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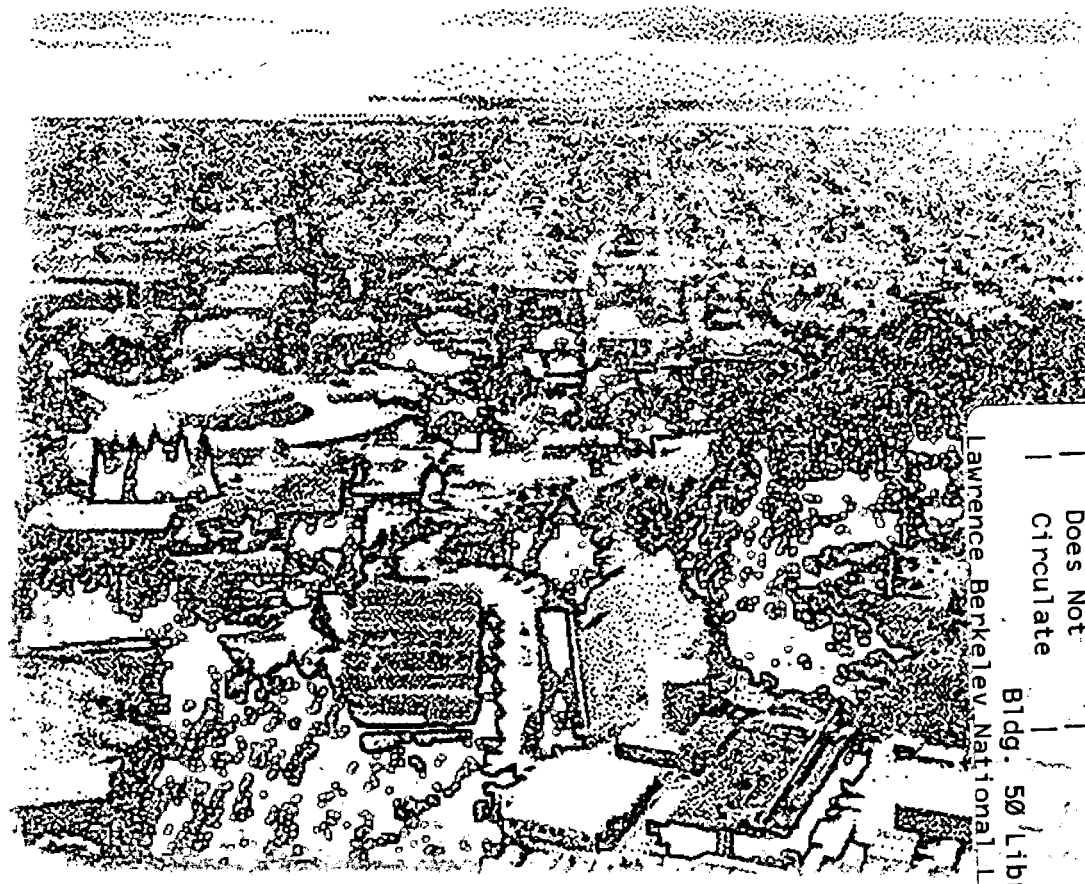

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Electromagnetic Method for Analyzing the Property of Steel Casing

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Abstract

In this report we present an innovative electromagnetic (EM) method for extracting information about a steel casing in terms of its electrical conductivity, magnetic permeability, and the casing thickness. The method is based on accurate evaluation of magnetic fields near the transmitting loop in a steel-cased borehole, and the least squares inversion of thus measured data. The need to make measurements close to the source stems from the two related considerations. One reason is that by making measurements close to the transmitter we can keep the formation response from entering the measurement to a minimum. The other reason concerns with the practical consideration involved in fabricating a borehole tool. The measurement accuracy in terms of PPM to the primary field can best be achieved when the transmitter and receiver are close to each other. To facilitate this requirement we can consider a single loop acting as the source and the receiver operating in time domain, or a closely coupled frequency-domain system with the source-receiver separation of just a few inches apart. The highlights of this report are summarized below.

1) The resolution in inverted casing parameters is directly related to the data quality. Data quality may be determined by the number of effective numerical digits. For example, a 10 PPM accuracy can be achieved if the data is accurate to 5 digits.
2) Individual parameters can be resolved almost exactly if data quality is better than 10 PPM. If data quality is better than 100 PPM (4 digit accuracy), all parameters can be accurately resolved to 0.1%. The resolving power rapidly deteriorates if data quality becomes worse than 100 PPM resulting in an overall accuracy of 3% for individual parameters.
3) The useful frequency band is 1 Hz to 100 Hz.

An interesting result observed in case when the data quality is worse than 100 PPM is that the lumped parameter, square root of conductivity-permeability product times thickness, is accurately resolved to 0.2%. This result is very encouraging because the lumped parameter can be used to accurately eliminate the casing effect from the measurement obtained in a crosshole survey configuration. The lumped parameter plays a fundamental role in the wavefield transform methodology (Lee et al., 1994).

Introduction

It has been shown (Wilt et al., 1995; Alumbaugh and Newmann, 1996) that EM imaging, in particular in borehole applications, can be effective in characterizing and monitoring subsurface processes involved in improved oil recovery operations and production management. The measurement uses low-frequency EM fields, typically from 1 Hz to 10 kHz, to map the electrical conductivity of the formation between source and receiver arrays using single hole, surface-to-borehole, or crosshole configuration (Wilt et al., 1995; Tseng et al., 1995). Data from crosshole EM surveys are interpreted using inversion or tomographic methods (Torres and Habashy, 1993; Lee and Xie 1993).

Except for exploratory and fresh-drilled wells, however, almost all the wells in oil fields are cased with metal pipes. Carbon steel is most commonly used. EM signals undergo a severe attenuation and phase shift as they transmit across a casing. Augustin et al. (1989) and Wu and Habashy (1994) showed that the attenuation due to steel casing renders measurement above a few hundred hertz extremely difficult. Even at lower frequencies, the casing has much stronger effect on the measured responses than the formation does. The nonuniformity of casing material and remanent magnetization will further complicate data interpretation. Nevertheless, Becker et al. (1997) indicated that if the casing properties are independently known, then the formation signal can be accurately recovered.

Recently, some progresses have been made in understanding casing properties (Wu and Habashy, 1994; Wilt et al., 1996). Three properties of the casing are particularly important in evaluating and analyzing EM field behavior; electrical conductivity, magnetic permeability, and the thickness of the casing wall. This paper describes a methodology for evaluating these parameters using single-hole measurements.

Numerical Model

To study the effect of steel casing on formation signals, Wilt et al. (1996) and Becker et al. (1997) used a computer code described by Augustin et al. (1989) and lately modified by Uchida et al. (1991). It is based on an analytical solution for an axial dipole source in axisymmetric model. The evaluation of the resultant integrals, which are expressed as Fourier cosine transforms, is done numerically using the digital Hankel transform and Gaussian quadratures. The code "Cas4i" allows for the calculation of frequency-domain EM fields inside and outside a uniform conducting pipe in a homogeneous whole space, and was verified with scale models (Wilt et al., 1996; Becker et al., 1997).

To evaluate magnetic fields accurately in the immediate vicinity of the transmitter loop, we have developed a new Fortran code based the theory described by Augustin et al. (1989). The accuracy has been greatly improved by treating the primary field analytically

and by implementing the fast Fourier transform (FFT) in evaluating the secondary field instead of the digital Hankel transform method used in the 'Cas4i' code.

The computations were done for a single-hole case shown in Figure 1. It was assumed that the casing is uniform and infinite in length and is in the uniform whole space. A single loop is used as both the transmitter and the receiver. The current carrying loop has a radius of 5 cm and the inner casing radius is 10 cm. We used 1 Amp current in the loop, so the effective magnetic moment of the loop is 7.85×10^{-3} Amp-m^2. The conductivity of well fluid and formation are 0 and 0.01 S/m, respectively. Except for the casing material itself, the magnetic permeability elsewhere is equal to that of vacuum. Figures 2 through 4 show the secondary vertical magnetic fields (H_z) evaluated at the center of the transmitter loop in response to parameter variations as a function of frequency. Figure 2 shows changes in the magnetic field for varying casing thickness with fixed conductivity and permeability. The frequency band that is sensitive to the changes in the thickness is about 20 Hz. Beyond 20 Hz, there is no appreciable changes observed. If we keep the thickness and the magnetic permeability constant and change the electrical conductivity (Figure 3), there is strong sensitivity at all frequencies above 1 Hz. Lastly, when the conductivity and thickness are held constant, then even stronger sensitivity can be observed with varying permeability. Especially strong is in the real part of the magnetic field response over the entire frequency band examined. Above 10 Hz the effect of casing conductivity on H_z fields is nearly the same as that of magnetic permeability (Figures 3 and 4). Information gathered by analyzing responses shown in these figures provide a useful guide line in establishing strategy for developing an inversion scheme. A preliminary conclusion is that we should use a frequency band between 1 Hz and 100 Hz for optimum inversion result.

Recovery of Casing Parameters

Wu and Habashy (1994) inverted EM responses of the Helmholtz coil surrounding the casing to estimate the conductivity and the magnetic permeability of the casing. They showed that it was successful in resolving the two parameters if casing thickness is known a priori. However, an attempt to invert for the casing thickness as an extra-unknown parameter produced unsatisfactory results because of the lack of sensitivity in the measurement to the casing thickness (Wu and Habashy, 1994).

We have adopted a scheme consisting of measurements inside the casing to estimate casing properties. This method seems to be more realistic to use in the field environment. The transmitter and receiver are coaxial and separated vertically by a distance of 10 cm. The radius of the loop source is 2.54 cm (1 inch) and the inner casing radius is 6.36 cm (2.5 inches). Again, 1 Amp current is used in the loop with its effective magnetic moment of 2.03×10^{-3} Amp-m^2. The conductivity of well fluid, steel and formation are 0, 0.5×10^7 and 0.01 S/m, respectively. The relative magnetic permeability of the wall is 125, while the other media have those of the free space.

Data used for reconstructing the model parameters are H_z fields, and they have been sampled logarithmically at seven frequencies ranging from 1.25 to 80 Hz. We have used the Marquardt-Levenberg least-squares (LS) method to invert the H_z-field data (Kim et al., 1997). Once H_z fields for a theoretical model have been calculated, the following rms relative error, objective function, is used in the LS inversion as the objective function to be minimized,

$$E(\mathbf{m}) = \sqrt{\frac{1}{N}\sum_i \sum_j \left(\frac{f_{i,j}^O - f_{i,j}^C(\mathbf{m})}{f_{i,j}^O} \right)^2},$$

where f^O is the observed H_z fields, f^C is the H_z fields calculated for model $\mathbf{m}$, subscript i = 1 to 2 indicates the real and imaginary parts of the fields, subscript j = 1 to 7 indicates the sampling frequencies, and $N = 2 \times 7$ is the number of data. In the LS inversion we solved the system of resulting data misfit equations directly using Householder transformation without forming the normal equation.

Table 1 shows the selected frequencies (column 1), total magnetic fields generated by the new code (column 2), and data (column 3, 4, and 5) to be used for the inversion with varying number of effective digits. It can be safely assumed that the number of digits chosen to represent the data reflects the accuracy of the data in terms of PPM. Table 2 shows inversion results corresponding to the three different data sets shown in Table 1. It appears that individual parameters can be resolved almost exactly if data quality is better than 10 PPM. If data quality is better than 100 PPM (4 digit accuracy), all parameters can be accurately resolved to 0.1%. The resolving power is greatly reduced with data worse than 100 PPM accuracy, resulting in an overall accuracy of 3% for individual parameters. Note that although the resolutions of individual casing parameters are low, a lumped parameter $(\sigma\mu_r)^{1/2}d$ can be accurately evaluated (0.2%) within the noise level. This result is very encouraging because the lumped parameter is equivalent to the traveltime in q-domain analysis (Lee and Xie, 1993). In the imaging scheme using the traveltime tomography the parameter can be used to effectively remove the casing effect from data (Lee et al., 1994).

Future Work

The proof of concept demonstrated in this report may be verified by first making measurements in a steel casing, carrying out the inversion, and then evaluating the result by comparing with the parameters measured independently for the steel casing. In order to make such measurements, we consider two types of systems that can be deployed inside casing. One is the time-domain system (Figure 5), and the other is the frequency-domain system (Figure 6). The time-domain system allows the medium store EM energy in the form of magnetic energy while the current is on. When the current is turned off, this energy is released and the energy release is detected by the same loop in a transient form. The transient magnetic field is then Fourier transformed to provide the frequency

responses, which in turn will be used for extracting casing parameters following the method described in this report. The frequency-domain system is simpler than the first one, but it requires careful measurement because the measurement is made in the presence of the powerful primary field. If the transmitter-receiver separation is small, then there is an established technique to make this measurement extremely accurately using a bucking coil. Essentially, the bucking coil is located between the transmitter and the receiver, and acts as a secondary transmitter that effectively cancels out the primary field at the receiver position.

Once the casing property is known, we can back out the formation response based on the findings in which EM coupling between the casing and the formation is negligible (Becker et al., 1997). Using thus corrected data, various inversion approaches can be considered to map conductivity distributions between boreholes. One approach that has not been thoroughly tested is the wavefield transform (q-domain) approach. The basic idea of q-domain inversion is to 1) transform magnetic field data into pseudo-wave fields, 2) to compute travel times, and then 3) to use traveltime tomography to construct a conductivity distribution. Lee et al. (1994) formulated the problem in the frequency domain as an integral transform:

$$H(\omega) = \int_0^\infty e^{-\sqrt{i\omega}q} U(q) dq, \tag{1}$$

where $H(\omega)$ is the magnetic field and $U(q)$ is the fictitious wave field. Although Lee and Xie (1993) obtained a full waveform of $U(q)$ and used it for the imaging, only first arrivals of $U(q)$ is needed for traveltime tomography. Using the traveltime q, we can conduct the traveltime tomography for the velocity v_q and therefore conductivity imaging using the relationships

$$q = \sqrt{\sigma\mu} d, \quad \text{and} \quad v_q = \frac{1}{\sqrt{\sigma\mu}}, \tag{2}$$

where d represents the distance traveled by the wavefield.

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Wu, X., and Habashy, T.M., 1994, Influence of steel casings on electromagnetic signals. *Geophysics*, **59**, 378-390.

Table 1. Data used for inversion. Data accuracy is simulated by choosing appropriate number of digits for each inversion.

Frequency (Hz)	Data			
	Exact	6 digits	5 digits	4 digits
1.25	(.230111,-.169831e-2)	(.230111,-.169831e-2)	(.23011,-.16983e-2)	(.2301,-.1698e-2)
2.5	(.229802,-.334959e-2)	(.229802,-.334959e-2)	(.22980,-.33496e-2)	(.2298,-.3350e-2)
5.0	(.228666,-.635707e-1)	(.228666,-.635707e-1)	(.22867,-.63571e-1)	(.2287,-.6357e-1)
10.0	(.225255,-.107206e-1)	(.225255,-.107206e-1)	(.22526,-.10721e-1)	(.2253,-.1072e-1)
20.0	(.218761,-.143485e-1)	(.218761,-.143485e-1)	(.21876,-.14349e-1)	(.2188,-.1435e-1)
40.0	(.212169,-.162315e-1)	(.212169,-.162315e-1)	(.21217,-.16232e-1)	(.2122,-.1623e-1)
80.0	(.195715,-.264381e-1)	(.195715,-.264381e-1)	(.19572,-.26438e-1)	(.1957,-.2644e-1)
Error (ppm)		1 – 10	10 - 100	100 – 1,000

Table 2. Inversion for casing parameters. Vertical magnetic fields are sampled at 7 frequencies between 1.25 and 80 Hz. Transmitter-receiver separation is 10 cm. Three data sets with varying accuracy (Table 1) are used for the inversion.

Parameter	Given	Initial	Inversion		
			6 digits	5 digits	4 digits
σ (S/m)	0.5×10^7	1.0×10^7	0.5001×10^7	0.4997×10^7	0.4836×10^7
μ_r	125	100	125.0	124.9	120.9
d (cm)	0.62	1.0	0.6199	0.6202	0.6401
$(\sigma\mu)^{1/2}d$	0.1738	0.3545	0.1738	0.1737	0.1735
RMS error		0.7641×10^{-2}	0.2339×10^{-6}	0.1967×10^{-5}	0.1827×10^{-4}

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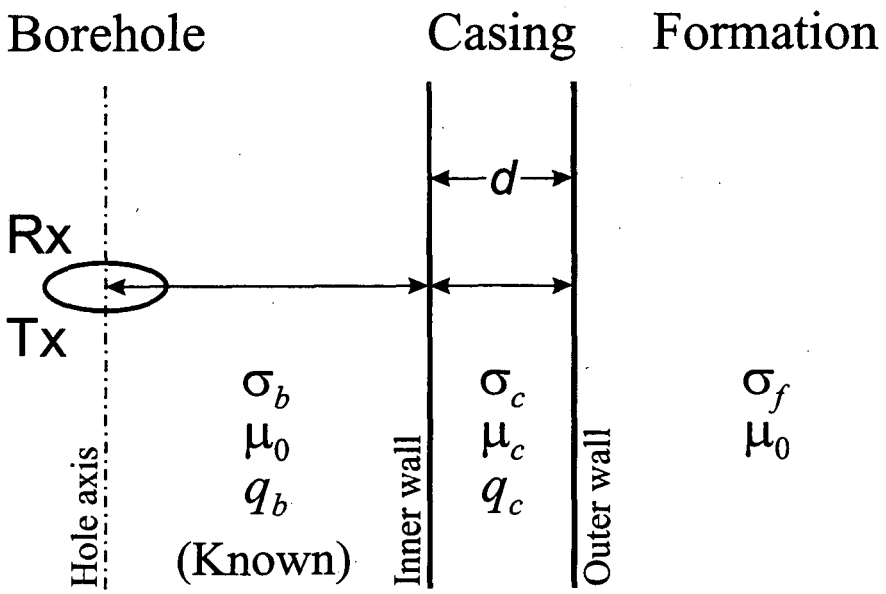


Figure 1. Single loop transmitter and receiver in steel cased borehole

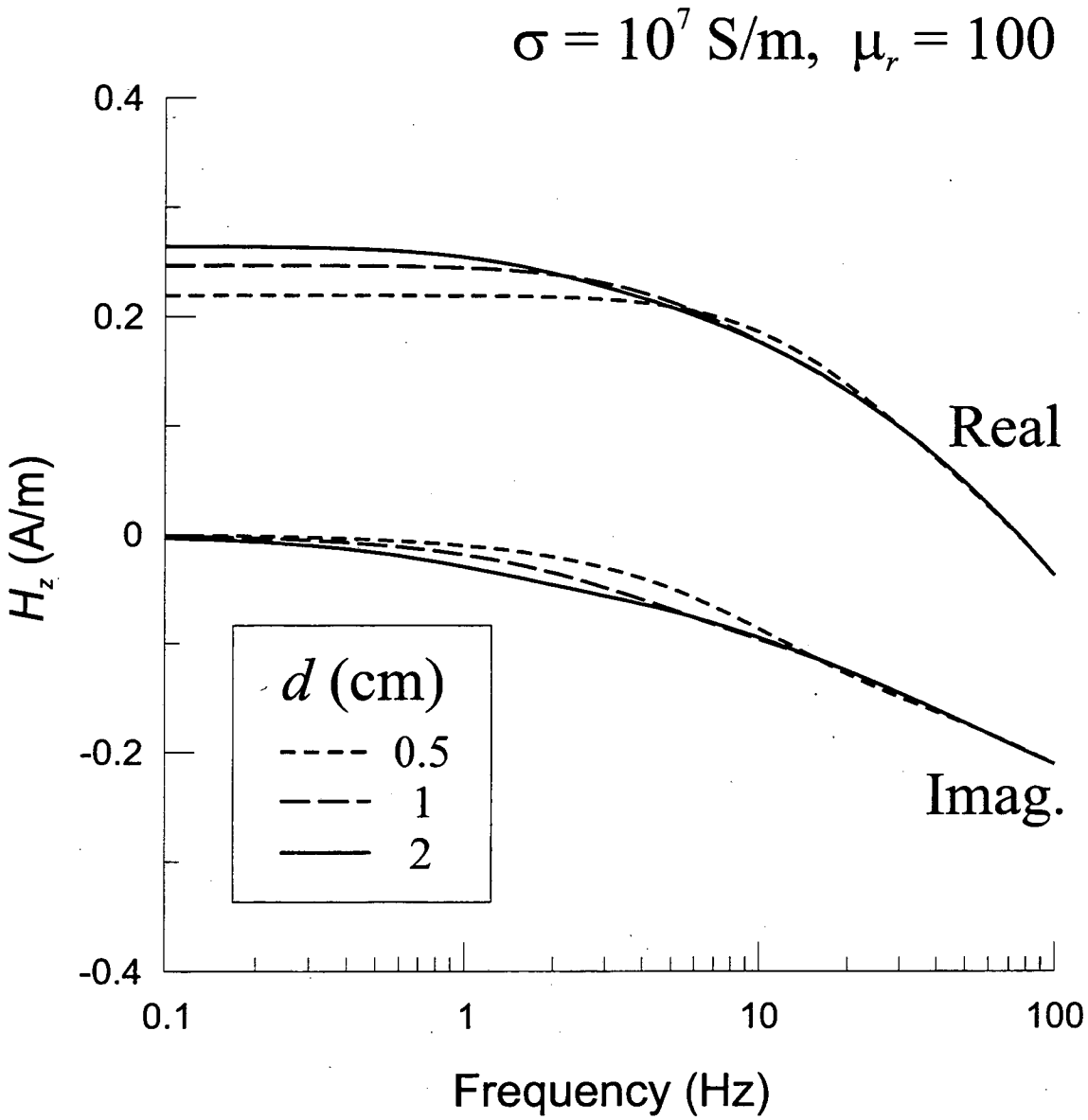


Figure 2. Vertical magnetic field measured at the center of the loop. Casing thickness is the variable

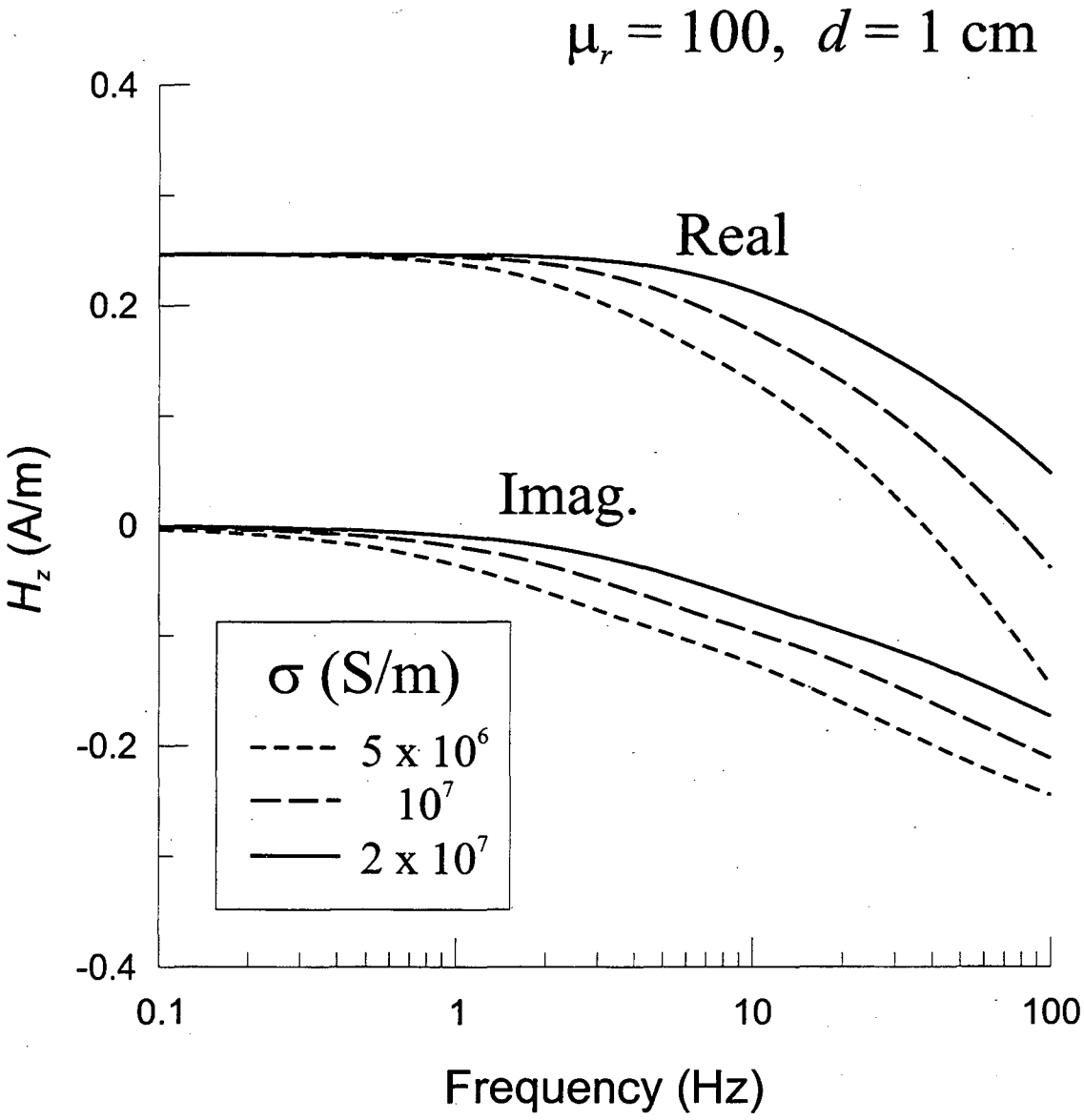


Figure 3. Vertical magnetic field measured at the center of the loop. Casing conductivity is the variable

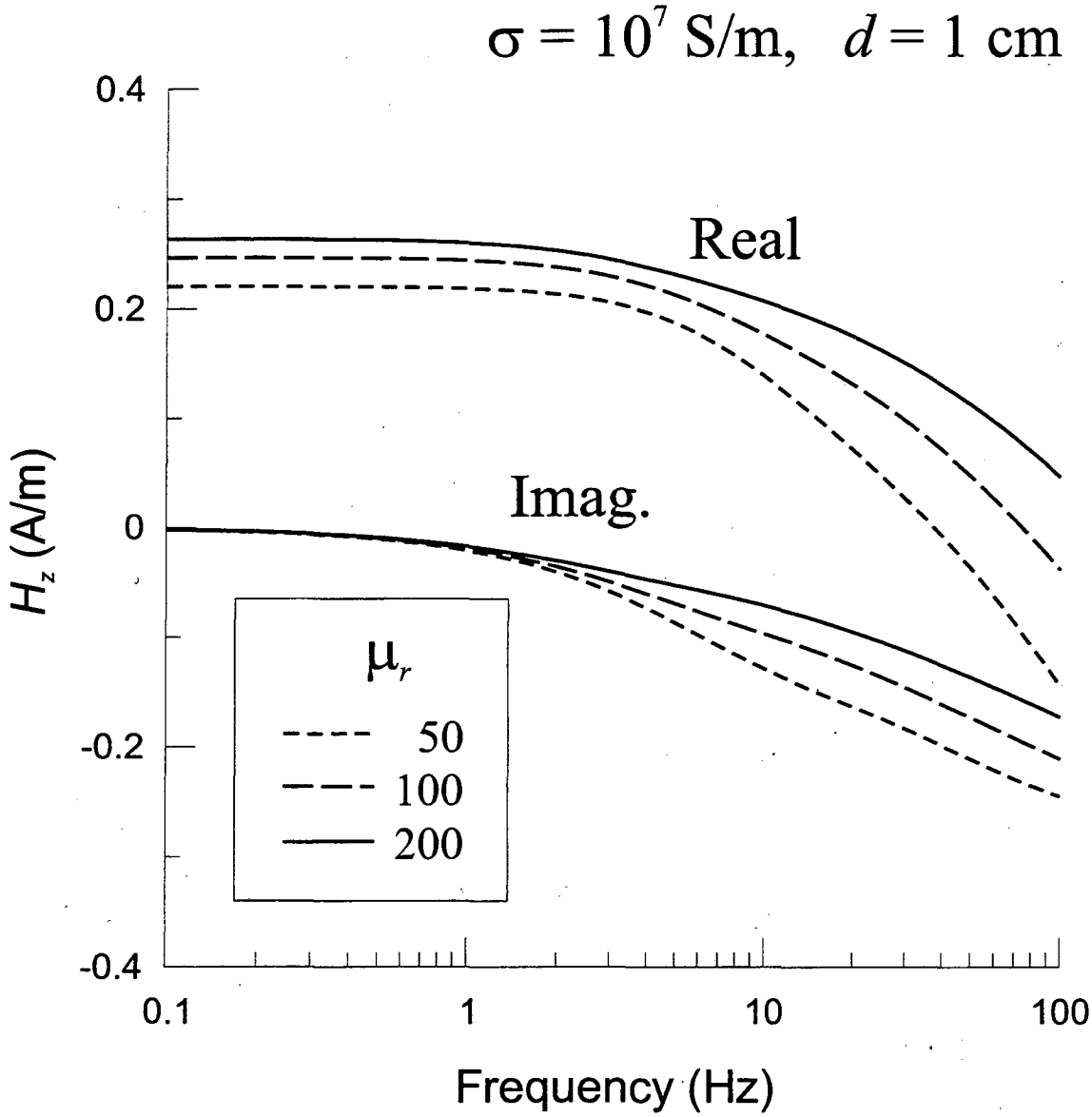


Figure 4. Vertical magnetic field measured at the center of the loop. Casing permeability is the variable

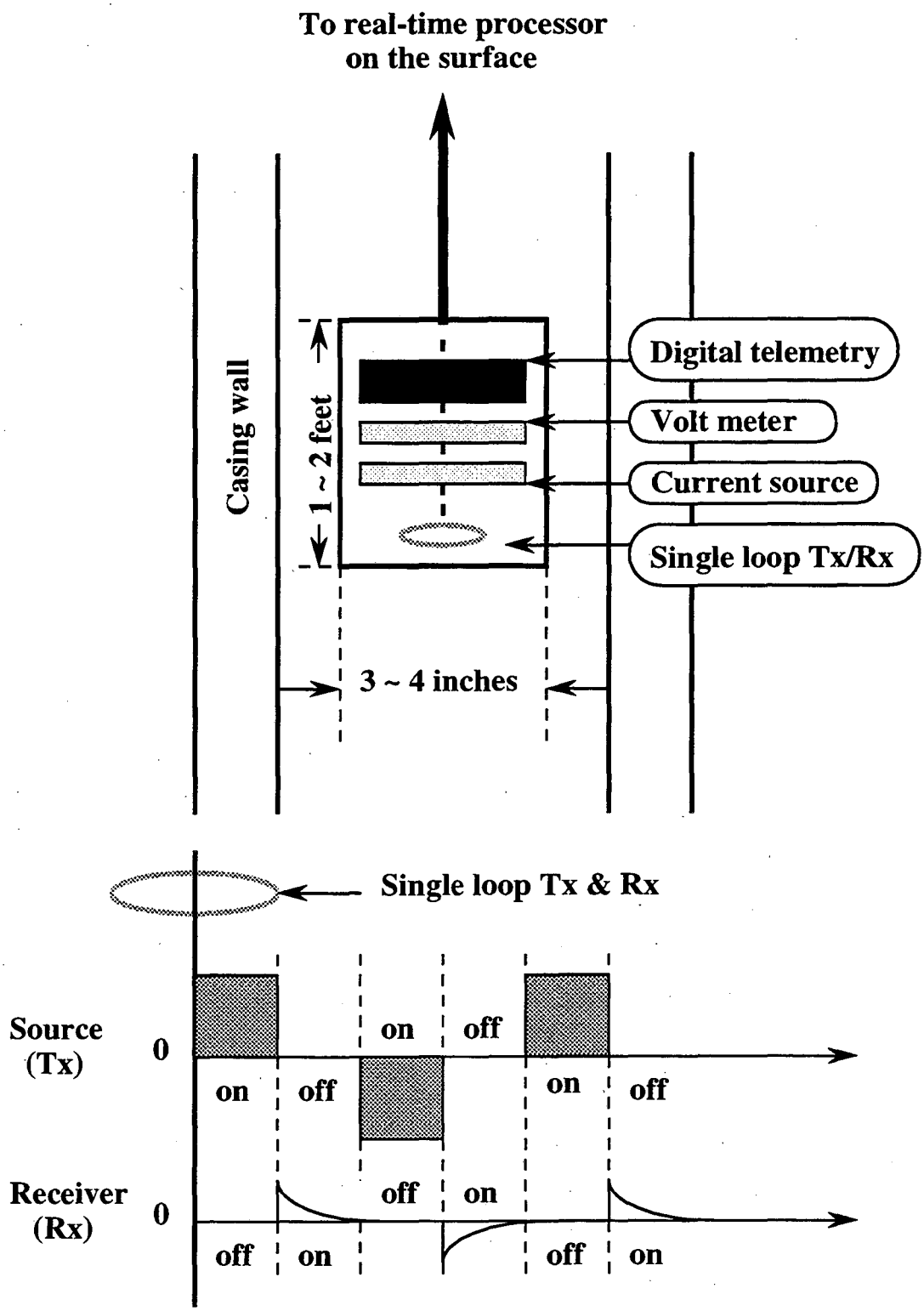
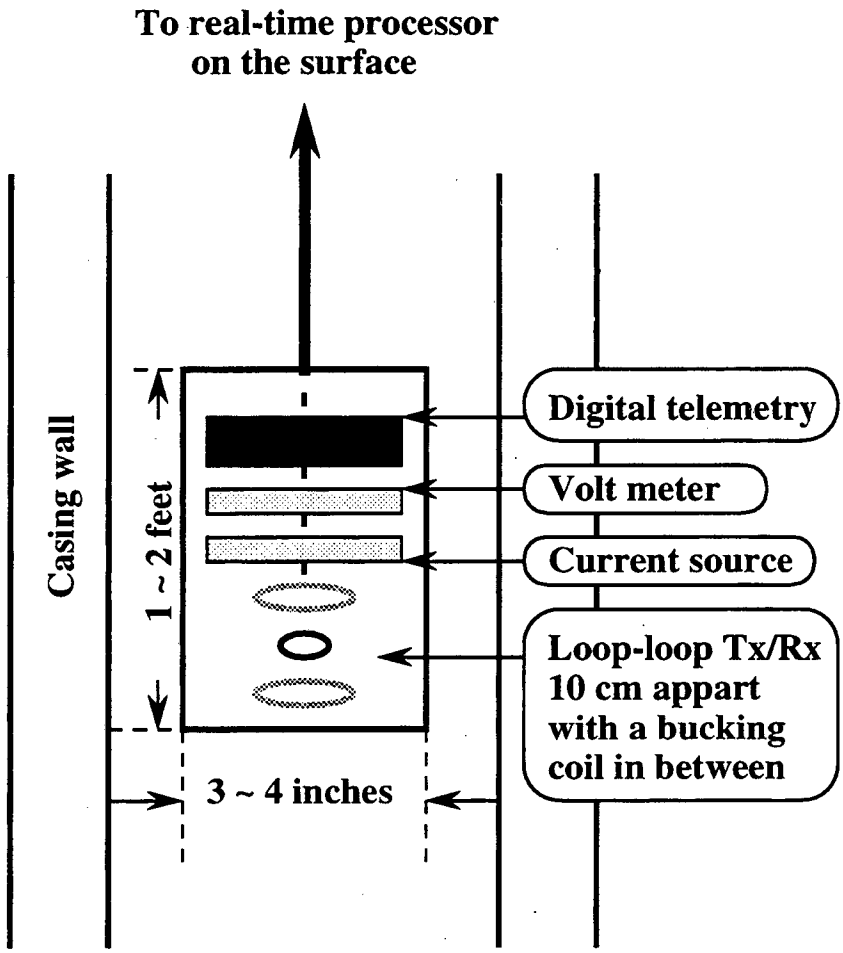


Figure 5. Time-domain electromagnetic tool for analyzing casing parameter



Frequency-domain system
7 frequencies between
1.25 Hz to 80 Hz

Figure 6. Frequency-domain electromagnetic tool for analyzing casing parameter

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