Subsurface Electromagnetic Measurement through Steel Casing

Alex Becker, Bing Wang, Ki Ha Lee, Lawrence Berkeley National Laboratory, and Mike Wilt, Lawrence Livermore National Laboratory

Summary

Numerical calculations show that useful information can be obtained in an electromagnetic crosswell survey where one of the wells is cased in steel. Our simple model is based on the assumption of an infinitely long uniform casing embedded in a homogenous full space. Nevertheless the results indicate that if the pipe characteristics are independently known then the formation signal can be accurately recovered. This is best done at a single frequency where the pipe attenuation is modest. In fact we show that the optimal frequency for formation signal recovery is defined mainly by the pipe parameters and is largely independent of the formation conductivity.

Introduction

This feasibility study of subsurface electromagnetic measurements is a direct outgrowth of our previous work in fiber cased wells. As previous reported by Wilt et al. (1995), we demonstrated the practicality and utility of interwell measurements on an oil field scale, at Devine, TX and at Lost Hills, CA. On a smaller scale, we carried out a demonstration of interwell and surface to borehole EM tomography with controlled experiments at the University of California Richmond Field Station (Tseng et al., 1995). Since virtually all oil wells are cased in steel, it was natural that our studies on interwell electromagnetic measurements were extended to situations where at least one well is cased in steel.

Results of previous theoretical work and numerical calculations by Augustin et al., (1989), Uchida et al., (1991) and Wu et al., (1994) all pointed to the possibility of extracting a formation signal from electromagnetic measurements through casing. In particular, the Augustin results showed that the casing acts as a strong low pass filter. The Wu paper demonstrated further that the signal attenuation process in the casing resembles the attenuation of a plane wave in a conductive medium so that the controlling factor is the ratio of the pipe thickness to the skin depth. Neither of these two studies considered the crosswell configuration and their results needed to be re-examined. Finally we note that while Uchida et al. suggested that interwell EM tomography was feasible they also indicated that the casing attenuation factor was to some degree a function of position of the external source. This last feature of signal transmission through casing was seen as a possible difficulty in interpreting signals filtered by the casing.

In this study we demonstrate that the formation signal can be accurately recovered from interwell electromagnetic data. To do this we examine the effects of a uniform casing, of infinite length, on the signal of an external dipole source sited directly in a homogenous conductive medium (whole space). At this stage of the work we must assume that the casing parameters are independently known from ancillary measurements made within the casing. The formation signal can be optimally detected by a careful choice of the measurement frequency range which is only determined by the casing parameters.

Numerical Computations

1). The numerical model

The data required for this study were generated with the "**Cas4i**" computer program written by Uchida et al., (1991). It is based on an analytical solution for an axial dipole source and cylindrically symmetric medium boundaries. The evaluation of the resultant integrals is done numerically. The theoretical background for the "**Cas4i**" code is virtually identical (except for source position) to the code used to generate the Augustin et al., (1989) data.

The computations are done for an "infinitely" long pipe located in a uniform, unbounded conductive medium. The computational parameters are illustrated in Figure 1. Here we have three regions for which the dimensions, the magnetic permeability and the electric conductivity can be specified. In the present case, for the numerical calculation we used a standard iron pipe model where the metal had a relative magnetic permeability of 100 and an electric conductivity of 10^6 S/m. The inner casing radius "b" is 10 cm and the pipe is 1 cm thick. The unit moment source radius "a" is 5.64 cm. The formation conductivity varies from 10 to 500 mS/m. Well fluid resistivity equals that of the formation. For the results shown here, the transmitter and receiver are coplanar. They are separated laterally by a distance of the order of 100 m.

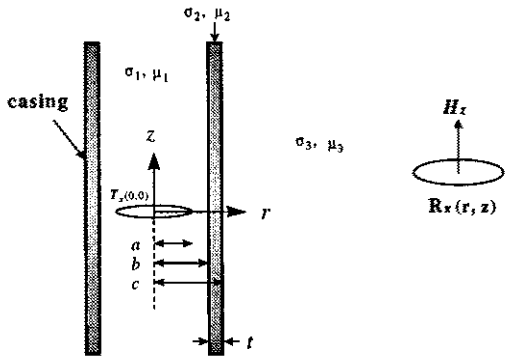

Fig. 1. Computational Parameters

2). Code Verification

Although the experimental results presented by Augustin et al., (1981) already confirmed the validity of the "Cas4i" code, it was thought prudent to verify the code for the source-receiver configuration of interest here. The tests were done in the laboratory on a 2.5 m length of common 3" OD iron pipe. Approximate measurements of the pipe parameters indicated a relative magnetic permeability of about 120 and an electrical conductivity of about 10^7 S/m. The pipe had an inner radius of 3.2 cm and a 0.5 cm thickness. The experimental arrangement is shown in Figure 2. The transmitter loop had an effective area of 0.53 m^2 carrying a current of about 2 A. The receiver was a Develco 9200c fluxgate magnetometer with a cut-off frequency well above the 10 ~ 500 Hz measurement range. The receiver and transmitter were coplanar and separated by a distance of 40 cm.

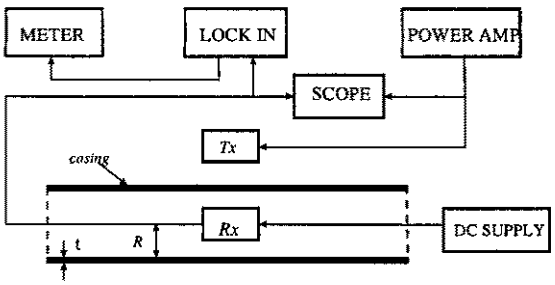

Fig. 2. Laboratory Experiment Setup

A single frequency test of the code involved a transmitter traverse outside the pipe. The traverse was parallel to the pipe axis at 40 cm radial distance from the receiver which was stationary within the pipe. The transmitter and receiver axes were parallel to the pipe length. The results for this test, that was done at 100 Hz are shown in Figure 3. Once again, within the limits of experimental error, we see good agreement between numerical and experimental data. More importantly however we note that the shape of the field strength variation is very similar to that which would be observed in free space.

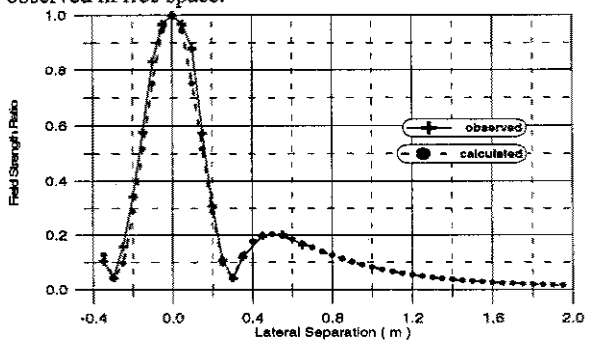

Fig. 3. 100 Hz Profile at 40 cm Radial Separation

Numerical Results

1). Attenuation and phase shift characteristics

Most of our numerical investigations were dedicated to a study of the casing transfer function for a receiver-transmitter system with axes parallel to the casing axis. Typical data for a common casing size and a coplanar receiver-transmitter are shown in Figure 4. Here we have a coplanar system with a one hundred meter receiver-transmitter separation and our standard casing model. For comparison purposes, we show , on the same scales, the pipe transfer function (i.e. free space response) and the filtered formation signal for a 0.1 S/m formation conductivity. As we have observed previously, the casing attenuation factor expressed in dB and the casing induced phase shift vary linearly with the casing induction parameter. The effect of the formation appears at a casing induction parameter value of 2.5 which corresponds to a frequency of about 20 Hz.

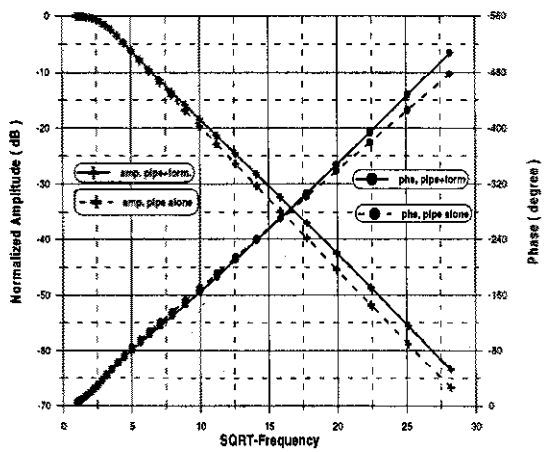

Fig. 4 Casing Transfer Function and Formation Signal

et al. Our findings for the free space effects of the casing used in the previous example, at 300 Hz, confirm the Uchida data which showed that the casing attenuation and phase shift characteristics exhibited limited spatial variability. In our example, the average casing attenuation factor is about 38.6 dB and varies by no more than about ± 1 dB or ± 12 % throughout the region of interest. The predominant phase shift is about 65°, but this can rise to nearly 90° or fall below 50° in regions very close to the source.

2). Recovery of formation signal

It is our contention that the formation signal can be recovered if the transfer function for the casing is known. To demonstrate this point, let us again consider the data shown in Figure 4. If the proposition is true, then one can simply obtain the formation signal by taking the formation plus casing data, and correcting it for the attenuation and phase shift attributable to the casing. The phase correction simply involves a subtraction of the "free space" casing related phase shift from the simulated "observed" phase shift for the casing in the formation. Similarly, the formation signal is obtained by taking the "observed" casing in formation signal and dividing it by the casing attenuation factor for the primary, "free space" field. We found that the formation signal phase and amplitude can be recovered to better than a few millidegrees and 1%.

Choice of Optimal Frequency

In the foregoing discussion, we made no distinction between the primary "free space" transmitter field and the secondary field related directly to the eddy currents in the formation, but considered the sum of the two as the formation signal. However in order to demonstrate the existence of an optimal frequency range for the proposed interwell measurements through casing, let us consider the eddy current contribution alone. The pertinent data are displayed in Figure 5, where for our standard test pipe, we show the attenuation characteristic and the secondary field for a 0.1 S/m formation and coplanar coils at a 100 m separation. If we ignore the inductive coupling, the observable formation signal is simply as the product of the last two quantities. Under the present circumstances, it exhibits a broad peak at about 20 Hz. A more striking presentation of this phenomenon can be made by normalizing the filtered formation signal by the free space transmitter field at the receiver position and plotting the data in log-linear form. This is done in Figure 6 for a number of different formation conductivity values including the 0.1 S/m value considered in the previous illustration. The coplanar configuration and the 100 m spacing is maintained for all four cases.

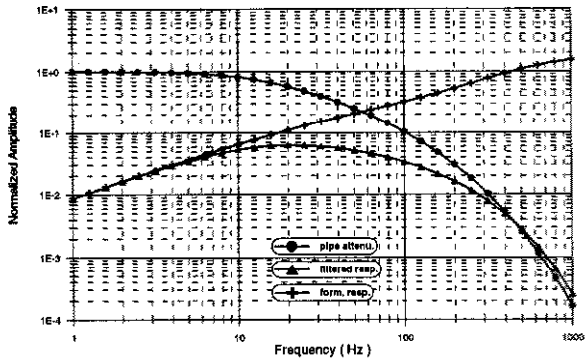

Fig. 5. Filtered Formation Signal

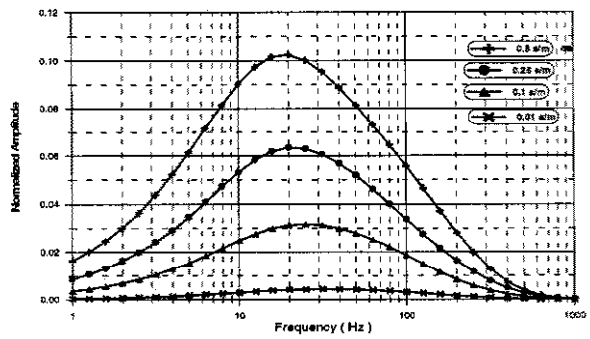

Fig. 6. Optimal Response

We note that while the amplitude of the optimal filtered formation signal varies smoothly with the formation conductivity from less than 1% of the free space primary field for the 0.01 S/m formation to more than 10% for the 0.5 S/m formation, the optimal response frequency remains nearly invariant at about 20 Hz. It then appears that the optimal frequency must be a function of the pipe parameter only.

This phenomenon can be qualitatively explained if we admit a number of approximations to the discussion.

Assume that the pipe attenuation function is given by

$$\alpha = e^{-p}$$

where p is pipe induction parameter which equals to pipe thickness/skindepth in pipe.

Further assume that the formation signal is given by

$$s = 2q^2$$

where q is formation induction number and equals to coil separation / skindepth in formation.

The filtered signal is then given by

$$F = s\alpha = 2q^2 e^{-p}$$

it can be readily shown that $q^2 = cp^2$

where $c = \left(\frac{r}{t}\right)^2 \frac{\sigma_f}{\mu_r \sigma_p}$

here:
r: coil separation.
t: pipe thickness,
μ_r: relative pipe permeability
σ_f: formation conductivity,
σ_p: pipe conductivity.

We then have

$$F = 2cp^2 e^{-p}$$

this function has a well defined maximum at p=2 as observed previously, the corresponding optimal frequency is only a function of pipe parameters and occurs at the point where the pipe exhibits about 14 dB of attenuation.

It must be immediately reiterated that the argument presented above is only as good as the approximations and would lead to an optimal survey frequency of about 50 Hz for the stated pipe parameter whereas the numerical data for the parameters used to generate the Figure 5 results indicate an optimal frequency half as big. The answer to this paradox lies in noting that the formation signal shown in Figure 5 rises as $f^{2/3}$ (f is frequency) instead of f as assumed the argument above. So that

$$F = cp^{4/3} e^{-p}$$

with an optimal value of p=4/3 which corresponds to an optimal frequency of about 23 Hz as observed.

Conclusions

Reviewing the numerical and experimental results, we are very optimistic that our goal of developing a technology for subsurface measurements through casing and the needed data interpretation methods can be reached. Realistically, we expect to do this within two years of further research effect. As we have stated above, the results of our work indicate that

1). Field scale measurements through casing can be made.
2). Numerical data confirm our hypothesis that the formation signal can be detected through a steel casing and can be uniquely extracted from the measured data, if the physical properties of the casing are known or can be accurately established.

Acknowledgments

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References

Augustin, A.M., Kennedy, W.D., Morrison, H.F., and Lee, K. H., 1989, A theoretical study of surface to borehole electromagnetic logging in cased holes: Geophysics, 54,90~99.

Kaufman, Alexander, 1992, Geophysical field theory and methods. Academic Press.

Tseng, H.W., Becher, A., Wilt, M.J., and Deszcz-Pan, M., 1995, A borehole-to-surface electromagnetic survey. SEG, Expanded Abstracts, EM 1.6. 65th Annual International Meeting.

Uchida, T., Lee, K.H., and Wilt, M.J., 1991, Effect of a steel casing on crosshole EM measurement. SEG, Expanded Abstracts, EM2.6. 61st Annual International Meeting.

Wilt, M.J., Lee, K.H., Becker, A., Spies, B., and Wang, B. 1996, Crosshole EM in steel-cased boreholes. SEG, Expanded Abstract, EM1.5. 66th Annual International Meeting.

Wilt, M.J., Alumbaugh, D.L., Morrison, H.F., Becker, A., Lee, K.H., and Deszcz-Pan, D. , 1995, Crosswell electromagnetic tomography: System design considerations and field results: Geophysics, 60, 871-885.

Wu, Xu and Habashy, T.M., 1994, Influence of the steel casings on electromagnetic signals: Geophysics, 59, 378~390.