Pitfalls in GPR Data Interpretation: Differentiating Stratigraphy and Buried Objects from Periodic Antenna and Target Effects

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Abstract. Periodic events in ground penetrating radar (GPR) data may result from antenna and target effects rather than reflections from geologic features. One of the most common pitfalls in GPR data interpretation is to identify each event on a radar cross-section as scattering from a discrete horizon, without considering other possible sources of these events. Soil electrical properties and surface roughness affect ground penetrating radar antenna radiation and waveform characteristics. An impedance mismatch occurs over soils with electrical properties different than those for which the antennas were designed to perform optimally over, and results in periodic ring-down, which can be misinterpreted as stratigraphy or multiple reflections. In addition, target resonance can introduce additional periodic features that can lead to misinterpretation in regards to the number of targets present. Co-pole and cross-pole antenna configurations can be combined with polarization dependent scattering characteristics of subsurface objects to recognize and reduce antenna ring-down for improved imaging and interpretation.

Introduction

Ground penetrating radar (GPR) is commonly used for a wide variety of non-destructive subsurface investigations (Davis and Annan, 1989). Radar waves are radio frequency electromagnetic waves that are produced by a transmitter antenna, scattered from interfaces between media having contrasting electrical properties, and recorded by a receiver antenna. The amplitude of the GPR response depends on many factors, including GPR system and antenna characteristics, the target signature, and propagation effects associated with the electrical properties of the ground. Antenna and system induced artifacts can easily be misinterpreted as stratigraphy, multiples, buried objects, or other geologic features. This paper briefly describes and gives examples of several of the more commonly observed antenna and target effects that can lead to GPR data misinterpretation. Data recorded using parallel transmitter and receiver (co-pole) and orthogonal transmitter and receiver (cross-pole) antennas are used to demonstrate antenna ring-down and scattering from some of the more commonly observed geologic and environmental features.

Dipole antennas and polarization dependent scattering

Most of the energy radiated from dipole or bow-tie antennas, the most common GPR antennas, is linearly polarized and the electric fields vibrate predominantly along the long axis of the antenna (Annan 1973; Engheta et al. 1982; Smith 1984). A complete polarization mismatch results when the receiver antenna and incident field polarizations are both linearly polarized and oriented at right angles to each other. Rotating ideal dipole antennas orthogonal to each other (crossed-dipoles) also results in a complete polarization mismatch, unless the polarization of the transmitted fields are altered by a mechanism such as scattering or anisotropy.

Crossed-dipole antennas are not commonly used in GPR, but have been used successfully to study anisotropy and depolarization (Tillard, 1994; Luzitano and Ulrych, 1996). This paper uses crossed-dipoles as a tool to recognize and reduce antenna ring-down for improved imaging and interpretation. First we will discuss scattering sources of cross-polar energy and then discuss and illustrate with examples, how cross-pole data can aid in identifying and reducing antenna ring-down.

An object will not be visible with ideal crossed-dipole antennas (perfect isolation) unless it scatters a cross-polarized component. A specular reflection from a smooth, flat plane does not introduce field components (cross-components) that were not originally present in the incident field. However, depolarization occurs for non-normal incidence angles (bistatic antennas) when the incident field contains components oriented both parallel and orthogonal to the plane of incidence, because of differences in Fresnel reflection coefficients for these two components (Kraus, 1984). In addition, a smooth cross-dip...
tilted plane (bistatic GPR survey oblique to dip) can introduce cross-polarized components and it is therefore no longer sufficient to consider each of the two orthogonal field components independently (Mitzner, 1966; Beckman, 1968). A rough plane regardless of tilt, as well as edges and buried objects that are small compared to the wavelength of the incident field can also scatter cross-polarized components. Pipes and rebar are also visible with crossed-dipole antennas because their linear geometry results in scattered field components oriented parallel to the long axis of the dipole receiver antenna.

**Antenna impedance mismatch and ring-down**

Most GPR antennas are located on or just above the ground to couple electromagnetic energy into the ground efficiently. The close proximity of the antenna to the ground causes the antenna current distribution and impedance to be strongly influenced by the ground. The antenna impedance changes with different soil types, moisture contents, and surface roughness. Many GPR antennas are designed for use over ground having a particular impedance. Ground impedance that differs from the intended antenna design produces an impedance mismatch between the antenna and feed cable. This causes the currents to bounce back and forth between the antenna feed and the ends of the antenna elements (Figure 1). The currents decay and radiate over extended time intervals, and thus the radiated or received pulse is not a clean single pulse. The resulting antenna ring-down reduces resolution, is a source of noise, and wastes signal power.

Antenna ring-down is often times reduced by loading the dipole or bow-tie antenna with discrete resistors on the ends of the elements or by placing tapered resistors along the antenna elements (Clarke and Rodriguez-Tellez, 1998; Shlager et al., 1994). Resistive loading absorbs some of the energy that has not been radiated and provides the additional benefit of increased bandwidth. However, the price for resistive loading is the loss of efficiency and sensitivity. An alternative to resistive loading is to elevate the feed point and form a horn-fed bow-tie with the horn’s cavity filled with a dielectric (Chen, 1997). The elevated feed reduces the ground’s effect on antenna impedance.

**Examples of antenna ring-down and resonance**

GPR surveys were run at a site characterized by clay-rich glacial soils with abundant standing water. The wet, heterogeneous soils produced a strong impedance mismatch between the antenna and feed cables. This impedance mismatch resulted in antenna ring-down that limited resolution and contaminated the image with horizontal banding (Figures 2 and 3). Data were acquired using coincident antennas (closely spaced common-offset) with both co-pole and cross-pole antenna configurations.

Antenna ring-down results from an impedance mismatch between the transmitter and receiver antennas with the ground. This impedance mismatch causes the transmitter antenna to transmit several pulses that decay with time, rather than a single clean pulse. Additional antenna ring-down can take place on the receiver antenna as currents bounce back and forth between the feed and ends of the antenna. The period of antenna ring-down is determined by the amount of time required for currents to travel between the antenna feed and ends of the antenna elements. The velocity of these antenna currents is a function of antenna design, but they propagate with a velocity that is intermediate between the velocity in air and soil. Antenna ring-down could be misinterpreted as stratigraphy that is not present, or as multiples that result from multiple reflections from the same boundary.

Antenna ring-down can be observed on directly radiated energy (direct arrivals) and energy scattered from subsurface objects. The polarization match of co-pole antennas causes the receiver antenna to be sensitive to the large amplitude direct air and ground wave energy radiated by the transmitter antenna. Direct arrival energy is 20 dB lower on the cross-pole component due to the polarization mismatch between the receiver antenna and the fields directly radiated by the transmitter antenna. Antenna ring-down can also be observed on waves scattered from subsurface objects. The duration of antenna ring-down is a function of the reflected amplitudes, antenna impedance mismatch, and antenna damping. Antenna ring-down can also be observed on the cross-pole component when subsurface objects scatter large amplitude, cross-polarized energy.

Figure 2 shows co-pole and cross-pole GPR data acquired at an abandoned industrial site. Hyperbolas produced by rebar are easily visible in the concrete tank pad on the cross-pole data, and this demonstrates the ability of crossed-dipole antennas to image linear targets. The abundant horizontal banded, directly radiated antenna ring-down energy, masks the rebar on the co-pole data. The polarization mismatch achieved with cross-pole antennas reduces directly radiated antenna ring-down energy and allows for improved images of targets that scatter cross-polarized energy. A coarse gravel road is also visible on the cross-pole component because it is a heterogeneous volume that scatters cross-polarized energy.
In Figure 3, the GPR survey traversed standing water centered at a distance of 15 m. The direct arrival over water is visible at nearly the same time as over the soil, but appears much fainter. Many factors such as antenna design affect the direct arrival, but the directly radiated air wave is a major contributing factor. Finite difference time domain (FDTD) modeling (Turner, 1994; Radzevicius et al., 2000) demonstrate that increasing permittivity results in more directive antenna patterns with less energy radiated into the air relative to the ground. The high relative dielectric permittivity of water (approximately 80 for water compared to 5 for moderately dry quartz sand) results in less energy being radiated into the air and thus reduces the air wave contribution of direct arrivals. In addition, surface roughness and other near surface heterogeneities may cause scattering and increased direct arrival amplitudes over the heterogeneous soils compared to the more homogeneous water. The standing water bottom is clearly visible at 7 ns on both the co-pole and cross-pole data, and no reflections take place before this time over the water because it is homogeneous. However, antenna ring-down is visible on direct arrival co-pole data over water, and is characterized by a shorter period than would be produced by a multiple reflection from the water bottom. Antenna ring-down (before 7 ns over standing water) is produced by multiply transmitted and received pulses directly radiated between transmitter and receiver antennas, rather than energy scattered from subsurface features. The antenna ring-down is not easily visible before 7 ns over standing water on the cross-pole data because of the polarization mismatch between crossed-dipole antennas and direct arrivals that reduces antenna ring-down by 20 dB.

Larger amplitude antenna ring-down is visible after the 7 ns water bottom reflection. The high permittivity of water results in a more directive antenna pattern with energy focused into the subsurface relative to the air and thus reduces direct arrivals relative to subsurface reflections. Due to the homogenous nature of the water, this radiated energy is not scattered until it reaches the large electrical contrast at the water bottom that results in large amplitude reflections. The focused antenna patterns, homogenous water, and the large water-soil impedance contrast combine to produce large amplitude reflections from the water bottom. Antenna impedance mismatch of transmitter and receiver antennas at the air-soil interface causes the water bottom reflection to appear as multiple events, as opposed to a sharp reflection resulting from a single, clean, input wavelet.

The water bottom is easily visible on the cross-pole data because the interface is rough and thus scatters a cross-polarized component. This scattered cross-component results in antenna ring-down below the standing water bottom on the cross-pole component. Significant antenna ring-down is present on the cross-pole component (Figure 3b) to the left of the standing water (distance 0 to 12 m) and results from scattered cross-components produced by a coarse gravel road. Abundant antenna ring-down is present throughout Figure 3a on the co-pole component since no scattered cross-component is needed to produce antenna ring-down.

In addition to antenna ring-down and multiples, target resonance can also introduce periodic features into GPR data and may make it difficult to determine the number of vertically buried objects. The frequencies at which a cylinder resonates are a function of its geometry and the electrical properties of the surrounding medium. For cylinders, the dominant resonance occurs at the first harmonic, where the resonator is one half the wavelength of the incident wave. This is similar to sound waves in an organ pipe where antinodes form at the open ends of the pipe. To demonstrate resonance, data were collected with 450 MHz (in air) centerband Sensor and Software antennas over two 1.25 cm diameter copper pipes having lengths of 11.5 cm and 171 cm, and buried at depths of 28 cm and 33 cm respectively. The close proximity of the ground shifts the center frequency to a lower frequency depending on soil conditions and antenna design. Multiple hyperbolae (Figure 4a) illustrate that resonance takes place with the 11.5 cm length pipe, while only a single hyperbola is visible with the 171 cm length pipe (Figure 4b). The 171 cm pipe is much longer than the dominant wavelengths radiated by the 450 MHz centerband antenna (approximately 30 cm at 450 MHz in soil). Resonance is also important for attribute analysis and target identification (Chan et al., 1981; Chen and Peters, 1997).

Conclusions

Antenna and target effects such as antenna ring-down and target resonance can introduce periodic events into GPR data that may be misinterpreted as multiple reflections, stratigraphy, or multiple buried objects. Antenna ring-down results from antenna impedance mismatch and has a period determined by the time required for currents to travel back and forth between the antenna feed and ends of the antenna elements. A combination of co-pole and cross-pole antenna configurations are useful in the study of antenna effects and subsurface properties. Primary antenna ring-down is visible on direct air and ground wave energy and its period is determined by antenna element current velocity and length. Antenna ring-
down amplitudes are larger on the co-pole configuration because of a polarization match between the receiver antenna and direct arrivals. Scattered energy can produce additional antenna ring-down later in time. Objects that scatter cross-polarized components, such as rough surfaces, can introduce antenna ring-down on the cross-pole component.

Resonance is another periodic feature observed in GPR data when the dominant GPR wavelengths approach the dimensions of the buried object. The period of resonance is determined by target geometry and electrical properties. It is necessary to differentiate resonance produced by a single target from several vertically buried targets, when interpreting GPR data. Recognizing antenna effects and target resonance, as well as understanding their mechanisms, reduces GPR data misinterpretation and provides additional information about the subsurface.

References


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(Received February 14, 2000; Revised May 5, 2000; Accepted August 1, 2000.)
Figure 1. Generalized dipole antenna showing sources of impedance mismatch.
Figure 2. Co-pole (a) and cross-pole (b) GPR profiles illustrating the ability of cross-pole antennas to image linear objects and reduce antenna ring-down.
Figure 3. Co-pole (a) and cross-pole (b) GPR profiles illustrating the ability of cross-pole antennas to image rough planar objects and reduce antenna ring-down.
Figure 4. Co-pole GPR survey over: (a) 1.25 cm diameter copper pipe with a length of 11.5 cm and buried at a depth of 28 cm, and (b) 1.25 cm diameter copper pipe with a length of 171 cm and buried at a depth of 33 cm.