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EVALUATION AND DESIGN OF A LARGE SPACING LOOP-LOOP ELECTROMAGNETIC TOOL

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MASTER

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ABSTRACT

This paper investigates the potential use of a large spacing loop-loop electromagnetic logging tool to detect resistivity anomalies as far as 25 meters away from the borehole wall. A three-dimensional whole space electromagnetic modelling code was used to evaluate the responses of such a tool to various transmitter and receiver loop orientations, operating frequencies, loop spacings, resistivity contrasts, anomaly sizes and anomaly distances. Anomalies were modeled as finite extent sheets of various thicknesses which terminated before intersecting the borehole wall. It was found that both coplanar and coaxial loop orientations provide strong anomaly responses, but the coaxial loop orientation has superior depth penetration and is a less complex tool to design and build. For such a coaxial tool, anomalies could be detected as far from the borehole wall as half the loop spacing. For rock resistivities on the order of 100 ohm-m, contrasts greater than 2:1 and loop spacings of 75 meters the optimal operating frequency is shown to be 10 kHz. At these loop spacings, anomalies must be thicker than 10 meters to be detected. It is further shown that for coaxial loops the nature of the response curves allows one to estimate the distance of an anomaly from the borehole wall although no angular location is possible.

A coaxial loop-loop electromagnetic tool design that is currently being built is presented. This tool provides for a downhole power supply to a transmitter loop with a magnetic moment between 100 and 1000 A/m^2 that is electrically isolated via a fiber optic link from the variably spaced receiver located above. Signal detection is provided by a high sensitivity lock-in amplifier. The errors are conservatively estimated for this design at 5%. Thus anomalies resulting in a secondary field less than 5% of the primary transmitted field are deemed undetectable.

1. INTRODUCTION

Clay zones in the vicinity of an underground nuclear test can result in zones of mechanical weakness and provide a possible escape mechanism for the nuclear test gases. Clay zones whose closest point is 35 m from the borehole can be of significant concern. It therefore is of great importance to nuclear test containment to know if any clay zones exist in the borehole vicinity, in particular, to be able to detect clay zones that "pinch out" before reaching the borehole.

Present induction logging tools create a magnetic field that penetrates deeper into the formation than the magnetic field of a single coil. The transmitter-receiver spacing, however, is generally on the order of one meter and hence the radius of investigation is limited to about 3 meters. Within 3 meters of the borehole, clay zones could well be detected with current resistivity or induction logging tools. Beyond the 3 meter range however, present tools are inadequate. To detect clay zones pinching out as far as 35 meters from the borehole a new logging tool must be designed. This tool must also operate within the large (3 meter) diameter holes used in nuclear test containment.

Sweeney and Harben (1985) considered the usefulness of applying a large spacing dipole-dipole resistivity tool to detect clay zones in the vicinity of the borehole. The modelling results demonstrate that with certain minimum limitations on the size, resistivity contrast, and lateral distance from the borehole, clay zones can indeed be detected. The physical design of such a large spacing dipole-dipole resistivity tool for the large (3-4 meters) diameter holes presents a major problem: the mechanism for making good electrical contact with the borehole wall. A way to circumvent the electrical contact design problem is to use electromagnetic methods.

This paper presents the analysis and design of a loop-loop large spacing downhole electromagnetic tool for detection of clay zones within a tuff and alluvium matrix. First, a brief background on surface loop-loop electromagnetic methods will be given followed by a section on source and receiver loop orientation. Next a discussion on measurement sensitivity will be presented followed by the modelling strategy used. The computer modelling results follow. The specific design of the tool is then discussed followed by a brief conclusion.

2. BACKGROUND

Portable loop-loop electromagnetic prospecting techniques have been popular since about 1958. In almost all portable loop-loop systems the transmitter loop and receiver loop are about the same size with the plane of the loops oriented in the horizontal plane (see Fig. 1). Both transmitter and receiver are moved, and a fixed spacing is maintained between them (100-300 ft.). The receiver is oriented so that the primary transmitted field, the direct unperturbed field, is measured along with the desired secondary field which is due to the target anomaly. To cancel the primary field at the receiver, a reference coil attached to the transmitter coil is connected to a compensator which is connected in series with and opposing the receiver coil. The compensator is adjusted on barren ground to cancel both amplitude and phase of the primary field at the receiver. The receiver measures both in-phase and quadrature components of the secondary field usually as a percent of the primary field. The sensitivity of such systems (percentage of secondary field to primary field) is 1-2%.

To conduct a horizontal loop survey the distance between the loop is fixed by a cable. The compensator is then adjusted to cancel the primary field. Two workers, one at each coil move along lines perpendicular to geologic strike. Readings of both in-phase and quadrature components are recorded.

3. LOOP ORIENTATION

In conducting a downhole loop-loop electromagnetic survey, the transmitter and receiver loop must maintain a fixed orientation and spacing with respect to one another during the survey. One can choose several possible orientations in fixing the loop-loop geometry. For simplicity and ease in data interpretation, loops are either null coupled (planes of the loop perpendicular) or full coupled (coaxial or coplanar loops) as shown in Fig. 2.

Null coupled loops have the advantage of eliminating the primary field at the receiver. This is because the primary magnetic field flux runs parallel to the plane of the receiver loop in a full space. The secondary field, due to the anomaly, does not generally run in the direction of the primary. Hence some of the field flux passes through the plane of the receiver loop and generates a current that can be measured. It would appear this is the best way to orient loops but due to several difficulties it is in fact not usually done. The chief difficulty is maintaining the loops in a null coupled geometry. Slight errors, of say 10° in the orientation allows 17% of the primary field flux to pass through the receiver loop. This gives an erroneous indication of a sizable secondary anomaly field. Furthermore, coupling of the primary field through the receiver cable can occur, again giving an erroneous indication of the presence of a secondary magnetic field. Consequently null coupled loops were not considered here.

Full coupled loops require the large primary field component at the receiver be cancelled. This is accomplished by using a reference coil and a compensator as discussed earlier. A further advantage of using a compensator is that it also bucks any cable coupling. Full coupled loops in a borehole electromagnetic prospecting system either have the transmitter and receiver coil axis coincident with the borehole axis (coaxial) or the transmitter and receiver loop are contained in the same plane with axes perpendicular to the borehole axis (coplanar).

Coaxial loops provide no possibility of angular resolution of an anomalous body. However, depth and distance from the borehole are determinable. The advantage of coaxial loops lies in the simplicity of the orientation and independence of the response of the two loops to angular position or rotation within the borehole.

Coplanar loops do allow for some possibility of angular resolution as well as depth and lateral distance determinations. When the anomaly is located on one side of the loops, however, very little secondary field is detected hence the downhole orientation of the loops must be tracked, and readings taken at several angular positions, to provide assurance of anomaly discrimination over a full 360°.

Since coaxial and coplanar loops offer relative advantages and disadvantages both orientations have been considered in the modelling to follow.

4. MEASUREMENT SENSITIVITY

The magnetic moment of a coil, M, is defined by

$$M = nIA$$

where n is the number of windings, I is the current and A is the loop area. It is clear that increasing any of the right hand quantities increases M and this increases both primary and secondary fields by that factor. Commercial manufacturers of loop-loop electromagnetic systems use small portable battery operated transmitter units with the coil magnetic moment around 100 amp-m^2. A downhole unit can be designed to use a much larger current source, provided care is taken to match the transmitter impedance with the coil inductance (often this is done by a series resonating capacitor). For the loop spacings, optimum frequency and resistivity contrasts expected in containment applications, we would expect primary fields to be on the order of 10^{-4}-10^{-5} amps/meter and secondary fields to be on the order of 10^{-5}-10^{-6} amps/meter.

The lowest detectable magnetic fields at the receiver coil is on the order of 10^{-7} amps/meter. This assumes the use of a low noise lock-in amplifier. A receiver (coil and amplifier) with a sensitivity of 10^{-7} amps/meter is still well below the level of the secondary fields expected. At these magnetic field levels most manufacturers claim that a secondary field of 1 to 2% that of the primary can be detected with a compensating type system.The natural electromagnetic noise field was monitored by Maxwell & Stone (1963) in several U.S. locations, times of day, and seasons. Within the frequency band of 10-100 kHz the peak magnitude of the magnetic field is always below 10^{-7} - amps/meter. At the frequency range of interest the open borehole is not "seen" by the magnetic field due to the large wavelength relative to the borehole diameter. Furthermore, this field rapidly attenuates with depth such that at 700 meters the peak magnetic field noise is below 10^{-11} - amps/meter. We conclude the natural magnetic noise field will not be a concern in a downhole loop-loop electromagnetic system.

The primary source of error in a loop-loop system occurs from slight errors in both the spacing of the coils and the orientation of the coils. For a coplanar loop-loop orientation of 60 meters separation, decreasing that distance by slightly over 1 meter can produce an apparent in-phase anomaly of 6% [Telford et al. 1980]. A relative tilt of 10° between the two loops can cause an in-phase apparent anomaly of 1.5%. A coaxial loop-loop orientation gives similar results. In designing a loop-loop system it is critical to maintain correct coil separation and orientation. By rigidly mounting the coils to a sectioned structure the spacing should conservatively be maintainable to within 1/2 a meter and 10° tilt error tolerances.

The expected noise level on the recorded data results from errors in transmitter/receiver electronics, loop spacing, and loop orientation. Transmitter/receiver electronics limit commercially manufactured equipment to error bounds of 2%. Loop spacing, when maintained within 1/2 a meter, accounts for up to 1.5% error and orientation, when maintained to within 10°, accounts for 1.5% error. A conservative estimate on the total error in a downhole loop-loop system is 5%. Hence secondary fields less than 5% of the primary field are assumed to be within the error inherent in the system.

5. COMPUTER MODELLING

The computer code used for analyzing the models discussed in this paper is called CAVPH and was written by Clyde Dease of LLNL. It has been tested and found to agree with known analytical solutions. The program assumes a whole space three dimensional geometry of uniform magnetic permeability, resistivity and dielectric constant. Within this space, regions of different resistivity and/or dielectric constant are modelled as a collection of cubes. For the resistivities and frequencies of interest to this application, conduction currents completely dominate displacement currents, so variations in dielectric constant does not effect the modelled results. Throughout the models, a dielectric constant of 10 is used, a typical value for the unsaturated tuff and alluvium found in the expected area of use.

CAVPH calculates the primary electric and magnetic fields at the receiving position as well as the total scattered or secondary field arising from the anomalous body. Each cube making up the anomaly is calculated as an individual scatterer with the origin at the center of the cube. Results from all cubes are then vectorally summed to give the resultant secondary electric and magnetic field at the receiver position. It should be recognized that the magnitude of the secondary field is slightly smaller in magnitude than reality since the code calculates the secondary field from the cube center. This means that all modelled results are conservative estimates of the response one would actually measure in the field. Furthermore, magnetic sources are modelled as a magnetic dipole with a moment of unity.

Two anomaly models were analyzed. In both cases the purpose was to approximate a layer of low resistivity clay in a uniform matrix that terminates or "pinches out" before intersecting the borehole. Both models consisted of 25 meter cubes 4 deep in the x and y direction and centered 25 meters from the borehole. In one model (see Fig. 3) two such layers were used centered about the Z=0 reference making the anomaly 50 meters thick in the Z direction. The other model consists of only one layer centered about the Z=0 reference level, making the anomaly 25 meters thick. It should be noted that restricting the x and y dimensions of the anomaly is required by the computer code and leads to conservative estimates of the secondary field response from a true semi-infinite layer.

In running a model the receiver is positioned one loop-spacing below the transmitter loop. The transmitter loop is positioned 100 meters below the Z=0 reference level and the system is moved upwards in 5 meter increments until the transmitter is 100 meters above the Z=0 reference level. Each reading is plotted at the midpoint between the transmitter and receiver. The readings plotted are the real and imaginary (in-phase and quadrature) components of the complex ratio of the secondary field to the primary field. In an actual field tool these quantities would be read directly from the receiver. The curves are plotted as in a borehole log, with the x axis as a fraction of the secondary-to-primary-field and the y axis as depth in the borehole.

6. MODELLING RESULTS

In Fig. 4 we see how varying the frequency of the transmitter loop affects the response with coplanar loops. The first column of curves is the real part of the complex ratio of the secondary to primary field while the second column is the imaginary part of the ratio. The 50 m thick anomaly is centered at Z=0 and has a resistivity of 5 Ω-m while the surrounding medium has a resistivity of 100 Ω-m (a 20:1 contrast). The anomaly terminates 25 meters from the borehole. With a coplanar transmitter-receiver separation fixed at 100 meters, the effect of frequency on response is isolated. In the top row the frequency is 1 kHz and the response is small. The response of the real part is less than 5% over the anomaly and the imaginary part is 8%, just above our detectability limits. This is to be expected at low frequencies when the wavelength is so large as to not "see" an anomaly of only 50 meters thickness. The second row shows the results when the transmitter is operated at 10 kHz. The real response is 23%, far above our detectability limits. Furthermore, the peak is centered about the anomaly with a full width at half maximum (FWHM) of 70 meters, on the order of the anomaly thickness. Thus, we see a strong real part response and good vertical resolution at this frequency. The third row shows the results for 50 kHz and the bottom row shows the results at 100 kHz. In both cases we see a marked reduction in the real response and a 10-12% imaginary response. Most significantly, at higher frequencies the skin depth decreases to the point of significantly reducing the magnitude of the secondary magnetic field. Since detectability requires the field ratio to be above 5% and the absolute magnitude of the secondary field to be above 10^{-7}amps/meter, it is important to operate at a low enough frequency to assure a detectable secondary field. Figure 5 shows the change in the peak magnitude of the secondary field with frequency for coplanar and coaxial loops. The coplanar loop curve peaks around 10 kHz and drops off by an order of magnitude by 100 kHz. We conclude that for the coplanar loops the maximum anomaly response occurs at about 10 kHz and the magnitude of the secondary field is at a maximum also. Consequently the optimum transmitter operating frequency for these anomalies is 10 kHz.

Figure 6 shows the same model and parameters as Fig. 4 except the loops are oriented coaxially. There is little response at the low frequency of 1 kHz as expected. At 10 kHz there is a large real response over the anomaly of 18% and an imaginary response of 10%. The FWHM of the real response is 120 m making the vertical resolution significantly less than that for the coplanar orientation. The peak, however, is centered at the midpoint of the anomaly. Furthermore, the broad nature of the anomaly means the loops are "sensing" the anomaly well before and after straddling it. This allows one to gain information on anomalies nearer the borehole bottom with a coaxial loop orientation. At 50 kHz and 100 kHz the real response increases significantly while the imaginary response changes in sign. It would appear that a higher operating frequency would be desirable; however, referring back to Fig. 5, we see the magnitude of the secondary field is greater for 10 kHz, thereby improving the signal-to-noise ratio. This curve peaks at 10 kHz as the coplanar loop curve does. The conclusion is that for coaxial loops the optimum frequency of operation is also 10 kHz.

Although angular rotation of coaxial loops about the borehole axis can have no significant effect on the measurement results, angular rotation of coplanar loops can. The results shown in Fig. 4 were those for coplanar loops with the loop axis pointing at the anomaly. When the coplanar loops are rotated such that the loop axes point 90° from the anomaly, there is no significant response. Unlike the coaxial loops, coplanar loops can give some indication of the angular location of an anomalous body, however, this means coplanar loops must be rotated within the borehole to known angles and readings taken at several angles to assure 360° sensing for anomalous bodies. This is a significant complication for the tool design.

Transmitter-receiver separations were varied for both coplanar and coaxial loops at 10 kHz with all other quantities fixed as in Fig. 4. For coplanar loops the peak real response decreases from 23% at 100 meter separation to 13% at 75 meter separation. The response is not detectable at 50 meter separation. Furthermore, the Full Width At Half Maximum (FWHM) decreases from 70 meters to 50 meters as the spacing changes from 100 meters to 75 meters. For coaxial loops (see Fig. 7) the real response only decreases from 18% to 16% as the spacing is changed from 100 m to 75 m. For this spacing change the FWHM decreases from 120 m to 100 m, about the same as the coplanar loops. At 50 m spacing, however, the coaxial loops still give a detectable response of 9% with the FWHM decreasing to 80 m. The conclusion is that the coaxial loops probe deeper for a given spacing than the coplanar loops. A rule of thumb is that the loop spacing should be more than twice the distance you wish to probe. It should be noted that too large a loop spacing results in a weak signal at the receiver and poor vertical resolution of an anomaly. By adjusting the spacing, the distance of the anomaly from the borehole can be estimated.

The effect of a conductivity contrast was modelled for coplanar loops with a fixed 100 m separation at 10 kHz. The peak response of the real (in phase) part decreases from 23% to 13% as the contrast goes from 20:1 to 5:1. At 2:1 contrast the response is not at detectable levels. An important point is that the FWHM of the curves does not change with contrast. We conclude that contrast changes affect the peak response but not the shape or extent of the curve.

Figure 8 is the result for coaxial loops when the thickness of the anomaly is halved to 25 meters. In all cases the resistivity contrast is 20:1 and the frequency is 10 kHz. Coplanar results show the effect of reducing the transmitter-receiver spacing from 100 m to 75 m and to 50 meters. The peak real response decreases from 17% to 10% to below detectability. The FWHM decreases from 60 m to 45 m when the spacing changes from 100 m to 75 m. The result for the 50 m thick anomaly with coplanar loops was a FWHM of 70 m for 100 m spacing and 50 m for 75 m spacing. Thus although the FWHM of the response decreases with a decreasing anomaly thickness, the FWHM is more strongly affected by the loop spacing chosen. Therefore, to estimate anomaly thickness, an accurate series of master curves must be generated for different loop spacings and anomaly thicknesses to compare to an actual field result. The coaxial results show a peak response of the real part of 15% for 100 m spacing, 13% for a 75 m spacing and 8% for a 50 m spacing when the anomaly is 25 m thick. The FWHM goes from 110 m to 90 m to 60 m as the spacing is decreased. As in the coplanar case, the FWHM is more strongly affected by spacing than anomaly thickness. The coaxial real response remains detectable at 50 m separation for a 25 m thick anomaly.

Figure 9 summarizes the peak responses of the real part for both coplanar and coaxial loops as the loop spacing changes. Curves are for both the 50 m thick anomaly and the 25 m thick anomaly. The results show the real response of the coaxial loops to be slightly less than that of the coplanar loops for large separations. For smaller separations the coaxial loops provide a larger real response than the coplanar loops and hence provide a detectable response at smaller separations than the coplanar loops.

7. TOOL DESIGN

The design of a large-spacing, large-hole loop-loop electromagnetic logging tool is complete and the tool is currently being built. A coaxial loop-loop tool was chosen as a "first cut" since there is no need to be concerned with angular orientation within the borehole as in a coplanar system. The tool is designed so that the loops are coaxial thereby sensing a full 360° but without angular discrimination. The transmitter and receiver coil are identical, both 50 turn loops 6 feet in diameter. The transmitter coil is the lower loop and is powered from a downhole source. A fiber optic link connects it to the upper loop, the receiver coil. This link provides the phase of the transmitter current to the receiver. The receiver coil connects to a coaxial cable running to the surface. On the surface a lock-in amplifier is used to read the in-phase and out-of-phase secondary field. A schematic of the tool is seen in Fig. 10.

The transmitter coil is driven by a downhole gel cell powering a Class E high-efficiency tuned power oscillator (Ebert et al., 1981). A changeable series resonating capacitor bank allows the power oscillator to resonate at 10 or 50 kHz. This design guarantees that the transmitter is always operating at the resonant frequency of the series coil/capacitor circuit which results in the maximum current, despite slight drifts in the components due to temperature. Although the output frequency of the oscillator will change a few percent with the drifting resistance and capacitance this has negligible effect on the primary transmitted field or secondary induction fields. The transmitter coil current is monitored by the surface lock-in amplifier via the fiber optic and coaxial cable link. The transmitter coil is designed to operate at currents as high as 8 amps thereby generating a magnetic moment up to 1000 amp/m^2.

The receiver coil signal is passed through a downhole pre-amplifier before being sent up the coaxial cable to the surface. A lock-in amplifier on the surface receives the transmitter current as a reference signal. The reference signal is then used to determine the in-phase and out-of-phase components of the receiver coil signal. A separate current meter monitors transmitted current. A "buck box" on the surface is used to cancel the signal from the receiver coil due to the direct transmitted field.

The coils are maintained level by suspension from the main cable and by the suspended transmitter package and receiver centering weight. Flexible fiberglass poles attached radially outward from the coils center the coils within the borehole. The fiber optic link connecting the transmitter and receiver coil is in 10 meter sections allowing for variable spacing (in multiples of 10 meters) and ease in deployment. The block diagram of the tool can be seen in Fig. 11.

8. CONCLUSION

Based on modelling, the large spacing loop-loop electromagnetic tool operating at 10 kHz shows promise in detecting low resistivity clay zones in the vicinity of a borehole. For anomalies 25 m thick or more, EM responses well above the detectability limit were calculated. Furthermore, by adjusting the spacing of the loops, the distance of the anomaly from the borehole wall can be estimated. Anomalies closer than half the loop separation are within the "detectability zone" of such a tool.

Due to the promising modelling results and the relative ease and simplicity of developing and fielding such an EM logging tool an experimental program was instituted. A coaxial loop-loop tool was chosen as a "first cut" since there is no need to be concerned with angular orientation within the borehole as in a coplanar system. Furthermore, the coaxial system has the advantage of detecting an anomaly above or below the vertical extent of the loops.

The coaxial loop-loop tool described has been designed and is currently being assembled. The tool is designed to perform optimally in geologies of a tuff and alluvium matrix with resistivities on the order of 100 Ω-m and relatively large anomalous targets. It should be noted that by suitably designing a tool for shorter spacing, smaller loop areas and higher operating frequencies, logs can be made for much smaller and closer anomalous targets.

ACKNOWLEDGMENTS

We wish to thank Nancy Howard for first suggesting this type of investigation, Norm Burkhard for providing the support for the initial modelling and Joe Hearst for supporting the tool development. Special thanks to Clyde Dease whose computer code ran flawlessly and to Barbara Sokoloski for typing. I would also like to thank members of the Engineering Research Division Electromagnetic & Acoustic Sensing Group for many helpful suggestions. This work was supported by the Nuclear Test Containment Program.

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BIOGRAPHICAL SKETCHES

Philip E. Harben obtained his B.S. and B.S.E. Degrees from University of Michigan, 1976, in Applied Mathematics and Environmental Science Engineering. He obtained his M.S. Degree from U.C. Berkeley, 1982, in Engineering Geoscience. He has been with the Lawrence Livermore National Laboratory for the past seven years. His current research interests include: borehole logging tools, seismic signal processing and NMR imaging.

Gale Holladay was born June 11, 1927 in Safford, Arizona. He received a B.S. Degree in Electrical Engineering from the University of Arizona in 1954 and a M.S. Degree in General Engineering from University of California, Davis, in 1974. He wrote test procedures for navigational equipment at Boeing, Seattle from 1954 to 1957. Since 1957 he has worked at the Lawrence Livermore National Laboratory, where he has designed and fielded instrumentation for nuclear diagnostics, environmental science, and geophysical measurements.

Peter W. Rodgers is a geophysicist at Lawrence Livermore National Laboratory. He received his Ph.D. in Geophysics and Electrical Engineering in 1965 from the University of California (Berkeley), where he was also an Assistant Professor. He has worked for Northrop Aircraft Co., Shell Development Co., and the government of New Zealand. His areas of interest are seismology, geophysical instrumentation, and electromagnetic exploration methods.

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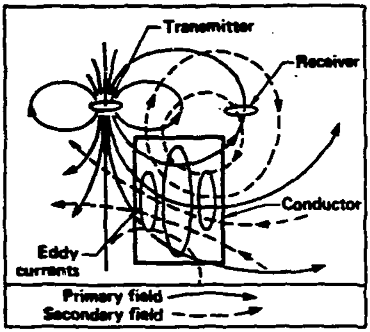

Figure 1. A general picture of electromagnetic induction prospecting.

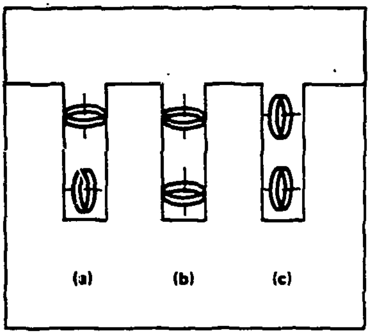

Figure 2. Loop-loop orientations: (a) null-coupled, (b) coaxial, (c) coplanar.

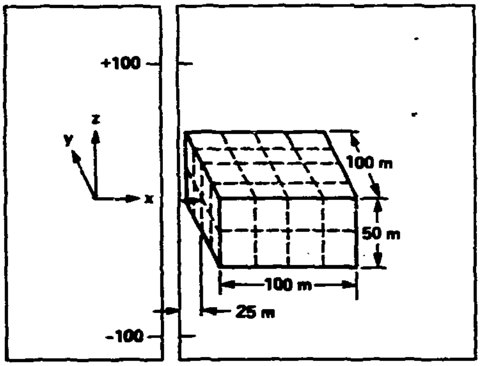

Figure 3. Anomaly geometry for 50-m-thick layer. The anomaly is constructed of 32 cubes all 25 m on a side.

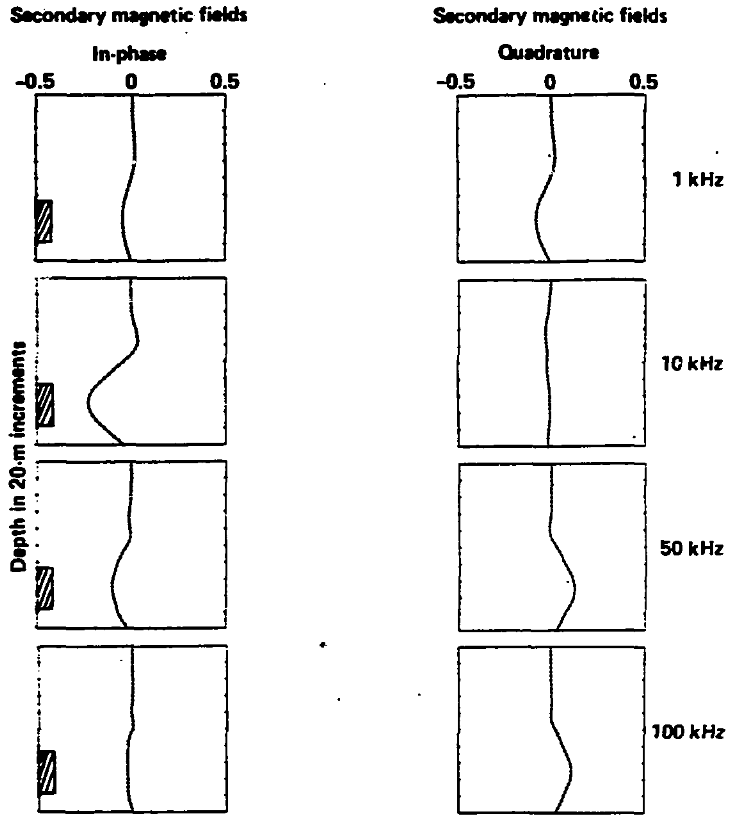

Figure 4. Real (left column) and imaginary (right column) part of the response for coplanar loops. Each row is the result for a different frequency: top to bottom is 1 kHz, 10 kHz, 50 kHz, 100 kHz, respectively. Note that the vertical location of the anomaly is shown (tic marks are 20 m apart). The in-phase and quadrature fields are shown as a fraction of the primary field. The anomaly is 50 m thick.

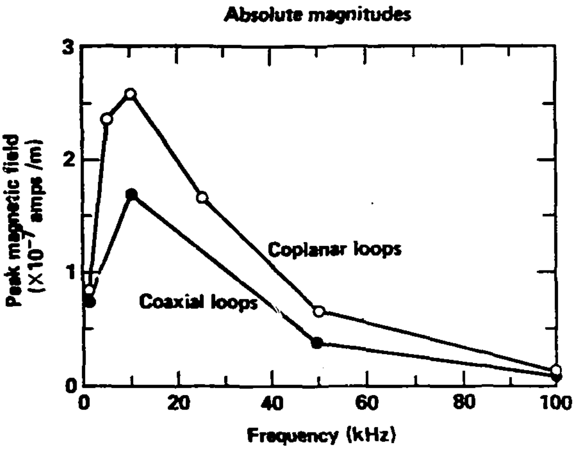

Figure 5. Peak magnitude of the magnetic field for coplanar (white points) and coaxial (black points) loops as a function of frequency.

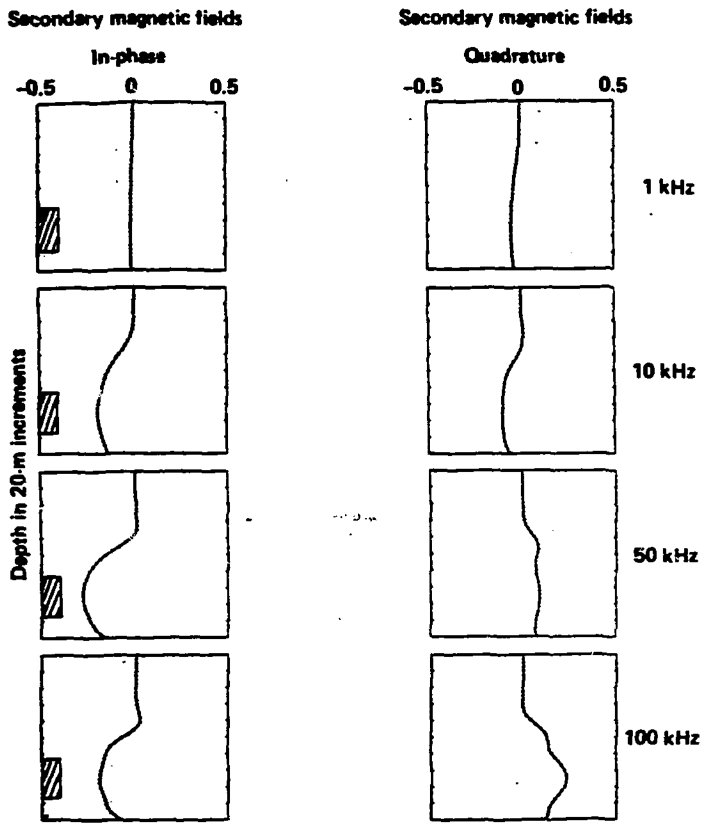

Figure 6. Same layout as Figure 4 except the loops are coaxial and facing the target.

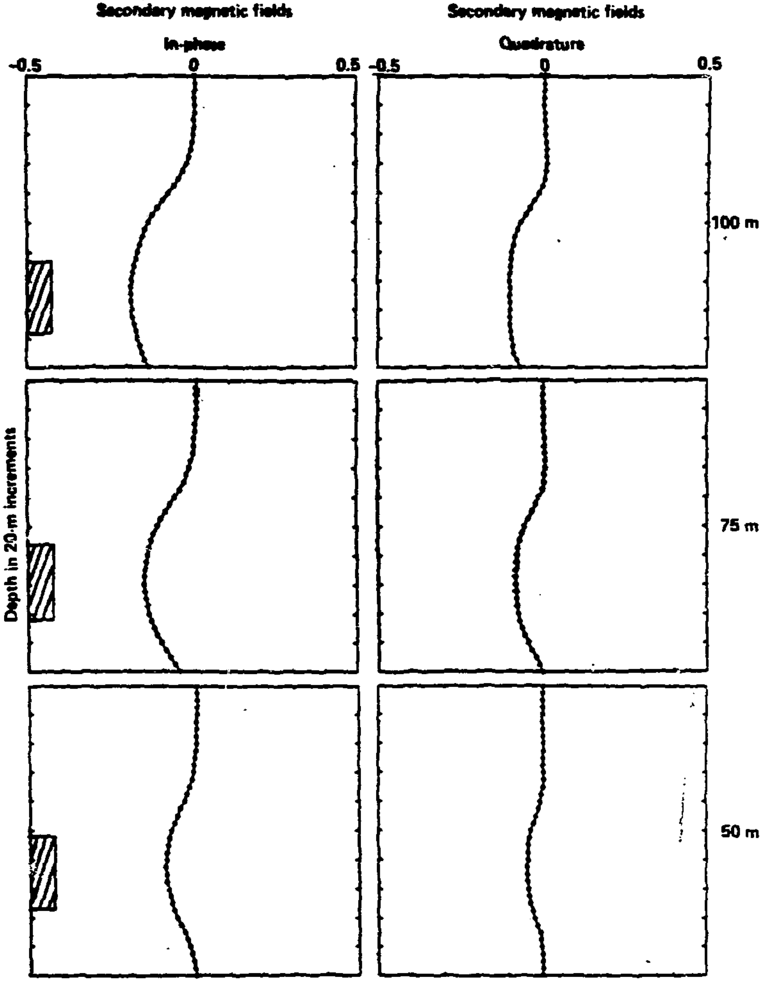

Figure 7. Results for coaxial loops when loop-loop spacing is changed from 100 m (top row) to 75 m (middle row) to 50 m (bottom row). Anomaly is 50 m thick.

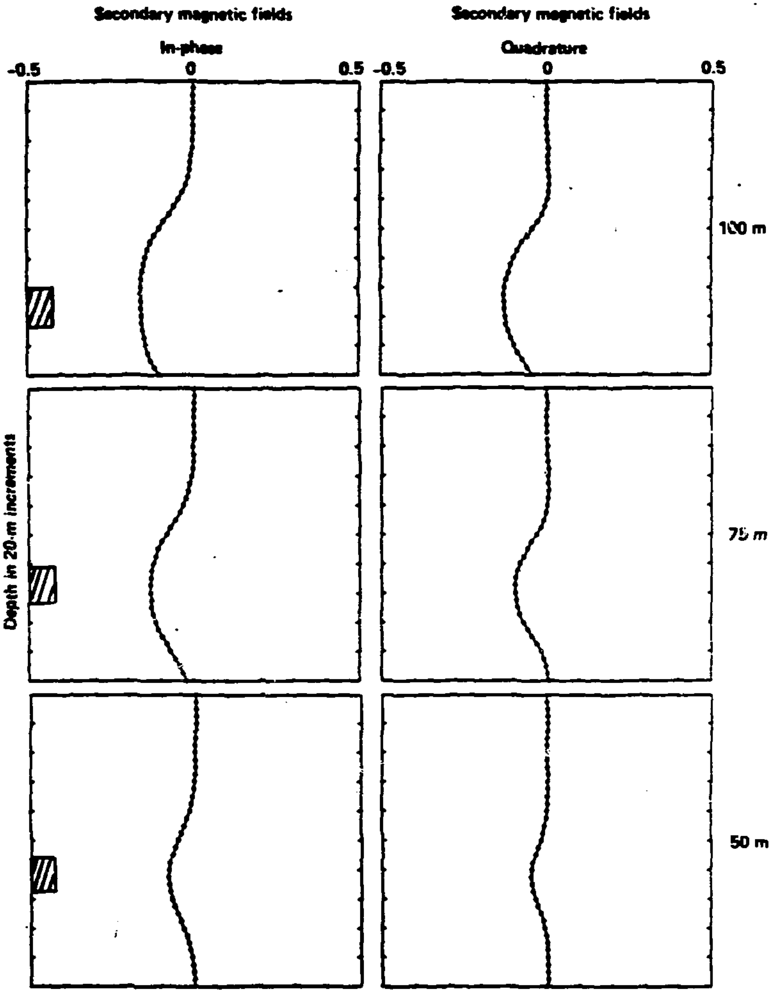

Figure 6. Results for coaxial loops when loop-loop spacing is changed from 100 m (top row) to 75 m (middle row) to 50 m (bottom row). Anomaly thickness is 25 m.

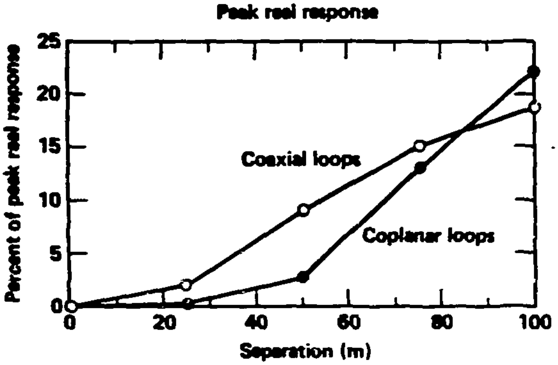

Figure 9. Peak real response of coplanar (black points) and coaxial (white points) loops expressed as percentage of secondary to primary magnetic field as a function of loop separation distance.

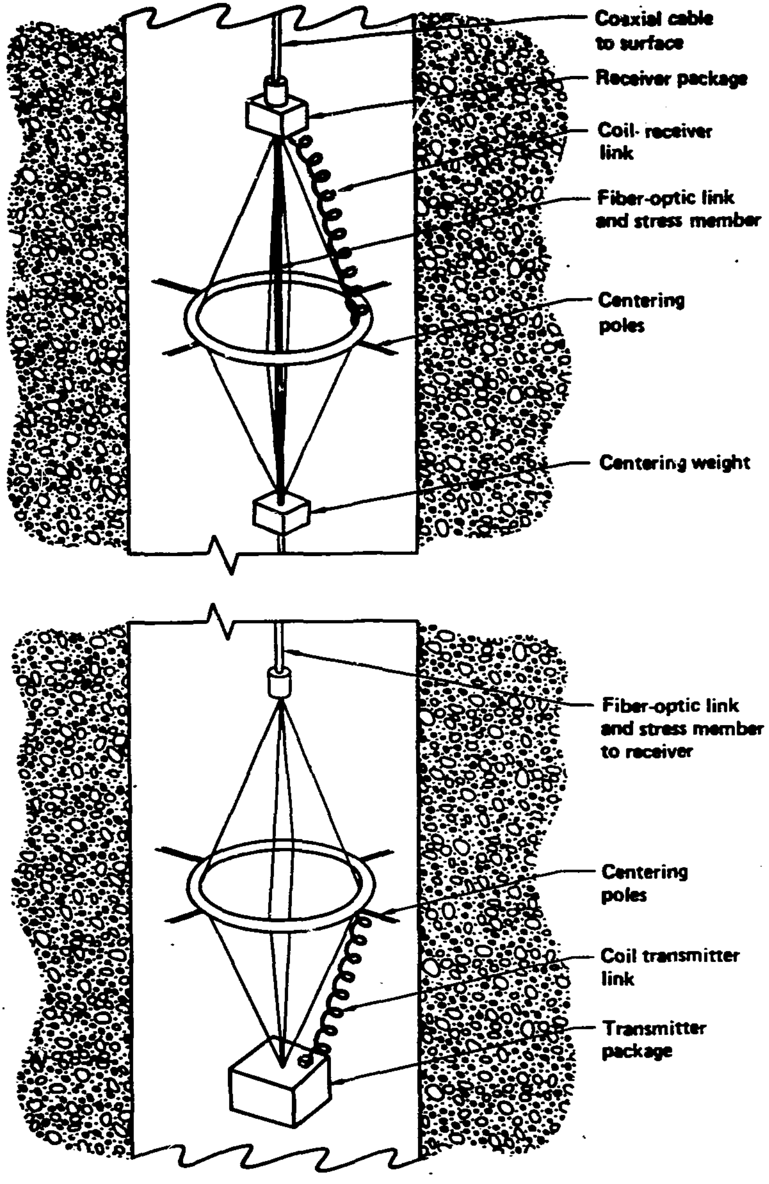

Figure 10. Loop-loop EM logging tool schematic.

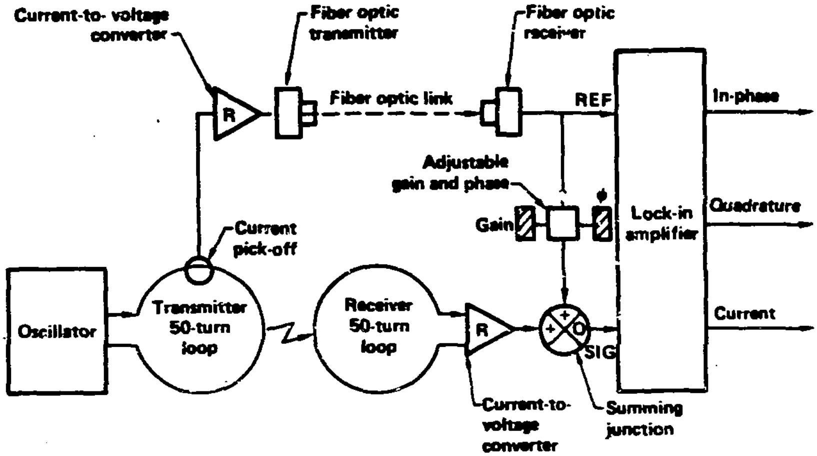

Figure 11. Block diagram of the loop-loop EM tool.