Non-geologic events in single- and cross-hole radar data
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Summary

Accurate analysis of borehole radar data depends upon the proper identification of events and the precise measurement of amplitudes and travel times. This paper discusses and provides data examples of non-geologic events that can influence borehole radar measurements and complicate data interpretation. Data demonstrate that refracted air events can arrive prior to direct arrivals in cross-hole surveys, and that conductive cable-related effects can introduce artifacts and multiple events into records. Additionally, non-traditional variable offset soundings (VOS) are shown to be useful for studying propagation characteristics, recognizing possible cable-related effects, and providing insight in regards to coupling mechanisms between antennas and cables.

Introduction

Depending on the objectives of a particular study, measurements can be acquired using a single borehole or multiple boreholes (Figure 1). Single-hole measurements are typically made while raising or lowering the antennas with a constant separation (reflection mode). In addition to reflection measurements, variable offset soundings (VOS) can be made by keeping the position of one antenna stationary and stepping the other antenna away at a constant interval. A VOS using borehole antennas is similar to a wide angle reflection and refraction (WARR) sounding made using surface antennas, in that data are recorded while varying the spacing between antennas to provide a means of measuring propagation characteristics of the radar signal as a function of antenna offset.

Cross-hole measurements between two boreholes can be made by raising or lowering both antennas at the same rate to acquire a constant offset profile (COP). A multiple offset gather (MOG) can be acquired using two boreholes by fixing the transmitter antenna in one hole and raising the receiver antenna in the other hole. Numerous MOG’s made with the transmitter antenna located at different depths are often merged and processed to create attenuation, dispersion, and velocity tomograms.

Difficulties in establishing system parameters, the improper setting of time zero, system drift, and deviations in positioning of the antennas are problems that can occur during borehole radar data acquisition. Other factors that can affect measurements include the antenna radiation pattern, refractions generated by high velocity contrasts, wave guiding in a borehole or layered sediments, and resonance effects. Additionally, previous studies have demonstrated induced currents on borehole radar cables (Wright et al., 1986; Sato and Thierbach, 1991).

Borehole Radar Systems and Antennas

Borehole radar systems typically utilize dipole antennas that radiate electromagnetic fields with the electric field vector components predominantly oriented parallel to the long axis of the transmitter antenna. The radiation pattern of a dipole antenna in a dry borehole with a homogenous surrounding medium is similar to that of a dipole in a whole space (Sato and Thierbach, 1991), however, changes in the surrounding geologic medium and fluid filling the borehole can significantly alter the pattern.

The electronics and power source necessary to generate and record pulses radiated by borehole antennas can be located at the ground surface or adjacent to down-hole antennas within probe casings. Systems have been developed that use non-conductive cables for signal transmission and are suitable for use in most boreholes (Sato and Miwa, 2000). However, several commercial systems designed for shallow earth studies locate the power source and electronics at the ground surface, and therefore must rely on conductive cables for signal transmission.

Data acquisition

Data presented in this paper were acquired using a commercial borehole radar system at a site characterized by highly varying unconsolidated glacial sediments. Measurements were made using omni-directional antennas in permeable PVC cased wells with the water table at a depth of 4.1 m. The radar system employed utilized 30.0 m long conductive cables for signal transmission between surface-located electronics and the antennas. Data were high cut filtered at 120 MHz to reduce system noise, and all data presented are displayed with constant gain.

Refracted air event example

A cross-hole common offset profile acquired using 100 MHz antennas in holes with a separation of 4.36 m and an accompanying geologic log are shown in Figure 2. Event A is the direct arrival from the transmitter antenna to the receiver antenna through the geology, and Event B is a refracted air event. A decrease in direct arrival time with decreasing depth for event A agrees with the position of the water table. The amplitude of event A decreases above the water table due to attenuation associated with the increased
presence of clay-rich sediments. Event A yields a bulk geologic velocity of 0.062 m/ns at 4.7 m depth, and 0.067 m/ns at 2.7 m depth. At 2.7 m depth it can be seen that the direct arrival is the earliest recorded event. At 2.2 m depth interference between the direct arrival and refracted air event does not allow these two events to be distinguished from one another, however, at 1.7 m depth it can be seen that the refracted air event arrives the earliest.

Assuming the calculated velocity at a depth of 2.7 m is constant above this depth, the critical angle of incidence for a refracted wave traveling along the surface at the velocity of air is 12.9 degrees. The expected arrival time using this angle of incidence for a refracted air event at 2.7 m depth is approximately 90 ns, which agrees with the actual arrival time of event B in Figure 2. Although event B arrives later in time than event A at 2.7 m depth, the amplitude of the events are similar, as the refraction ray path travels less distance in the geology than the direct arrival. Below this depth the amplitude of event B decreases relative to that of event A, as an increasingly greater proportion of it’s travel path occurs in the lossy geology relative to air. Using the assumed constant velocity of 0.067 m/ns above 2.7 m depth, a reflection at this depth would be received later in time than a refracted air event, at approximately 100 ns, due to the reflection ray path distance through the geology being greater.

**Cable-related event examples**

Single-hole VOS records acquired using antennas with measured center frequencies of 100 MHz and 200 MHz (in air) are shown in Figure 3. The two linear events indicated as events A and B that intersect at roughly time zero (0 ns), have equal but opposite slopes (velocity = 0.21 m/ns). Both events are the result of the receiver antenna recording fields radiated by the pulse from the surface electronics traveling on the transmitter cable. Event A arrives earlier than time zero and records the pulse on its way down the cable to the transmitter antenna. Event B is an upward traveling pulse that resulted from a partial reflection of the initial downward traveling pulse at an impedance contrast at the cable and antenna connection.

Event C in Figure 3 is the direct coupling between the antennas. The direct coupling consists of the direct ground wave and also a wave radiated from the transmitter cable, both of which have a similar travel path and timing. The wave radiated from the transmitter cable that is recorded by the receiver antenna is the result of induced currents propagating along the transmitter cable (which functions as an electromagnetic waveguide) above the transmitter antenna. When the transmitter antenna is parallel to the cables, radiated fields that are polarized parallel to the long axis of the transmitter antenna induce currents on the transmitter cable and radiate fields that are detected by the receiver antenna. Evidence for induced currents on the transmitter cable is not observed when the antennas are aligned orthogonal to the cables (Guy and Radzevicius, 2001), because of a polarization mismatch that occurs when the radiated fields are polarized orthogonal to the conductive cables. Events D, E, and F are multiples of events A, B, and C, with a period of 286 ns, and result from a partial reflection of the upward traveling pulse (event B) that occurs at an impedance contrast at the cable and system electronics junction on the surface. The two-way travel distance of the pulse through the cable (60 m) agrees with the observed 286 ns period of these events.

A single-hole reflection record acquired using 100 MHz antennas is presented in Figure 4. Event A, present prior to time zero is the result of the upward and downward traveling pulses labeled as events A and B in Figure 3. Changes in the direct coupling velocity with depth are evident, and are related to geology and water content changes. The direct arrival is slightly reduced in amplitude above the water table relative to that below the water table, and likely results from a combination of changes in antenna coupling and increased attenuation associated with the increased presence of clay-rich sediments.

A multiple of event B with a period of 286 ns is indicated as event C in Figure 4. An extended time window would reveal additional events every 286 ns resulting from continued internal cable reflections, with the multiple events becoming progressively lower in amplitude and lower in frequency with time. When the transmitter and receiver antennas are located below and above the depth of the water table respectively, the transmitted energy is reflected and refracted away from the receiver antenna resulting in a lower amplitude direct arrival (labeled as D).

**Conclusions**

Refracted air events and cable-related events can have a significant impact on recorded borehole radar data, and can lead to errors in data analysis and interpretation if not recognized. Data examples presented in this paper have demonstrated that refracted air events can arrive prior to the direct arrival in cross-hole surveys. Currents induced on conductive cables and partial reflections occurring in cables at system impedance mismatches can introduce additional data artifacts. VOS measurements are not typically acquired during borehole radar studies, but offer a means for studying antenna coupling and propagation characteristics, and the potential for recognizing possible effects of conductive cables on recorded data.
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References


Figure 1: Single-hole and cross-hole antenna configurations used to acquire reflection, variable offset sounding, constant offset profile, and multiple offset gather radar measurements. Wave propagation ray paths are also shown.

Figure 2: Cross-hole common offset profile acquired in holes with a separation of 4.36 m and an accompanying geologic log. Event A is the direct arrival from the transmitter antenna to the receiver antenna through the geologic medium. Event B is a refracted air event which is received earlier in time than the direct arrival above an antenna midpoint depth of 2.2 m.
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Figure 3: Single-hole 100 MHz and 200 MHz VOS records. Event A results from the receiver antenna recording radiated fields from the transmitter cable by the initial pulse traveling from the surface electronics to the transmitter antenna. Event B results from an upward traveling pulse that was partially reflected from an impedance contrast at the cable and transmitter antenna connector. Event C is the direct coupling between the transmitter and receiver antennas (see text for discussion). Events D, E, and F are multiples of events A, B, and C respectively, with a period of 286 ns.

Figure 4: Single-hole fixed offset reflection record. Event A is a low amplitude event resulting from the upward and downward traveling pulses in the transmitter cable. Event B is the direct antenna coupling. Event C is a multiple of the direct coupling with a period of 286 ns. A zone of apparent attenuation associated with the position of the water table is labeled as D. See Figure 2 for an accompanying geologic log.