A Short-Pulse Electromagnetic Transponder for Hole-to-Hole Use

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Abstract—We have made hole-to-hole observations through nearly 20 m of granite using an electromagnetic transponder (an active reflector) in one borehole and a single-hole short-pulse radar in another. We found that the transponder is inexpensive, operationally simple, and effective in extending the capability of a short-pulse borehole radar system to allow hole-to-hole operation without requiring timing cables. A detector in the transponder senses the arrival of each pulse from the radar (which may be milliseconds in amplitude); each pulse detection triggers a kilovolt-amplitude pulse for retransmission. The transponder "echo" may be stronger than that of a passive reflector by a factor of as much as 120 dB. The result is an increase in range capability by a factor which depends on attenuation in the medium and hole-to-hole wavepath geometry. Single-hole reflection-mode echoes are still available at times prior to the transponder pulse arrival. The transponder is helpful in yielding velocity information, because the radar-transponder distance is known and the echo time is observed. Field tests have demonstrated that the transponder is a useful alternative to employing timing cables in some short-pulse hole-to-hole measurement situations.

Keywords—Transponder, short-pulse, hole-to-hole, borehole radar.

I. INTRODUCTION

The U.S. Geological Survey developed and now uses a single-hole short-pulse radar in deep boreholes in low-loss media such as dry salt or granite [1]. The primary intended application is studies of potential nuclear waste disposal sites. Until our development of a borehole transponder, this radar was not capable of hole-to-hole operation. The single-hole limitation was due to the requirement that the radar be compatible with existing seven-wire logging cable currently used for other geophysical logging tools in the Survey. The radar-radiated (and reflected) signal is ideally a single cycle of a sine wave and has a corresponding frequency spectrum extending into the VHF (30 MHz to 300 MHz) band, but the 2000-m-long cable strongly attenuates signals at frequencies above 2 kHz. This cable cannot carry radio-frequency (RF) signals from the receiver to the recorder, so down-hole sampling and conversion of the radio-frequency signal to an audio-frequency replica is required. In this technique, all fast timing signals are generated down-hole and not passed through the cable. The cable carries the audio-frequency replica to the surface.

Whenever adjacent boreholes are available, hole-to-hole observations are an effective means of augmenting reflection results with transmission results. A hole-to-hole short-pulse system operates with a transmitter in one borehole and a receiver in another borehole, and requires timing synchronization signals between holes [2]. The timing signals are usually generated at the surface and passed to both receiver and transmitter by cables which are sometimes standard logging cables or may be coaxial or fiber-optic.

We have developed a transponder (active reflector) which, in some cases, can produce the same result as a hole-to-hole system without requiring a timing cable. The time reference is automatically established by the radar-radiated signal.

In this paper we suggest that a transponder may be an alternative to timing cables for making some short-pulse hole-to-hole measurements. First, we describe the transponder and its theory of operation. Second, we discuss field tests using the transponder. Third, we present data processing results. Finally, we conclude by summarizing our findings concerning the transponder in hole-to-hole measurements.

II. THE TRANSPONDER: DESCRIPTION AND THEORY OF OPERATION

The transponder (Fig. 1) is used with a short-pulse radar. The radar transmits a signal which is sensed by the transponder. When the transponder senses the incident signal, it generates an "echo" pulse, which is received and recorded by the radar. Inhomogeneities will cause some radar-radiated energy to be scattered or reflected to the radar receiving antenna and will also cause velocity and/or attenuation changes in the propagation path between the radar and the transponder.

Both the radar and the transponder are housed in dielectric tubes (Fig. 2). The transponder tube is 3 m long and 8.4 cm in diameter. The radar pressure vessel is 11.4 cm in diameter and may be configured as one tube 4.9 m, 6.1 m, or 7.3 m long, or the transmitter and receiver may be put in separate pressure vessels each 2.4 m long with arbitrary separation between the vessels. Timing signals are passed from the radar receiver to the radar transmitter through a fiber-optic cable and, in the case of separate pressure vessels, the battery-powered transmitter is suspended on a nonmetallic rope to reduce the coupling between the transmitting and receiving antennas.

The transponder is a much simpler device than the radar,
Fig. 1. Schematic of radar and transponder. The transponder is triggered by an incident wave from the radar transmitter. If a region of contrasting permittivity is between the boreholes, a reflection will occur along with changes in velocity and attenuation between boreholes.

Fig. 2. The radar and the transponder. The radar may be housed in two packages or in one as shown here. In this most compact configuration the radar is 4.9 m long and 11.4 cm in diameter. The transponder is 3 m long and 8.4 cm in diameter.

because it requires no sampler or timing circuits. It consists of a detector, a pulser, battery packs, and transmitting and receiving antennas (Fig. 3).

The detector consists of a wide-band video amplifier, a monostable multivibrator, and some protective circuitry for the video amplifier. The amplifier has a bandwidth of dc to 120 MHz and external gain-select pins which permit voltage gain settings up to a maximum value of 400 (52 dB). The video amplifier boosts the signal from the receiving antenna to a level which will trigger a monostable multivibrator, which generates a unipolar pulse, which in turn triggers the pulser. When the multivibrator is triggered into its quasi-stable state, it remains there for a pre-determined period and ignores any further input from the video amplifier until it returns to the stable state. This feature ensures that transients induced on the receiving antenna by the firing of the pulser have had adequate time to die out, thereby preventing self-triggering. The output from the multivibrator is buffered through an emitter-follower stage to ensure enough current to trigger the avalanche transistor pulser through a pulse transformer. The video amplifier is
protected from high-voltage spikes by Schottky-barrier diodes at the input terminals, because the receiving antenna is closely coupled to the transmitting antenna. Without this protection, a very large voltage would be impressed on the video amplifier terminals when the pulser energizes the transmitting antenna.

The avalanche transistor pulser is a six-stage Marx-bank. Six capacitors are separated by five transistors which act as switches. The capacitors are charged in parallel and discharged in series through the transistors, multiplying the charging voltage. In theory, an n-stage Marx-bank should produce output pulses with a peak voltage n times the charging voltage, but in practice output voltage multiplication is limited by component and stray circuit impedance.

The six-stage pulser gives voltage multiplication of about three to four when driving a 50-Ω load, depending on the transistor type used.

Two battery packs are used, a low-voltage rechargeable pack, and a nonrechargeable high-voltage pack for the pulser. The use of a dc-to-dc converter to derive the high voltage from low-voltage batteries was abandoned because the converter produced so much switching noise, even with filtering, that the transponder would self-trigger on the noise. The battery packs are adequate for 5 h of operation.

The transmitting antenna is a resistively-loaded dipole. The resistors damp undesired ringing so that the radiated pulse is short. The receiving antenna is not loaded because maximum receiving sensitivity is desired. The transponder antenna lengths were chosen to be about the same as that of the radar antennas (1.5 m).

Since the transponder is totally self-contained, requiring neither power nor signal cables, it is suspended on a dielectric rope. Electrical isolation of the transponder prevents cable-guided wave propagation and undesirable cable and surface reflections that obscure desired returns and might cause transponder triggering errors.

Because the transponder is triggered by sensing a wave incident upon it, the electronic delay-time between transponder excitation and response is an important parameter, particularly since it depends somewhat on the amplitude of the incident wave. Laboratory measurements indicate a delay of 40 ns for large-amplitude signals. The delay increases to as much as 50 ns for incident signals which are just at the limit of detection. The variations in delay-time are caused by the rise time of the video amplifier, the non-ideal nature of the monostable multivibrator threshold detector, and the finite bandwidth of the incident radar signal itself. For a fixed-amplitude incident signal, however, the delay is quite consistent and timing jitter is not a problem. The maximum timing shift of 10 ns leads to a range estimation error or 0.75 m in a medium of relative permittivity of 4; range errors are smaller for higher permittivities.

The maximum usable borehole separation is limited by the requirement that the radar-radiated signal level at the transponder significantly exceed the noise level. The noise is made up of both external RF signals such as television and FM radio transmissions, and internal electronic noise in the transponder. The usable separation cannot be increased by increasing the gain on the video amplifier, unless the incident radar signal is sufficiently above the noise level. Fortunately, the peak radiated power of a short-pulse radar can be several kilowatts. If the transponder is triggering on noise, rather than the incident radar signal, the result at the radar receiver is an easily-recognized burst of nonsynchronous noise. Nevertheless, the maximum usable distance between the radar and the transponder must be expected to be somewhat less than for a short-pulse hole-to-hole system using timing cables if other factors, such as transmitted power, are equal.

III. FIELD TESTS

We carried out field tests of the transponder used with the reflection-mode radar at a site near Gold Hill, Colorado, where several shallow (50 m) boreholes exist. The country rock is Boulder Creek granite; however, it is far from homogeneous, containing gold ore vein deposits, aplite and pegmatite dikes, and other inclusions [3]. The bulk dc resistivity is about 1000 Ω-m, with velocity in the VHF range reported to be about 127 m/μs and attenuation of about 1.2 db/m [4]. At higher frequencies, it is reported that the attenuation is anomalously high and has an unexpected frequency dependence [5].

We tested the transponder using two procedures: first, we lowered the transponder to a fixed depth in one borehole while the radar was moving in an adjacent borehole; and second, we moved the transponder while the radar was fixed in one position. In both cases our raw data (Figs. 4 and 5) were dominated by ringing in the radar probe. Figs. 4 and 5 are density plots of the amplitude of the recorded radar signal as a function of time (abscissa) and depth in the borehole (ordinate). The time axis can be converted to distance from the radar if the propagation velocity in the medium is known. The depth is plotted increasing downward and refers either to the radar depth or to the transponder depth depending on which is moving. The transponder winch was hand operated and indicated transponder depths are approximate. The earliest vertical stripes, beginning at about 106 ns, are due to the arrival of the direct wave from the transmitter to the radar receiver. The 106 ns includes uncalibrated radar system electronic signal propagation delays, so propagation speed between transmitter and receiver cannot be directly deduced from this time interval. The following ringing, due to inadequate decoupling between the receiving and transmitting antennas in the radar probe, obscure the transponder signal, which is only faintly visible in the data.

We found from these tests that the transponder worked, even though data processing was needed to remove the effects of ringing in the radar probe. The ringing is not an inherent limitation of the radar, but is a function of antenna separation, borehole diameter, borehole fluid, rock characteristics, and any wave damping materials which may be used. In the tests considered here the ringing was severe and no useful reflection-mode information was obtained. In other environments the radar has functioned...
Fig. 4. Density plot of raw data when transponder is at fixed depth and radar is in motion. The indicated depth refers to the depth of the radar in the borehole. The time axis may be converted to distance if propagation velocity is known. The data sampling begins prior to the arrival of the direct wave from the radar transmitter to receiver, indicated by the horizontal arrow. Strong oscillations, resulting in the vertical stripes, largely obscure the transponder return, indicated by the diagonal arrow.

Fig. 5. Density plot of raw data when radar is at fixed depth and transponder is in motion. Depth refers to depth of the transponder and is approximate, since speed control on manually operated transponder winch was not precise. If the radar and data sampling are completely consistent the vertical stripes will be exactly uniform since the radar is not moving. The vertical arrow indicates the partially obscured transponder signature.

IV. DATA PROCESSING AND ANALYSIS

The obscuring ringing in Figs. 4 and 5 may be partially removed by the simple means of subtracting an average waveform. This is done by digitally finding the average of all the records and subtracting the average from each record in the data set. Fig. 6 shows the enhanced data when the transponder is at a fixed depth and the radar is in motion. The strong diagonal bands are due to cable-guided waves which propagate up the borehole, reflect from the surface, and propagate back down to the receiver. The hyperbolic-shaped feature is due to the return from the transponder. Although the amplitude varies, the shape is smooth, as would be expected in a locally homogeneous medium, except for one jump of about 30 ns near the bottom of the transponder return. The jump is larger than the 10 ns maximum variation in delay-time noted in the laboratory. Possible explanations include an encounter with a region of lower velocity, or a multipath condition in which the wave which arrives first is attenuated to the point that it does not trigger the transponder, but a later arrival does trigger it.

When the transponder is in motion and the radar stationary, subtraction of an average waveform should exactly remove the radar contribution and leave only the effect of the transponder. Fig. 7 shows that the radar signature is not completely removed. This reveals slightly inconsistent performance of the radar. Nevertheless, the results are quite good and the transponder signature is clear. We conclude that poor radar probe performance, due to inadequate antenna decoupling, can be largely overcome by use of a transponder and data processing.

The faint ghost of the transponder signature, which appears at a time approximately appropriate to a second round trip between the radar and the transponder, was unexpected. The transponder electronics do not allow a second firing of the transponder pulser within this time window, and the signal appears to be too strong to be simply a second round-trip between the antennas in the radar and transponder. Nor is the ghost due to digital aliasing. The explanation appears to be the excitation of a cable-guided wave which propagates to the surface and back down.

As a further aid in data processing, we again logged the
Fig. 7. This is derived from Fig. 5 by subtraction of the computed average waveform. The fact that the vertical stripes are not entirely removed is an indication of some variation in the radar performance. The result does make the transponder signature quite clear, however. The faint replica of the transponder signal, indicated by the arrow, was not expected. The source of this replica appears to be a cable-guided wave.

Fig. 8. These data are derived from Fig. 4 by repeating the radar run with no transponder in the second borehole, and subtracting the second data set from the first. As discussed in the text, the result is not perfect, but does make the transponder signal, indicated by the arrow, much more visible.

same borehole with the radar, but with no transponder in the adjacent borehole, with the intention of subtracting the resulting data set from the data shown in Fig. 4. In theory, if the radar performed identically both times, the result would be due only to the operation of the transponder. In fact, however, several discrepancies occurred, including an inability to set the winch speed precisely and repeatably, an inadvertent gain change between runs which may have been due to operator error, and a heretofore unnoticed electronic delay-time drift which is particularly great shortly after system start-up. The two data sets could be usefully subtracted only after digitally normalizing and time-shifting one with respect to the other. The necessary time-shift was found by maximizing the cross-correlation function of corresponding waveforms in the two sets of data. The digitizing was somewhat coarse, but the result, shown in Fig. 8, shows that this process removes most of the surface echo signature and enhances the transponder signature in regions where it is weak.

Fig. 7 shows that the amplitude of the transponder signature is larger at the top than at the bottom. In Fig. 8, the opposite is true. We conclude that the amplitude of the waveform is greater when the transponder is situated above the radar. This could be due to the electrical properties of the rocks at the particular site, but also suggests that either the radiation pattern of the transponder is somewhat skewed in the down-hole direction or the receiving pattern of the radar is skewed in the up-hole direction. Since energy from the radar transmission propagates up the borehole on the cable, an up-hole skew in the radiation pattern is the likely explanation. From the 12.2-m-distance between boreholes, the calculated propagation velocity is 129 m/µs after subtraction of 40-ns-electronic delay-time. This compares well with the propagation velocity of 127 m/µs measured by other workers [3].

V. CONCLUSIONS

We have built and tested a transponder for use with a single-hole reflection-mode short-pulse borehole radar. The transponder operated through a slant-distance of almost 20 m in lossy granite. The transponder eliminates the need for timing cables between a conventional time-domain transmitter and receiver, and its use required no modifications to our existing single-hole radar. The transponder is inexpensive to build and simple to operate. Use of the transponder extends useful probing distance and enhances ability to characterize the medium between two boreholes by permitting the simultaneous acquisition of reflection-mode and transmission-mode data. The maximum usable distance is limited by noise and attenuation and will be less than that for a hole-to-hole short-pulse system which uses timing cables if parameters such as radiated power are the same for the two systems.

REFERENCES

Letters

A Potential Global Soils Data Base

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Abstract—A general procedure is outlined for refining the existing world soil maps from the existing 1:1 million scale to 1:250 000 through the interpretation of Landsat MSS and TM images, and the use of a Geographic Information System to relate the soils maps to available information on climate, topography, geology, and vegetation.

Keywords—Soils, remote sensing, Landsat, predictive modeling.

INTRODUCTION

Reliable soils information is needed for productivity assessments, climate modeling, modeling of geochemical cycling, the assessment of land resource degradation, and determination of land suitability. The ability to make these assessments on a global basis depends on the availability of soil maps at an adequate scale, within the framework of a comprehensive soil classification system.

GLOBAL SOIL MAPS

The Soil Survey of the United States Department of Agriculture initiated a World Soil Map Project in 1945 [1]. Dr. Marline G. Cline headed the project and devised the system that was used, which followed the 1938 USDA soil classification system [2]. The project was made possible through work that the Soil Survey was asked to do for the Military Geology Branch of the U.S. Geological Survey. Under the administration of Dr. Charles E. Kellogg, the World Soil Geography Unit in the Soil Survey, SCS/USDA completed maps covering all the world at 1:1 million except for the United States, Australia, and a few African countries [3]. None of the maps have been published. Originals are retained at the Soil Geography Unit.

Soils were mapped at 1:1 million on Operational Navigation Charts (ONC's) at the great group level with phase separations based on terrain type and parent material. Where no soil maps were available, kinds of soils were predicted from inferences from genetic factors.

The World Soil Maps continue to be updated, particularly for use by the Foreign Agricultural Service's Crop Condition Assessment.