the number of reflection traces collected are calibrated for distance. For uneven ground, a small "hip wheel" has been developed that can attach to one's belt or the antennas, which feeds out thread as the antennas are moved along a survey transect. In this collection method, a small wheel in the device contains a large spool of thread, and the wheel's revolution is calibrated for distance. A certain number of turns of the wheel determines the number of reflection traces to collect per distance of ground covered as the thread is spooled out. With this method, at the beginning of each transect, the thread is tied to a stake in the ground that is spooled out as the antennas are moved. When each transect is recorded, the thread is discarded; at the end of a large survey, strands of thread litter the survey area.

There are many similarities and some differences between models and manufacturers of GPR units. Many newer models are compact enough so that one person can theoretically collect large numbers of transects alone. These systems place the antennas, power source, and control system on a cart that can be rolled along the ground, or placed in a backpack, relieving the antenna operator from having to be tethered to a base station (figure 3.7). Most can operate for many hours on rechargeable lightweight batteries, while others run on 12-volt batteries or household electric currents. All GPR systems contain one or more internal hard drives that store a software program to drive data acquisition and for reflection data storage. Systems typically have a number of different ports that allow acquired data to be transferred to a personal computer after a survey is complete. Newer models save data on flash memory cards or chips that can hold many hundreds of megabytes of data with little power usage, making these systems very lightweight and allowing data to be quickly downloaded to other computers for processing.

All GPR systems employ a computer screen that is necessary for presurvey calibration and allows reflection profiles to be viewed in real time during collection. Screens are sometimes built into the control box of the system or one can used from a peripheral laptop computer (figure 2.2).

All manufacturers are continually introducing new GPR system models, striving for compactness, longer-life battery usage, transportability, and ease of data collection. There have been some recently developed systems that are "dumbed-down" versions of more standard GPR units, which can be used to find pipes or voids in the ground quickly for buried utility location that don't require complex postacquisition processing. These simple systems have little ability to be calibrated to unusual field conditions or store complex data sets that can later be processed with GPR software and should be avoided for most archaeological applications.

There is one type of GPR system that uses a "stepped-frequency" technology, which focuses a narrow radar beam of varying frequencies into the ground. This technique, which uses a coiled antenna system (Noon et al. 1994; Tomizawa et al. 2000; Valle et al. 2000), has not yet seen significant archaeological application and will not be discussed further in this book. Others can be used to collect radar reflections within or between bore holes (Wright and Lane 1998) or by placing a transmitting antenna in a hole below a known archaeological feature and collecting radar pulses from an array of antennas located on the ground surface above.

Standard GPR systems consist of three main elements, the control unit (pulse generator, computer, and associated software), the antennas (paired transmitting and receiving antennas), and the display unit (computer screen) (figure 2.2). The control unit produces a high-voltage electrical pulse, which is sent through cables to the transmitting antenna, which amplifies the voltage and shapes the pulse, emitting it. Cables that transmit the electrical pulses come in varying lengths and are manufactured of either coaxial copper filament or fiber optic material. These cables connect the antennas to the system that might be located at a base station or on a survey cart or backpack. Fiber optic cables, which transmit a digital signal to and from the antennas, greatly reduce some of the equipment-related noise that can affect the signal clarity in some coaxial cables (Davis and Annan 1989). Fiber optic connectors, however, are not very "field durable," and the smallest amount of dust on a connection, or any rough wear during data acquisition, can cause them to malfunction. When only short fiber optic cables are needed to connect peripheral devices with the control unit, and all components are being transported on a cart or backpack, wear and tear of fiber optic cables can be minimized.

All GPR systems generate the electrical pulse necessary to create propagating radar waves directly at the antenna. Some systems transmit the waveform of the received wave returning from within the ground to the control system for recording as digital data, or as analog data in the form of voltage changes, which can then be digitized and stored at the control system (Annan and Davis 1992). Better data quality is usually obtained when the transmitted and received waves travel the least distance in analog cables, where system noise can be generated.

Most GPR systems use a hand-held marker device to record the surface position (fiducial mark) of the antennas along a survey transect during reflection data acquisition. When the marker is activated, some early-model control units impose a noticeable high-frequency sine wave, covering one recorded reflection trace in order to define the mark locations. When digital data are acquired, a fiducial mark is usually inserted into the data string as an identifiable bit of data in each reflection trace where a mark is placed. During data collection, the marker button can either be located on the antenna and operated by the person pulling it or attached to the control unit and operated by someone, at the command of the antenna operator. In continuous data acquisition, the marker button must be pushed at standard intervals along the antenna transects, usually every few meters or less, at stations that have been presurveyed using a tape measure. If data are collected with a survey wheel, and specific distances along transects do not need to be recorded in the data string, fiducial marks can be used to identify the location of surface obstacles or other features of note. When using the step method of data acquisition, the antennas' location on the ground is predetermined by the step spacing, and no marker device is necessary for navigation purposes.

DATA ACQUISITION SOFTWARE: SETUP PARAMETERS

Manual adjustments are always necessary prior to conducting any GPR survey (Kemerait 1994). In newer GPR units, some of the equipment adjustments can be automatically controlled by the acquisition software, but many of these can be (and usually should be) manually overridden. In older models, most of the precollection adjustments needed to be made manually with switches or knobs located on the control unit. Modern units use a software interface to do this, which can be controlled from a keyboard or touch pad or using an attached laptop computer.

Header Information

Most digital GPR units have a procedure where general header information can be input for each file or the grid as a whole. This information typically includes the date of the fieldwork, antenna frequency, site name, grid name or number, and other pertinent information or comments. Many units allow most of this information to be entered at the start of acquisition, and it can be modified for each transect and file within a grid, if desired. Often many of the significant acquisition settings discussed here are automatically recorded in the headers of each file or sometimes a separate file altogether for each profile, and they can be viewed later on, if good field notes are not kept, or lost.

Each profile within a grid is usually automatically saved as a separate file to the computer hard drive or other media as they are collected. The names and sequence of these data files should also be noted in a field book as they are being recorded. Files are usually recorded sequentially, with the first reflection profile in a grid saved as file1, and so on, as they are collected. To avoid confusion when more than one grid of data are being collected in a day, it is usually good to start each profile in a grid as file1 in a separate computer directory, and always keep good notes of their locations and orientations within those grids.

Time Window

All GPR systems allow the user to select the time period over which reflection data are recorded. The *time window* is defined as the amount of two-way travel time, measured in nanoseconds, that the receiving antenna will "listen" and record the reflected radar wave energy (figure 3.6). This window will normally open just before the radar pulse is transmitted and is closed after all reflections of interest, from the depth desired in the ground, have been recorded. If the velocity of the material and the approximate depth of the features to be resolved are known, the amount of time necessary for radar energy to travel down to and then be reflected back from the zones of interest can be estimated. The time window can then be adjusted so that it is open for at least this period so that all important reflections in all antenna transects within the survey grid are recorded. It should usually be adjusted so that more reflection data, from a greater depth, are being recorded than is necessary. Often, due to unforeseen subsurface velocity changes, reflections from features of interest could possibly be received at times later than preliminary calculations estimate, and if the time window is not open for long enough, they will not be recorded. It is also possible that buried horizons of interest might dip to greater depths or be covered with a greater thickness of overburden in some portions of a grid than initial estimates, also necessitating a longer time window in order to record them.

In most archaeological applications, a time window of 100 nanoseconds (two-way travel time) or less is usually sufficient to record reflections within 2 to 3 meters of the surface, depending on the velocity of radar wave propagation. In a material with a relative dielectric permittivity of 8, a 20-nanosecond window is capable of recording reflections to about 1 meter depth (table 4.1). These types of depth calculations are always independent of antenna frequency.

Table 4.1. Depth in Meters to a Reflector Through Media of a Given Relative Dielectric Permittivity

	Relative Dielectric Permittivity																
(ns)	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*15*	*20*	*30*	*40*	*50*	*60*	*80*
10	1.50	1.06	0.87	0.75	0.67	0.61	0.57	0.53	0.50	0.47	0.39	0.34	0.27	0.24	0.21	0.19	0.17
20	3.00	2.12	1.73	1.50	1.34	1.22	1.13	1.06	1.00	0.95	0.77	0.67	0.55	0.47	0.42	0.39	0.34
30	4.50	3.18	2.60	2.25	2.01	1.84	1.70	1.59	1.50	1.42	1.16	1.01	0.82	0.71	0.64	0.58	0.50
40	6.00	4.24	3.46	3.00	2.68	2.45	2.27	2.12	2.00	1.90	1.55	1.34	1.09	0.95	0.85	0.77	0.67
50	**7.50**	**5.30**	**4.33**	**3.75**	**3.35**	**3.06**	**2.83**	**2.65**	**2.50**	**2.37**	**1.94**	**1.68**	**1.37**	**1.19**	**1.06**	**0.97**	**0.84**
60	8.99	6.36	5.19	4.50	4.02	3.67	3.40	3.18	3.00	2.84	2.32	2.01	1.64	1.42	1.27	1.16	1.01
70	10.49	7.42	6.06	5.25	4.69	4.28	3.97	3.71	3.50	3.32	2.71	2.35	1.92	1.66	1.48	1.35	1.17
80	11.99	8.48	6.92	6.00	5.36	4.90	4.53	4.24	4.00	3.79	3.10	2.68	2.19	1.90	1.70	1.55	1.34
90	13.49	9.54	7.79	6.75	6.03	5.51	5.10	4.77	4.50	4.27	3.48	3.02	2.46	2.13	1.91	1.74	1.51
100	**14.99**	**10.60**	**8.65**	**7.50**	**6.70**	**6.12**	**5.67**	**5.30**	**5.00**	**4.74**	**3.87**	**3.35**	**2.74**	**2.37**	**2.12**	**1.94**	**1.68**
110	16.49	11.66	9.52	8.24	7.37	6.73	6.23	5.83	5.50	5.21	4.26	3.69	3.01	2.61	2.33	2.13	1.84
120	17.99	12.72	10.39	8.99	8.04	7.34	6.80	6.36	6.00	5.69	4.64	4.02	3.28	2.84	2.54	2.32	2.01
130	19.49	13.78	11.25	9.74	8.71	7.96	7.37	6.89	6.50	6.16	5.03	4.36	3.56	3.08	2.76	2.52	2.18
140	20.99	14.84	12.12	10.49	9.39	8.57	7.93	7.42	7.00	6.64	5.42	4.69	3.83	3.32	2.97	2.71	2.35
150	**22.48**	**15.90**	**12.98**	**11.24**	**10.06**	**9.18**	**8.50**	**7.95**	**7.50**	**7.11**	**5.81**	**5.03**	**4.11**	**3.56**	**3.18**	**2.90**	**2.51**
160	23.98	16.96	13.85	11.99	10.73	9.79	9.07	8.48	7.99	7.58	6.19	5.36	4.38	3.79	3.39	3.10	2.68
170	25.48	18.02	14.71	12.74	11.40	10.40	9.63	9.01	8.49	8.06	6.58	5.70	4.65	4.03	3.60	3.29	2.85
180	26.98	19.08	15.58	13.49	12.07	11.02	10.20	9.54	8.99	8.53	6.97	6.03	4.93	4.27	3.82	3.48	3.02
190	28.48	20.14	16.44	14.24	12.74	11.63	10.76	10.07	9.49	9.01	7.35	6.37	5.20	4.50	4.03	3.68	3.18
200	**29.98**	**21.20**	**17.31**	**14.99**	**13.41**	**12.24**	**11.33**	**10.60**	**9.99**	**9.48**	**7.74**	**6.70**	**5.47**	**4.74**	**4.24**	**3.87**	**3.35**
210	31.48	22.26	18.17	15.74	14.08	12.85	11.90	11.13	10.49	9.95	8.13	7.04	5.75	4.98	4.45	4.06	3.52
220	32.98	23.32	19.04	16.49	14.75	13.46	12.46	11.66	10.99	10.43	8.51	7.37	6.02	5.21	4.66	4.26	3.69
230	34.48	24.38	19.91	17.24	15.42	14.08	13.03	12.19	11.49	10.90	8.90	7.71	6.29	5.45	4.88	4.45	3.85
240	35.98	25.44	20.77	17.99	16.09	14.69	13.60	12.72	11.99	11.38	9.29	8.04	6.57	5.69	5.09	4.64	4.02
250	**37.48**	**26.50**	**21.64**	**18.74**	**16.76**	**15.30**	**14.16**	**13.25**	**12.49**	**11.85**	**9.68**	**8.38**	**6.84**	**5.93**	**5.30**	**4.84**	**4.19**
260	38.97	27.56	22.50	19.49	17.43	15.91	14.73	13.78	12.99	12.32	10.06	8.71	7.12	6.16	5.51	5.03	4.36
270	40.47	28.62	23.37	20.24	18.10	16.52	15.30	14.31	13.49	12.80	10.45	9.05	7.39	6.40	5.72	5.23	4.53
280	41.97	29.68	24.23	20.99	18.77	17.13	15.86	14.84	13.99	13.27	10.84	9.39	7.66	6.64	5.94	5.42	4.69
290	43.47	30.74	25.10	21.74	19.44	17.75	16.43	15.37	14.49	13.75	11.22	9.72	7.94	6.87	6.15	5.61	4.86
300	**44.97**	**31.80**	**25.96**	**22.48**	**20.11**	**18.36**	**17.00**	**15.90**	**14.99**	**14.22**	**11.61**	**10.06**	**8.21**	**7.11**	**6.36**	**5.81**	**5.03**

Determining the optimum time window in advance of data collection is extremely important. Some materials may have very high relative dielectric permittivities, and therefore radar energy travels through them at very slow rates. If that material also had a low conductivity, energy could conceivably travel quite deep in the ground but at a slow rate, and one would need to collect reflections over a longer time window. For instance, if an average surface soil is assumed with an RDP of 9, a 30-nanosecond time window would allow the collection of reflections to about 1.5 meters in the ground (see table 4.1). If later on it was determined that the actual RDP of the soil was 20 (perhaps it had a good deal of water in it that was not accounted for), then the radar propagation velocity would be much slower and that same time window would only have allowed collection to about 1 meter in the ground (again, see table 4.1). If this were determined only after data had been collected, and the features of interest were located between 1 and 1.5 meters in the ground, the whole survey would have to be repeated as the pertinent reflections from the depth of interest would not be within the programmed time window. This sad scenario has happened more often than many GPR practitioners would like to admit. It can only be overcome by spending a great deal of attention to local conditions, doing velocity analysis in advance (chapter 5), and adjusting setup parameters for the correct time window prior to data collection.

Samples per Reflection Trace

Once the time window is set, the number of samples necessary to record a reflected waveform must be selected for all digital GPR units. One sample is a digital value that defines a portion of the reflected waveform. The more digital samples there are to define a wave, the more accurate the form of that reflected wave becomes. The longer the time window is open, the larger number of samples are usually necessary to adequately define the reflection trace of the reflected wave.

Any number of data samples can be selected to define each reflection trace on most units, but by convention it is usual to select 512; however, 1,024 and 2,048 are also common sampling rates. Due to incremental sampling, which digitize one bit of data for each pulse generated, if 512 samples are selected to define each reflection trace, then there must also be 512 pulses transmitted into the ground in succession in order to record each trace. If this were the case, and a large number of reflection traces were also programmed to be collected every second, some GPR systems would not be capable of generating enough pulses and recording enough samples per second to adequately record the data programmed into the system.

The maximum resolution (defined by the shape of the waveform) that can be obtained is also dependent on the wavelength of the reflected waves that are generated by the antenna, which is a function of the antenna frequency (table 3.2). Higher-frequency antennas generate shorter-wavelength waves that are recorded in quick succession, which may need more digital samples to define them within a given time window, as they have a very complex waveform. When all these factors are considered, it is easy to see that a number of estimates and assumptions are necessary prior to determining the sampling definition. Some experimentation may be necessary in the field while the antennas are stationary in order to obtain the optimum sampling rate for the wavelength produced and time window allotted.

It is just as important in preacquisition adjustments to make sure that the time window is not open for too long as it is for too short a time. The longer the time window is open, the more samples per reflection are necessary for good resolution of the recorded waveform, and the more samples are necessary to record. If too much reflection data are being collected over a long time window beyond the depth of interest, too many samples would be needed to define the waves from depths at the far end of the range. Most of the digital data recorded would then be defining reflections far outside the depth of interest. If this were the case, storage capacity on a hard drive or other media could fill up quite quickly with useless data, especially if a large survey is being conducted.

Trace Stacking

The *stacking* of reflection traces, done with a *horizontal filter*, or *spatial filter*, (sometimes termed *horizontal smoothing*), can be applied prior to data acquisition or later during postacquisition processing (discussed in chapter 6). This data manipulation method arithmetically averages digital values of successive reflection traces so that one composite trace is recorded every certain distance along a transect (Fisher et al. 1992; Grasmueck 1994; Maijala 1992). Many GPR systems allow the operator to manually adjust the stack rate to any integer. This process will average sequentially any number of programmed traces, recording only the average from each of these sequentially, usually as a running average (Davis and Annan 1989). It is important to recognize that the more reflection traces that are stacked, the slower the antenna must be moved along the ground surface in continuous collection mode, or the more traces that must be recorded every distance along a transect in survey wheel mode, in order to achieve the same number of composite reflection traces per unit of ground covered.

This type of horizontal filtering of sequential traces will effectively remove waveforms that may have been generated from surface irregularities such as small bumps or dips in the ground surface (Fisher et al. 1992; Grasmueck 1994; Maijala 1992). It also filters out the effects of velocity changes due to minor water saturation changes, small rocks or voids in the subsurface, and changes in amplitude due to antenna coupling differences with the ground.

Stacking is usually a good idea when the antennas are collecting in continuous mode and are moving at a fairly slow speed (at an average human pace or less), and when fairly large features in the ground are the target. A trace stack of eight or more contiguous traces into each one that is recorded can then improve the quality of the subsurface reflection data and still yield good subsurface coverage. In this fashion, if 64 reflection traces are being measured every second in continuous data collection mode, and each 8 consecutive traces are stacked into one composite, then 8 would be recorded each second. If the radar antennas are moving at a rate of 16 centimeters per second along the ground surface, then there will be one reflection trace recorded for every 2 centimeters of ground covered (16 divided by 8). If a stack of 16 were applied (each 16 consecutive traces averaged into one), then the subsurface coverage would be one recorded reflection trace every 4 centimeters along the same transect.

The same method can be used to stack traces in survey wheel or step acquisition mode in order to average out reflections and smooth the reflection data. Unless the ground surface is very uneven or there is highly variable stratigraphy in the subsurface (that is not of importance to the questions at hand), it is usually best to collect all the reflection traces available and stack them later during data processing, if it is later determined to be necessary.

Transmission Rate

Radar systems typically transmit at a rate of more than 50,000 pulses per second (often measured in kilohertz [KHz]. With the presently available GPR technology, it is impossible to record each individual reflected trace generated from each transmitted pulse due to the rapidity at which the pulses are being transmitted, and then reflected back to the surface. To overcome this problem, radar systems sample incrementally, meaning that one pulse must be transmitted for each sample that is recorded. If the system were set up to stack 16 sequential traces into one recorded reflection trace, then there must be at least 512 pulses times 16 (8,192) transmitted for every one reflection trace recorded.

An understanding of transmission and recording rate usually becomes important only when determining the horizontal resolution of the recorded reflection data. Depending on the speed at which the antennas are moving across the ground, adjustments of the recording and stacking rates may be necessary in order to obtain good subsurface coverage. For instance, if it is necessary to record 4 complete reflection traces (defined by 512 samples) per second (after stacking 16 traces into one), then 8,192 sequential pulses times 4 (32,768) must be transmitted each second. If the radar system being used is only capable of transmitting at a rate of 25,000 pulses per second, there would not be enough pulses transmitted to allow for 4 recorded reflection traces per second. If this were the case, a few minor adjustments would need to be made prior to recording data: (1) The stacking rate could be lowered; (2) the antennas would need to be moved over the ground slower, recording more total reflection traces per distance covered; or (3) the time window can be shortened, necessitating fewer samples to define each trace (or all three of the above).

If the time window is fairly short, the stacking is minimized; and if the sampling rate is kept at 512 samples per reflection trace or less, there are usually more than enough pulses being transmitted into the ground in order to record the desired traces. The adjustments just discussed are usually required only if the antennas are moving at a high rate of speed (perhaps towed behind a vehicle), there are very high stack rates applied (more than 16 traces stacked into one), or an extremely high waveform resolution (many samples per reflection trace) is necessary in order to define the subsurface reflections within a large time window. These potential problems are partially overcome in many recently manufactured GPR units that transmit at rates much higher than 50,000 pulses per second, allowing much more latitude in these adjustments.

During survey wheel collection, if the sampling rate is not set high enough to allow the programmed number of reflection traces to be recorded per unit distance covered, most systems will usually notify the operator with a beep warning the operator to slow the antenna transport along the ground. This will then allow the sampling rate to “catch up” with the number of traces being recorded. When collecting data using the step method, there are always more than enough pulses being transmitted to allow for the recording of one reflection trace and the horizontal resolution becomes only a function of the distance between steps.

Time Zero Position

Prior to acquiring reflection data from within the ground a calibration must be made so that the first reflection recorded from any pulse emitted from the antenna is the reflection from the ground surface (also called the *direct wave*). This is done while the antenna is stable on the ground in the configuration that will be used for all subsequent data acquisition. When calibrated for the zero position, the first reflection visible is usually from the ground surface, and all subsequent reflections recorded in time will be received from horizons deeper in the ground (Yelf 2004). In all GPR systems with a video monitor, the direct wave can be displayed and is visible as the first large-amplitude wave after a period of no data recording (figure 3.6). Most GPR systems have an automatic programming procedure that will identify this first reflection and set the zero position so that the ground surface reflection is about 1 nanosecond or so into the time window, and all later reflections from deeper in the ground are recorded later in time. Older systems display the reflection trace on an oscilloscope in a similar fashion, and the first reflection from the ground surface must be manually adjusted, and then time zero can be set.

The time window should also always be placed so that the first recorded reflection from the ground surface is not at exactly time zero but just lagged a little below it, so that the ground surface can always be found in reflection profiles after returning from the field, if there is any question. Most systems will then lock that zero position, and all reflection profiles will be collected with the ground surface in the same place within the time window. Any time lag between zero time and the ground surface reflection can later be compensated for during data processing. If the automatic time zero function is not locked in position, it is possible that the computer that controls data acquisition might be constantly readjusting time zero as data are collected, and all traces in the ground will be recorded at different times relative to zero, making for a very confusing data set and potentially disastrous survey results.

Range Gains

Due to the conical spreading of the transmitted radar waves and the attenuation of radar energy as it passes through the ground, later reflection arrivals generated from deeper in the ground will almost always have lower amplitudes than earlier arrivals (figures 3.3 and 3.6). To recover these lower-amplitude waves, gain control (*range gaining*) is applied to all reflection traces in a profile during either acquisition or postacquisition processing (Jol and Bristow 2003; Leckebusch 2003; Maijala 1992; Shih and Doolittle 1984; Sternberg and McGill 1995). This will amplify those waves received from deeper in the ground so they are visible (figure 4.1). Range gain settings are standard on most GPR equipment, and most systems have software that will automatically adjust waveform amplitudes so they are all "on scale." Older systems must be manually adjusted (Fisher et al. 1994; Geophysical Survey Systems, Inc. 1987). There is usually a linear or exponential relationship between the amount of gain that must be applied to recorded wave amplitudes and the time it is received, with higher gains applied to reflections recorded later in the time window (figure 4.1).

There are two schools of thought with respect to range gains. One group of GPR practitioners and some GPR system manufacturers believe that no gains should be applied during data collection, and that amplitudes of reflected waves should only be adjusted after returning from the field. In this way, a raw data set will be collected that can be adjusted in any manner deemed appropriate after all reflection profiles are recorded within a grid. The other school of thought believes that gains should be applied at the time of acquisition so that the variables affecting amplitudes in the ground can be adjusted for immediately. In that way,

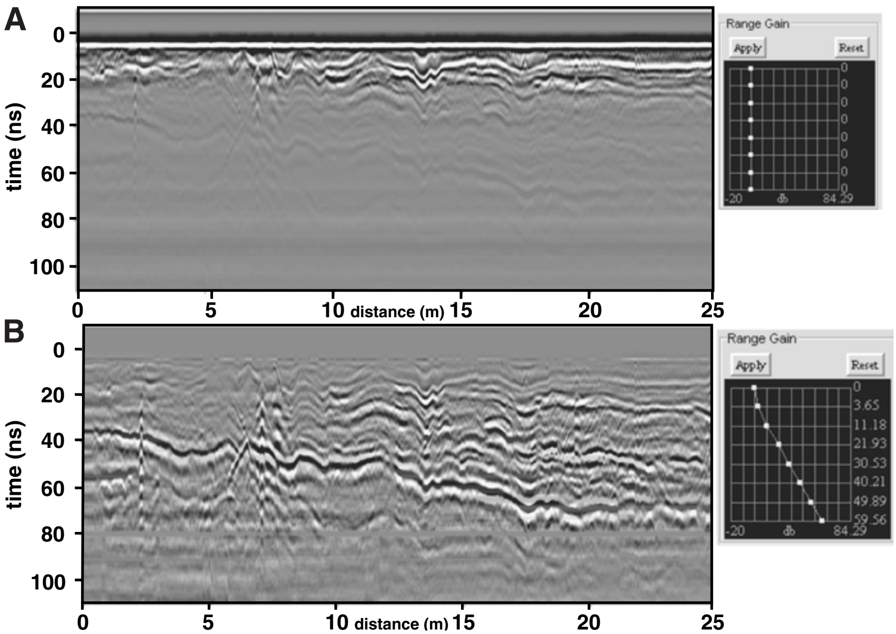

FIGURE 4.1
Range Gaining. Ungained reflection profiles in A have good near-surface resolution, but reflections recorded from deeper in the ground are low in amplitude and barely visible. When range gains are applied to the same reflection data, arithmetically enhancing the amplitudes from deeper in the ground, reflections become visible (B). Profile B shows a high-amplitude reflection in 300 MHz data, between 40 and 60 nanoseconds, generated from a sloping buried living surface at the Ceren site, El Salvador.

changes in soil moisture, the various depths of layers, and changing ground surface materials can be accounted and adjusted for. The idea in this latter method is that even if the gains were not perfectly applied in the field, postacquisition processing can be used to increase or decrease the amplitudes of reflected waves later on. But even this method of gaining can be fraught with problems. If the gains are set too high prior to collecting reflection profiles (increasing the amplitudes by large factors), and the antennas were then moved over an area with very reflective buried materials, then the increase in recorded amplitudes would "go off scale," and the highest values would be "clipped" and not recorded (figure 4.2). A recent "compromise" by one GPR manufacturer allows the user to set the gains in the field, but by default records amplitudes at 25 percent of the field settings to prevent inexperienced operators from amplitude clipping. This "dumbing down" of the acquisition procedures (which is becoming more common as GPR systems reach a broader number of users) is regrettable because one will still have to reprocess all reflection data anyway after returning from the field in an attempt to replicate the original field settings.

If one decides to set range gains in the field, it is very important to move the antennas over much of the ground to be surveyed during the calibration procedure before any reflection data are collected so that a general idea of the reflectivity (and therefore recorded wave amplitudes) of buried materials can be determined. In this way, the gains can be set at the location where the highest reflection amplitudes will likely be recorded and one can be fairly well assured that the remainder of the amplitudes recorded in all the reflection profiles within the grid to be surveyed will be "on scale" and not lost due to overgaining, resulting in amplitude clipping.

If the buried features of interest reflect little radar energy and therefore would be recorded as very low-amplitude reflections, it might be advisable to set the gains very high in order to be able to see them in the reflection profiles. This is done at the risk of clipping amplitudes of other features that might not be of interest. One survey was conducted in an area where large piles of buried brick rubble from collapsed walls were creating very high-amplitude reflections. The targets of the survey, however, were very subtle burial features in nearby graves adjacent to the collapsed brick walls. It was therefore decided to increase the gains of all reflections at all depths, which increased the amplitudes of the reflections from the bricks off scale (clipping them) but also increased the amplitudes of the subtle grave features so they were visible. The downside of this acquisition setup procedure was that the portions of the profiles crossing the

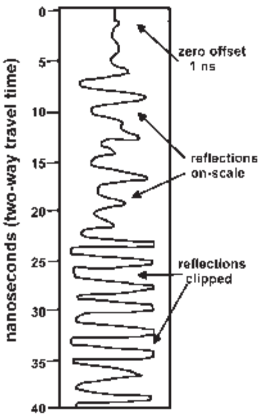

FIGURE 4.2
Trace Clipping. If range gains are misapplied, recorded waves can be "clipped," as shown in this waveform between about 25 and 40 nanoseconds.

highly reflective brick were overwhelmed with very high reflections, but these could be easily discounted as areas having intact burial features. The higher amplitudes recorded in the other areas of lower reflectivity where the graves of interest were located were then gained high enough to be visible.

If reflection data are highly attenuated with depth in the ground, often no reflections will be received from below a certain depth in the ground at all. If the time window were open to that depth, but no wave amplitudes from within the ground were being recorded, the automatic gain settings on most GPR systems will still increase whatever energy is available. Since there are no waves coming from within the ground, the range gain settings will increase only external noise that is being recorded in that portion of the time window. Anomalous and unusable data would then be recorded from those depths and must be ignored during later data analysis. Noise that is increased in this way (usually in the later portion of the time window) is generated from system noise within the GPR unit and other random interference, such as from FM radio transmission. Amplitude variations generated from differences in radar energy coupling due to changes in surface materials can also be accentuated in these later portions of the time window if no reflections from those depths are being recorded.

Once gains are set during the initial calibration of the GPR system, they should remain constant for the whole grid being surveyed with a particular antenna. If they are adjusted for any reason, the processed reflection data will display very different reflection amplitudes from the same depths in different parts of the grid, which may be confused with geologic or archaeological changes of importance. If the gain settings are changed either on purpose or by mistake and noted, it is still be possible to normalize the amplitudes of recorded reflections to achieve consistency using postacquisition data processing. Adjustment of any or all of the other setup procedures including the time window, stacking, filtering, and sampling rate will always necessitate regaining the amplitudes, as the waveform is also modified with these changes.

Vertical Filters

Vertical filters remove high- and low-frequency noise from recorded reflection traces that may be generated from system noise or frequency interference. Just as with range gaining, a school of thought believes all reflection data should be recorded in the field as raw data, and frequency filtering should only be applied during postacquisition processing. In this way all reflections, whether good or bad, are acquired. The thought is that if unfiltered data are acquired, what might be considered "bad data" can possibly be filtered and improved upon later.

The other idea is that filtering is necessary during collection so that reflections can be more easily visible and begin to be interpreted while they are being collected and are visible on the computer screen. Also, if filters are applied prior to collecting any data in the field, the optimum data quality can usually be arrived at, which might only be estimated at a later time. Some experimentation with filtering while still in the field is usually the most advantageous method, as the best data quality possible can often be collected immediately. If further filtering is necessary later on, good data can only be improved upon.

Some GPR units allow the recording of reflection data on two channels simultaneously, and therefore both raw and filtered reflection data can be acquired for each transect (Fenner 1992). Both data sets could then be processed once back in the office and compared, prior to choosing one or the other for final interpretation.

Vertical filters, also called *band-pass filters*, are employed to remove anomalously high- and low-frequency noise during data recording (Bucker et al. 1996; Fisher et al. 1994; Urliksen 1992). Terms for this filtering are *high-pass* and *low-pass*, which were originally coined for radio transmissions in the early twentieth century. The high-pass filter removes low-frequency waves (it allows the high frequencies to "pass by" a low-frequency cutoff where they can be recorded), which are often generated from "system noise" inherent to each particular radar device. These data can sometimes be seen on an oscilloscope or computer display of the recorded traces as long wavelengths superimposed on a standard reflection trace. The amount of low-frequency noise recorded will change with the antenna used, the cable length, and the type of control unit. It is usually a function of GPR system design.

Anomalously high-frequency data can be filtered out with low-pass filters (the frequencies lower than a cutoff frequency are allowed to "pass by" and are then recorded). These anomalous frequencies are usually received from FM radio transmissions or other electromagnetic disturbances nearby. High-frequency noise of this sort is easily visible when the antenna is not being moved and the generated waveform, visible on a computer display or oscilloscope, can be seen to be "flickering" because of the high-frequency noise. Because most antennas are capable of recording frequencies within one octave or so of their center frequency, a 400-megahertz antenna could be receiving energy from between 200 and 800 megahertz, or even higher in the frequency bandwidth. If a "clean" waveform is generated with high- and low-pass filters placed at 200 and 800 megahertz, then there is a good chance that high-quality reflections from within the ground will be recorded within the bandwidth of the 400-megahertz antenna and not external noise. If a good deal of noise is still being received at the antenna with these band-pass filters, it might be a good idea to decrease the low-pass filters to 600 megahertz or even lower, which would remove much of the higher frequencies, which are likely produced from nearby radio transmissions.

Care must be taken not to remove what may be reflections from within the ground during this type of filtering, but often data sets are so noisy that no coherent reflections are visible at all. One survey of note was collected in an incredibly noisy area, and it did not appear that any reflections were being recorded from within the ground at all but only noise (figure 4.3). Reflection profiles were so noisy that it appeared the survey would be a total failure. This noise was likely caused by a large amount of FM radio and other communication band noise in the urban area where the survey was conducted, which was bounded by two busy highways, near a cluster of radio antennas and very close to an airport. When both the high- and low-pass filters were narrowed to 50 megahertz on either side of the center frequency of the antenna, the background noise was effectively removed, and reflections in the ground from buried pit house floors became immediately visible (figure 4.3).

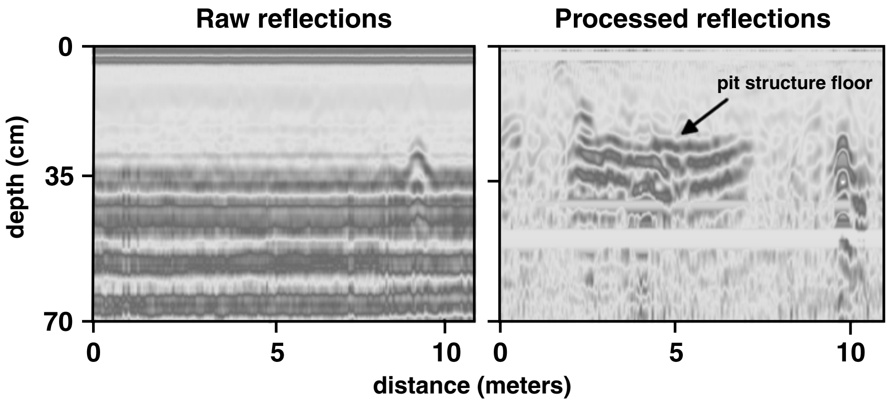

FIGURE 4.3
Frequency Filtering. Sometimes reflection data are collected that are so noisy that few usable reflections are immediately visible. When the data are frequency filtered and the background removed, important reflections from buried features are sometimes visible. These data were collected with a 500-MHz antenna in Tucson, Arizona. Almost 90 percent of the data were removed by vertical filtering, and the resulting reflections were regained to make the pit structure floor visible.

It is important to note that when vertical and horizontal filters are applied in the field prior to data acquisition, other adjustments such as the time window, sampling rate, transmit rate, and range gains must also be adjusted and possibly reset a number of times before any data are collected. All the manual adjustments noted here are part of an iterative process, and a number of experimental profiles should be collected, each with different settings applied, prior to gathering the final reflection data in transects. If good reflection data are being acquired at the necessary depths once the adjustments are set, then the settings should remain the same for all reflection profiles acquired within a grid. Often these calibration steps can take an hour or more, and it is prudent to always plan time for experimenting with all the preacquisition settings to assure the highest-quality data. The computer software included with some digital units can make many of these adjustments automatically or by employing standard stored settings set by the GPR system manufacturer. This is never a good idea. It is rather advisable to manually adjust settings for local conditions and never be lured into using preset parameters that might have worked well in the factory shop but are totally inappropriate for the local conditions encountered.