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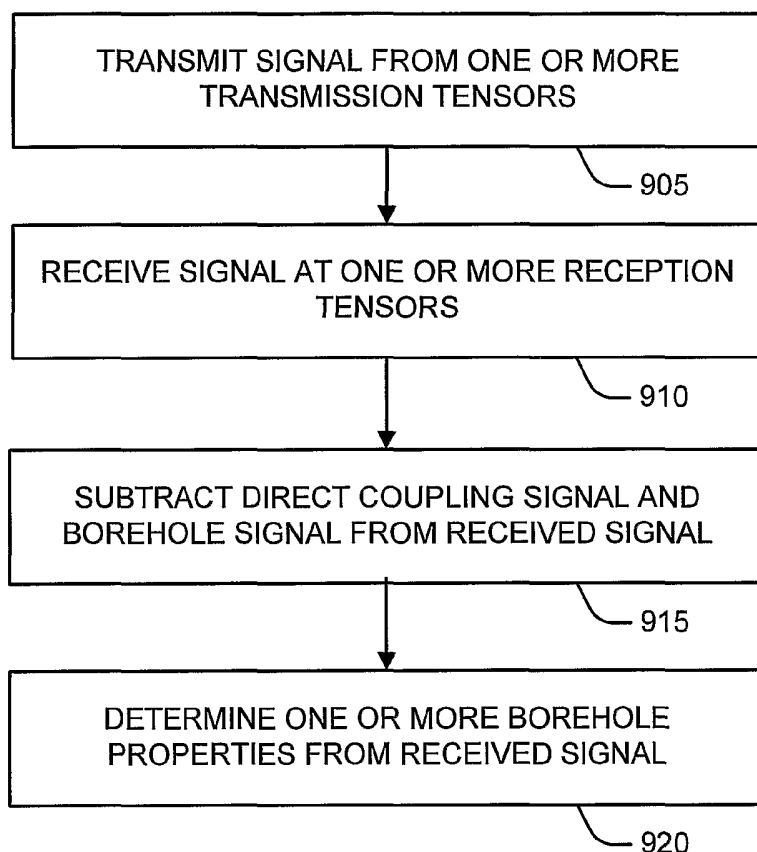
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(54) Title: MINIMIZING THE EFFECT OF BOREHOLE CURRENT IN TENSOR INDUCTION LOGGING TOOLS



(57) Abstract: Logging tools, methods, and computer programs for use in borehole logging are described. The logging tool includes three or more tensors, each tensor including one or more coils. Each coil is characterized by coil parameters including an axis orientation, a cross-sectional area, a number of turns, and a location. At least one of the coil axes is disposed at an angle to the borehole axis. One or more of the coil parameters are selected to minimize sensitivity to borehole current.

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Minimizing The Effect Of Borehole Current In Tensor Induction Logging Tools

Tensor induction tools may increase the amount of information that may be gathered during logging. Tensor induction tools with one or more elements whose magnetic axes are disposed at an angle to the borehole axis, however, may experience a borehole-current effect. The borehole-current effect refers to current induced in the borehole that distorts measurements of current induced in the formation.

Brief Description of the Drawings

Fig. 1 shows a system for downhole logging.

Fig. 2 shows an example logging tool.

Fig. 3 shows coils within an example tensor.

Fig. 4. is a block diagram of an example system for minimizing the effects of borehole current and direct coupling between one or more transmission tensors and one or more reception tensors.

Figs. 5-7 are block diagrams of an example system for minimizing the effects of borehole current.

Fig. 8 is a block diagram of an example system for minimizing direct coupling between one or more transmission tensors and one or more reception tensors.

Fig. 9 is a block diagram of an example system for determining one or more borehole properties.

Detailed Description

As shown in Fig. 1, logging equipment 100 (simplified for ease of understanding) includes a mast 105, draw works or winch 110, wireline 115, and logging tool 120. The logging tool 120 is placed in the borehole 125 to measure one or more properties of the formation surrounding the borehole 125. The logging tool 120 may be in communication with a processor 130. The processor 130 may receive data from the logging tool 120. The processor 130 may modify, analyze, or record the data from the logging tool 120. For example, the processor 130 may be an electromechanical plotter to plot data from the logging tool 120. The processor 130 may be in communication with a terminal 135 to receive input or provide output to an operator. The processor 130 and the terminal 135 may be integrated, or they may be separate. The processor 130 may control the draw works or winch 110 to control the movement of the logging tool 120 in the borehole 125. Although Fig. 1 illustrates an example wireline system, the systems, methods, and computer programs described

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herein may be used in other downhole system, including, for example, logging-while drilling systems.

An example logging tool 120 is shown in Fig. 2. The example logging tool 120 includes four tensors 205, 210, 215, and 220 to transmit or receive signals. One or more of the tensors 205, 210, 215, and 220 are transmission tensors for transmitting signals. One or more of the tensors 205, 210, 215, and 220 are reception tensors for receiving signals. In certain example logging tools 120, one or more of the tensors 205, 210, 215, and 220 may be transmission or reception tensors at different times. One or more of the tensors 205, 210, 215, and 220 may be joined by wiring or other circuitry to modify the signals received or transmitted by the tensors. One or more of the tensors 205, 210, 215, and 220 may be connected with one or more transmitters or receivers, which may be controlled by the processor 130.

Example elements within a tensor, such as tensor 205, are shown in Fig. 3. The tensor includes three coils 305, 310, and 315. Each of the coils 305, 310, and 315 may have a number of turns of wire about a core. Each of the coils 305, 310, and 315 may have a cross-sectional area. The number of turns, the cross-sectional area, and the orientation of each coil may alter the behavior of the coil in the presence of a signal. The coils 305, 310, and 315, shown in Fig. 3, are oriented mutually orthogonal to each other: the core of coil 305 is along the Z axis, the core of coil 310 is along the X axis, and the core of the coil 315 is along the Y axis. In general however, the coils 305, 310, and 315 may have a different orientation relative to each other.

Coils in reception tensors that are disposed at an angle relative to the axis of the borehole will receive a borehole signal due to the borehole current. Therefore, if tensor 205 is aligned with the borehole axis, coil 305 will not receive any borehole signal, while coils 310 and 315 will receive borehole signal because they are oriented orthogonal to the borehole axis. In practice, the tensor 205 may be disposed in the borehole 125 so that one or more of the coils 305, 310, and 315 may have a component orthogonal to the borehole axis.

Fig. 4 illustrates an example system for minimizing the sensitivity of logging tool 120 to borehole current. The system selects the one or more of the location, the cross sectional area, or the number of turns ("coil parameters") for each coil in the logging tool 120 to minimize the sensitivity to borehole current (block 405). The system may also select one or more of the coil parameters for each coil to minimize direct coupling between the reception tensors and the transmission tensors (block 410). In certain example implementations, blocks 405 and 410 may be performed simultaneously.

Returning to Fig. 2, in example implementations of logging tool 120 that follow, tensor 205 is a transmission tensor, while tensors 210, 215, and 220 are reception tensors. Among the reception tensors, tensor 215 is a main receiver tensor and tensors 210 and 220 are bucking tensors. The signal induced in the bucking tensors 210 and 220 may be subtracted from the signal induced in the main receiver tensor 215 by circuitry connecting the main receiver tensor 205 and the bucking tensors 210 and 220. Bucking tensor 210 may be Z_{b1} away from transmission tensor 205, main receiver tensor 215 may be Z_m away from transmission tensor 205, and bucking tensor 220 may be Z_{b2} away from transmission tensor 205.

An example system for selecting one or more of the coil parameters for each coil in the logging tool 120 to minimize sensitivity to borehole current (block 405) is shown in Fig. 5. The system may determine the borehole signal induced in each reception tensor due to the one or more transmission tensors (block 505). The system may then adjust one or more of the coil parameters to substantially cancel the borehole signal in the main receiver tensor 215 (block 510).

An example system for determining the borehole signal induced in each reception tensor due to the one or more transmission tensors (block 505) is shown in Fig. 6. The system may characterize the borehole current at location z that is induced by a transmission tensor, using the following equation:

$$I(z) \propto e^{-\left(\frac{z}{z_0}\right)} \quad (\text{Equation 1})$$

where I is the current (in Amperes), z is the distance along the borehole axis away from the transmission tensor, and z_0 is the characteristic length of the exponential attenuation determined by the square root of the ratio of the drilling fluid conductivity divided by the formation conductivity (block 605).

The coupling between a coil oriented orthogonal to the borehole axis and the borehole current may depend on the cross sectional area and the number of turns of the coil, and the strength of the borehole current. The borehole current, as shown above in Equation 1, may be a function of the distance z . Therefore, the signal induced in a coil oriented orthogonal to the borehole axis may be characterized by the following equation:

$$\Delta V \propto I(z) \cdot N_R \cdot S_R \quad (\text{Equation 2})$$

where ΔV denotes the borehole signal induced in the coil oriented orthogonal to the borehole axis, and S_R and N_R are the cross sectional area and the number of turns of the receiving coil, respectively (block 610). If the coil is not fully oriented orthogonal to the borehole axis, trigonometric functions may be used to determine the borehole current induced in the coil.

An example system for adjusting the location, cross sectional area, and number of turns of coils to substantially cancel the borehole signal in the main receiver tensor (block 510) is shown in Fig. 7. The system may adjust one or more of the location, cross-sectional area, and number of turns of the coils in one or more tensors (block 705). The system may then subtract the bore signal induced in one or more bucking receivers from the borehole signal induced in the main receiver tensor (block 710). For example, if induction tool 120 only included two reception tensors (e.g., bucking tensor 210 and main receiver tensor 215), the borehole signal induced in the reception tensors could be expressed as:

$$\Delta V \propto [I(z_m) \cdot N_m \cdot S_m - I(z_b) \cdot N_{b1} \cdot S_{b1}] \quad (\text{Equation 3})$$

By selecting the coil parameters the borehole signal (ΔV) may be set to be zero. In such a configuration, the induction tool 120 may have no, or very little, sensitivity to the borehole current. In certain implementations, however, the coil parameters in the reception tensors may be selected to cancel out the direct coupling between the one or more transmission tensors and the one or more reception tensors (block 410).

The borehole signal generated by the borehole current in the example induction tool 120 (Fig. 2) may be expressed by the following equation:

$$\Delta V \propto [I(z_m) \cdot N_m \cdot S_m - I(z_{b1}) \cdot N_{b1} \cdot S_{b1} - I(z_{b2}) \cdot N_{b2} \cdot S_{b2}] \quad (\text{Equation 4})$$

where the subscripts m , $b1$ and $b2$ denote the main receiver tensor 215 and the buckling tensors 210 and 220, respectively, N denotes the number of turns in a coil, S denotes the cross-sectional area of a coil, and I denotes the borehole current induced in the coil. For this example configuration of tensors, the system may solve the following equation to minimize the borehole signal (block 505):

$$I(z_m) \cdot N_m \cdot S_m - I(z_{b1}) \cdot N_{b1} \cdot S_{b1} - I(z_{b2}) \cdot N_{b2} \cdot S_{b2} = 0 \quad (\text{Equation 5})$$

The system may also adjust one or more of the coil parameters to minimize direct coupling between the one or more reception tensors and the one or more transmission tensors (block 410). An example system for performing block 410 is shown in Fig. 8. The example system may adjust the coil parameters to satisfy the following equation (block 805):

$$\frac{N_m \cdot S_m}{Z_m^3} - \left(\frac{N_{b1} \cdot S_{b1}}{Z_{b1}^3} + \frac{N_{b2} \cdot S_{b2}}{Z_{b2}^3} + \dots + \frac{N_{bQ} \cdot S_{bQ}}{Z_{bQ}^3} \right) = 0 \quad (\text{Equation 6})$$

The equation above is generalized for a system with one main receiver tensor and Q bucking receiver tensors. In the case of the example induction tool 120 shown in Fig. 2, the system may solve the following equation:

$$\frac{N_m \cdot S_m}{Z_m^3} - \frac{N_{b1} \cdot S_{b1}}{Z_{b1}^3} - \frac{N_{b2} \cdot S_{b2}}{Z_{b2}^3} = 0 \quad (\text{Equation 7})$$

In certain example implementations, the cross-sectional areas of the coils may be equal. In such an implementation, using Equation (1), Equations (5) and (7) may be rewritten as:

$$N_m - N_{b1} \cdot e^{\left(\frac{Z_m - Z_{b1}}{Z_0}\right)} - N_{b2} \cdot e^{\left(\frac{Z_{b2} - Z_m}{Z_0}\right)} = 0 \quad (\text{Equation 8})$$

$$\frac{N_m}{Z_m^3} - \frac{N_{b1}}{Z_{b1}^3} - \frac{N_{b2}}{Z_{b2}^3} = 0 \quad (\text{Equation 9})$$

In certain implementations, Z_m may be between several inches to hundreds of inches while N_m may be between one and hundreds of turns. Other constraints may be added to this set of equations, such as one or more of the following:

$$0 < \frac{Z_{b1}}{Z_m} < 1, \quad (\text{Equation 10a})$$

$$1 < \frac{Z_{b2}}{Z_m} < 2. \quad (\text{Equation 10b})$$

Once Z_m and N_m are fixed, Equations (8) and (9) may be simultaneously satisfied by adjusting Z_{b1} , Z_{b2} , N_{b1} and N_{b2} . Z_0 is a formation-related parameter that may represent the rate at which the borehole current decays along the borehole axis. In certain implementations, Z_0 may be set to a fixed value (e.g., $Z_0 = 5Z_m$).

In one example system for selecting the coil parameters to minimize the sensitivity to borehole current (405) and minimize direct coupling between reception tensors and transmission tensors (block 410), a main receiver tensor 215 may have the following properties $Z_m = 40 \text{ in.}$, $N_m = 70$. In one example system, the locations and number of turns of coils in of the bucking receivers 210 and 220 may be set to $Z_{b1} = (40-10) = 30$ inches and $Z_{b2} = (40+10) = 50$

inches. In the example system, solving for Equations (7) and (9) provides the solutions $N_{b1} = -17.912$, $N_{b2} = -53.793$.

Equations (7) and (9) may be underdetermined because they include six variables ($Z_m, N_m, Z_{b1}, N_{b1}, Z_{b2}, N_{b2}$), with only two equations to solve for the variables. Therefore, there may be an infinite number of solutions.

Fig. 9 shows an example system for measuring one or more borehole properties using a logging induction tool, such as induction tool 120. The system may transmit a signal from one or more transmission tensors (block 905). One or more reception tensors may receive the signal (block 910). The system subtracts out the direct coupling signal and the borehole signal from the signal (block 915). The system may determine one or more borehole and formation properties from the signal (block 920). For example, the system may determine one or more of the following: the formation conductivity, the electric anisotropy in the formation around the borehole 125, the relative dip of the formation, and the strike angles between the borehole and the formation.

The present invention is therefore well-adapted to carry out the objects and attain the ends mentioned, as well as those that are inherent therein. While the invention has been depicted, described and is defined by references to examples of the invention, such a reference does not imply a limitation on the invention, and no such limitation is to be inferred. The invention is capable of considerable modification, alteration and equivalents in form and function, as will occur to those ordinarily skilled in the art having the benefit of this disclosure. The depicted and described examples are not exhaustive of the invention. Consequently, the invention is intended to be limited only by the spirit and scope of the appended claims, giving full cognizance to equivalents in all respects.

Claims

What is claimed is:

1. A logging tool for use in a borehole penetrating formations, the logging tool comprising:
three or more tensors, each tensor including one or more coils, where each coil is characterized by coil parameters including an axis orientation, a cross-sectional area, a number of turns, and a location, where at least one of the coil axes is disposed at an angle to the borehole axis, and where one or more of the coil parameters are selected to minimize sensitivity to borehole current.
2. The logging tool of claim 1, where:
The location of a coil is its location along an axis of the logging tool.
3. The logging tool of claim 1, where:
one or more of the tensors include three coils, where the coil axes are substantially orthogonal to each other.
4. The logging tool of claim 1, where one or more of the tensors are transmission tensors for transmitting a signal.
5. The logging tool of claim 1, where one or more of the tensors are reception tensors for receiving a signal.
6. The logging tool of claim 1, comprising:
four or more tensors, where one or more tensors are transmission tensors, one or more tensors are reception tensors, and where one or more of the coil parameters are selected to minimize direct coupling between one or more transmission tensors and one or more reception tensors.
7. The logging tool of claim 6, where one or more of the reception tensors are bucking tensors.
8. The logging tool of claim 1, where the logging tool comprises four or more tensors, and where:
one or more tensors are transmission tensors; and
three or more tensors are reception tensors, where the reception tensors include a main receiver set of one or more tensors and a bucking receiver set of three or more tensors.

9. The logging tool of claim 8, where the borehole current at a location z induced by a transmission tensor is characterized by the equation:

$$I(z) \propto e^{-\left(\frac{z}{z_0}\right)}, \text{ where } I(z) \text{ is the borehole current induced at location } z, \text{ and where } z_0 \text{ is a characteristic length of the exponential attenuation.}$$

10. The logging tool of claim 9, where the borehole is in a formation characterized a formation conductivity at z , where the borehole comprises drilling fluid characterized by a drilling fluid conductivity at z , and where the characteristic length of the exponential attenuation is the square root of the ratio of the drilling fluid conductivity divided by the formation conductivity.

11. The logging tool of claim 9, where the borehole signal received by a reception tensor at z due to the borehole current is characterized by the equation:

$$\Delta V \propto I(z) \cdot N_R \cdot S_R, \text{ where } \Delta V \text{ is the borehole signal, } N_R \text{ is the number of turns of the reception coil, and } S_R \text{ is the cross-sectional area of the reception coil.}$$

12. The logging tool of claim 10, where the borehole signals received by a main receiver set of tensors are approximately equal to the borehole signals received by the bucking receiver set tensors.

13. The logging tool of claim 12, further comprising wiring between the main receiver set and the bucking receiver set to subtract the borehole signal received by the bucking receiver set from the borehole signal received by the main receiver set.

14. The logging tool of claim 13, where one or more of the coil parameters are selected to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

15. A method of measuring one or more borehole and formation properties using a logging tool comprising three or more tensors, each tensor including one or more coils, where each coil is characterized by coil parameters including an axis orientation, a cross-sectional area, a number of turns, and a location, where one or more of the coil parameters are selected to minimize sensitivity to borehole current, where one or more of the tensors are transmission tensors and one or more of the tensors are reception tensors, the method comprising:

transmitting a signal with one more of the transmission tensors;

receiving the signal with one or more of the reception tensors; and

determining the property based on the signal received by one or more reception tensors.

16. The method of claim 15, where the borehole is in a formation, and where determining the property based on the signal received by one or more reception tensors comprises:

determining an electric anisotropy of the formation; and
determining formation conductivity in different directions.

17. The method of claim 15, where the borehole is in a formation, and where determining the property based on the signal received by one or more reception tensors comprises:

determining a relative dip of the formation.

18. The method of claim 15, where the borehole is in a formation, and where determining the property based on the signal received by one or more reception tensors comprises:

determining a strike angle between the borehole and the formation.

19. The method of claim 15, where the logging tool comprises four or more tensors, and where one or more of the coil parameters are selected to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

20. The method of claim 19, where the borehole current at a location z induced by a transmission tensor is characterized by the equation:

$I(z) \propto e^{-\left(\frac{z}{z_0}\right)}$, where $I(z)$ is the borehole current induced at location z and z_0 is a characteristic length of the exponential attenuation.

21. The method of claim 20, where the borehole is in a formation characterized a formation conductivity at z , where the borehole comprises drilling fluid characterized by a drilling fluid conductivity at z , and where the characteristic length of the exponential attenuation is the square root of the ratio of the drilling fluid conductivity divided by the formation conductivity.

22. The method of claim 20, where receiving the signal with one or more of the reception tensors comprises:

receiving a borehole signal at z due to the borehole current, where the borehole signal is characterized by the equation:

$\Delta V \propto I(z) \cdot N_R \cdot S_R$, where ΔV is the borehole signal, N_R is the number of turns of the reception coil, and S_R is the cross-sectional area of the reception coil.

23. The method of claim 22, where the logging tool comprises four or more tensors, where the reception tensors include a main receiver set of one or more tensors and a bucking receiver set of three tensors, and where receiving the signal with one or more of the reception tensors further comprises:

receiving one or more borehole signals with the main receiver set that are approximately equal to the borehole signals received by a bucking receiver set of one or more reception tensors.

24. The method of claim 23, where receiving the signal with one or more of the reception tensors further comprises:

subtracting the borehole signals received by the bucking receiver set from the borehole signals received by the main receiver set.

25. The method of claim 24, where the logging tool comprises four or more tensors, and where one or more coil parameters are selected to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

26. A method of designing a logging tool for use in a borehole, the logging tool including three or more tensors, each tensor including one or more coils, where each coil is characterized by coil parameters including an axis orientation, a cross-sectional area, a number of turns, and a location, the method comprising:

for each tensor:

selecting one or more of the coil parameters to minimize sensitivity to borehole current.

27. The method claim 26, where one or more of the tensors include three coils, where the coil axes are substantially orthogonal to each other.

28. The method of claim 26, further comprising:

designating one or more tensors as transmission tensors for transmitting a signal.

29. The method of claim 26, further comprising:

designating one or more tensors as reception tensors for receiving a signal.

30. The method 26, where one or more tensors are transmission tensors and one or more tensors are reception tensors, and where the method further comprises:

minimizing direct coupling between one or more transmission tensors and one or more reception tensors.

31. The method of claim 30, where the logging tool includes four or more tensors, and where minimizing direct coupling between one or more transmission tensors and one or more reception tensors comprises:

for each tensor:

selecting one or more of the coil parameters to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

32. The method of claim 29, where one or more of the reception tensors are bucking tensors.

33. The method of claim 26, where the logging tool includes four or more tensors, the method further comprising:

designating one or more tensors as transmission tensors; and

designating three or more tensors as reception tensors, where the reception tensors include a set of one or more main receiver tensors and a set of two or more bucking tensors.

34. The method of claim 31, where selecting one or more of the coil parameters to minimize sensitivity to borehole current further comprises:

determining the borehole signal induced in one or more reception tensors.

35. The method of claim 34, where determining the borehole signal induced in one or more reception tensors further comprises:

characterizing the borehole current at a location z induced by a transmission tensor by the

equation $I(z) \propto e^{-\left(\frac{z}{z_0}\right)}$, where $I(z)$ is the borehole current induced at location z and where z_0 is a characteristic length of the exponential attenuation.

36. The method of claim 35, where the borehole is in a formation characterized a formation conductivity at z , where the borehole comprises drilling fluid characterized by a drilling fluid conductivity at z , and where the characteristic length of the exponential attenuation is the square root of the ratio of the drilling fluid conductivity divided by the formation conductivity.

37. The method of claim 36, where determining the borehole signal induced in one or more reception tensors further comprises:

characterizing the borehole signal received by a reception tensor at z due to the borehole by

the equation $\Delta V \propto I(z) \cdot N_R \cdot S_R$, where ΔV is the borehole signal, N_R is the number of turns of the reception coil, and S_R is the cross-sectional area of the reception coil.

38. The method of claim 36, where selecting one or more of the coil parameters to minimize sensitivity to borehole current comprises:
- selecting one or more of the coil parameters of one or more coils to minimize sensitivity to borehole current so that the borehole signals received by a main receiver set are approximately equal to the borehole signals received by a bucking receiver set.
39. The method of claim 38, further comprising:
- designing wiring between the main receiver set and the bucking receiver set to subtract the borehole signal received by the bucking receiver set from the borehole signal received by the main receiver set.
40. The method of claim 39, further comprising:
- for one or more tensors:
 - selecting one or more of the coil parameters to minimize direct coupling between one or more transmission tensors and one or more reception tensors.
41. A computer program, stored in a tangible medium, for measuring one or more borehole and formation properties using a logging tool comprising three or more tensors, each tensor including one or more coils, where each coil is characterized by coil parameters including an axis orientation, a cross-sectional area, a number of turns, and a location, where one or more of the coil parameters are selected to minimize sensitivity to borehole current, where one or more of the tensors are transmission tensors and one or more of the tensors are reception tensors, the computer program comprising executable instructions that cause a computer to:
- transmit a signal with one more of the transmission tensors;
 - receive the signal with one or more of the reception tensors; and
 - determine the property based on the signal received by one or more reception tensors.
42. The computer program of claim 41, where the borehole is in a formation, and where the executable instructions that cause the computer to determine the property based on the signal received by one or more reception tensors further cause the computer to:
- determine an electric anisotropy of the formation; and
 - determine formation conductivity in different directions.
43. The computer program of claim 41, where the borehole is in a formation, and where the executable instructions that cause the computer to determine the property based on the signal received by one or more reception tensors further cause the computer to:
- determine a relative dip of the formation.

44. The computer program of claim 41, where the borehole is in a formation, and where the executable instructions that cause the computer to determine the property based on the signal received by one or more reception tensors further cause the computer to:

determine a strike angle between the borehole and the formation.

45. The computer program of claim 41, where the logging tool comprises four or more tensors, and where one or more of the coil parameters are selected to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

46. The computer program of claim 45, where the borehole current at a location z induced by a transmission tensor is characterized by the equation:

$I(z) \propto e^{-\left(\frac{z}{z_0}\right)}$, where $I(z)$ is the borehole current induced at location z and z_0 is a characteristic length of the exponential attenuation.

47. The computer program of claim 46, where the borehole is in a formation characterized a formation conductivity at z , where the borehole comprises drilling fluid characterized by a drilling fluid conductivity at z , and where the characteristic length of the exponential attenuation is the square root of the ratio of the drilling fluid conductivity divided by the formation conductivity.

48. The computer program of claim 46, where the executable instructions that cause the computer to receive the signal with one or more of the reception tensors further cause the computer to:

receive a borehole signal at z due to the borehole current, where the borehole signal is characterized by the equation:

$\Delta V \propto I(z) \cdot N_R \cdot S_R$, where ΔV is the borehole signal, N_R is the number of turns of the reception coil, and S_R is the cross-sectional area of the reception coil.

49. The computer program of claim 48, where the logging tool comprises four or more tensors, where the reception tensors include a main receiver set of one or more tensors and a bucking receiver set of three tensors, and where the executable instructions that cause the computer to receive the signal with one or more of the reception tensors further cause the computer to:

receive one or more borehole signals with the main receiver set that are approximately equal to the borehole signals received by a bucking receiver set of one or more reception tensors.

50. The computer program of claim 49, where the executable instructions that cause the computer to receive the signal with one or more of the reception tensors further cause the computer to:

subtract the borehole signals received by the bucking receiver set from the borehole signals received by the main receiver set.

51. The computer program of claim 50, including executable instructions that cause the computer to:

select one or more coil parameters to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

52. A computer program, stored in a tangible medium, for designing a logging tool for use in a borehole, the logging tool including three or more tensors, each tensor including one or more coils, where each coil is characterized by coil parameters including an axis orientation, a cross-sectional area, a number of turns, and a location, the computer program including executable instructions that cause a computer to:

for one or more tensors:

select one or more of the coil parameters to minimize sensitivity to borehole current.

53. The computer program claim 52, where one or more of the tensors include three coils, where the coil axes are substantially orthogonal to each other.

54. The computer program of claim 52, further comprising executable instructions that cause the computer to:

designate one or more tensors as transmission tensors for transmitting a signal.

55. The computer program of claim 52, further comprising executable instructions that cause the computer to:

designate one or more tensors as reception tensors for receiving a signal.

56. The computer program 52, where one or more tensors are transmission tensors and one or more tensors are reception tensors, and where the computer program comprises further executable instructions that cause the computer to:

minimize direct coupling between one or more transmission tensors and one or more reception tensors.

57. The computer program of claim 56, where the logging tool includes four or more tensors, and where the executable instructions to minimize direct coupling between one or more transmission tensors and one or more reception tensors further cause the computer to:

for one or more tensors:

select one or more of the coil parameters to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

58. The computer program of claim 52, where the logging tool includes four or more tensors, the computer program comprising further executable instructions that cause the computer to:

designate one or more tensors as transmission tensors; and

designate three or more tensors as reception tensors,

59. The computer program of claim 52, where the executable instructions that cause the computer to designate three or more tensors as reception tensors further cause the computer to:

designate a set of one or more main receiver tensors and a set of two or more bucking tensors.

60. The computer program of claim 59, where the executable instructions that cause the computer to select one or more of the coil parameters to minimize sensitivity to borehole current further cause the computer to:

determine the borehole signal induced in one or more reception tensors.

61. The computer program of claim 60, where the executable instructions to determine the borehole signal induced in one or more reception tensors further cause the computer to:

characterize the borehole current at a location z induced by a transmission tensor by the

equation $I(z) \propto e^{-\left(\frac{z}{z_0}\right)}$, where $I(z)$ is the borehole current induced at location z and where z_0 is a characteristic length of the exponential attenuation.

62. The computer program of claim 61, where the borehole is in a formation characterized a formation conductivity at z , where the borehole comprises drilling fluid characterized by a drilling fluid conductivity at z , and where the characteristic length of the exponential attenuation is the square root of the ratio of the drilling fluid conductivity divided by the formation conductivity.

63. The computer program of claim 62, where the executable instructions that cause the computer to determine the borehole signal induced in one or more reception tensors further cause the computer to:

characterize the borehole signal received by a reception tensor at z due to the borehole by the equation $\Delta V \propto I(z) \cdot N_R \cdot S_R$, where ΔV is the borehole signal, N_R is the number of turns of the reception coil, and S_R is the cross-sectional area of the reception coil.

64. The computer program of claim 62, where the executable instructions that cause the computer to select one or more of the coil parameters to minimize sensitivity to borehole current further cause the computer to:

select one or more of the coil parameters to minimize sensitivity to borehole current so that the borehole signals received by a main receiver set are approximately equal to the borehole signals received by a bucking receiver set.

65. The computer program of claim 64, where the executable instructions that cause the computer to select one or more of the coil parameters to minimize sensitivity to borehole current further cause the computer to:

design wiring between the main receiver set and the bucking receiver set to subtract the borehole signal received by the bucking receiver set from the borehole signal received by the main receiver set.

66. The computer program of claim 65, where the executable instructions that cause the computer to select one or more of the coil parameters to minimize sensitivity to borehole current further cause the computer to:

for one or more tensors:

select one or more of the coil parameters to minimize direct coupling between one or more transmission tensors and one or more reception tensors.

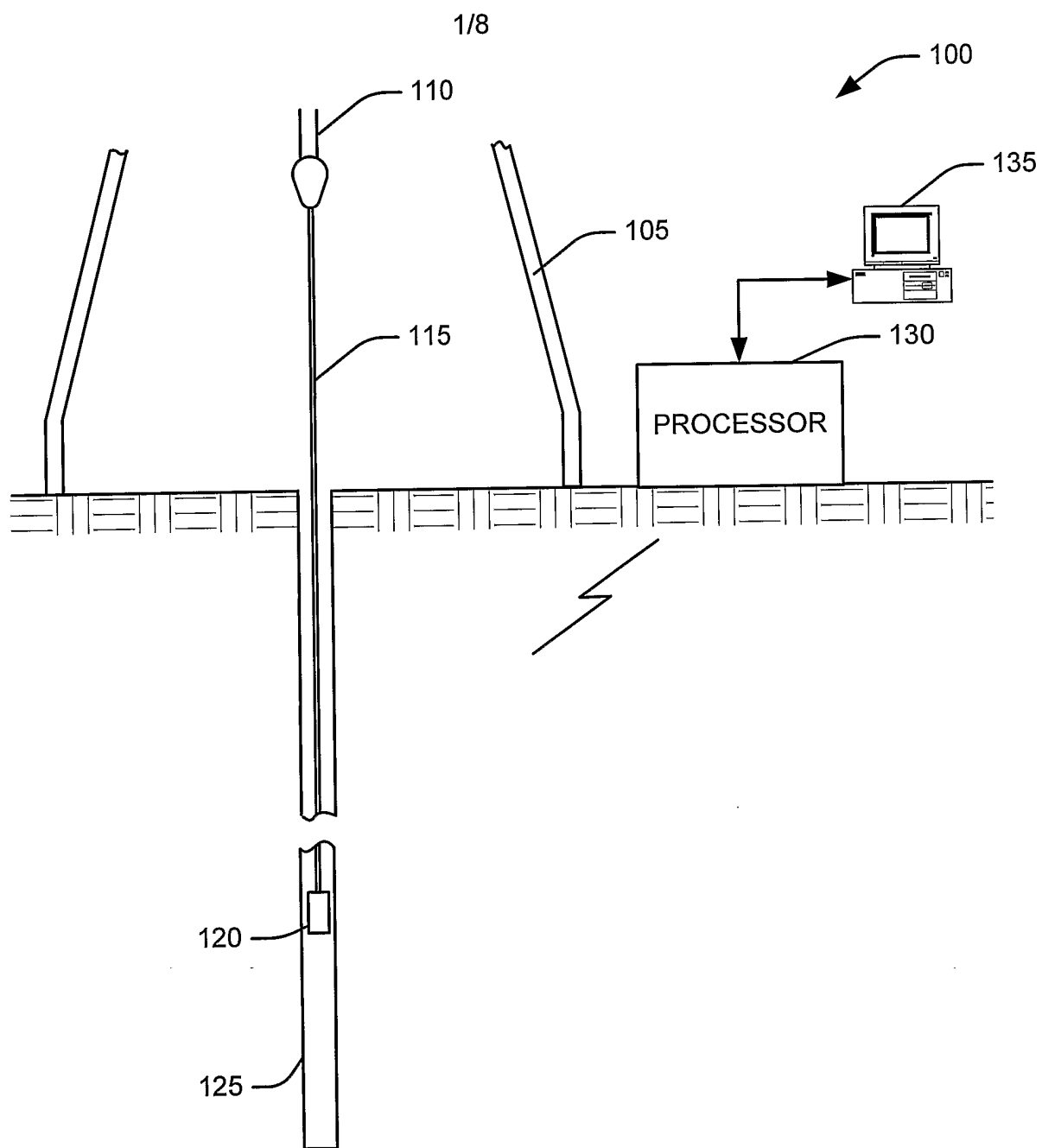
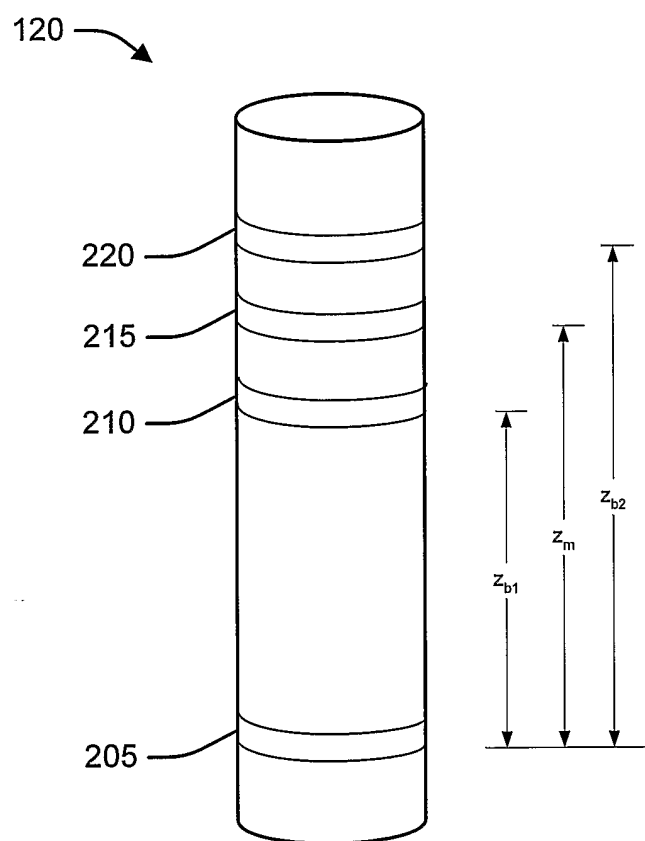


FIG. 1

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**FIG. 2**

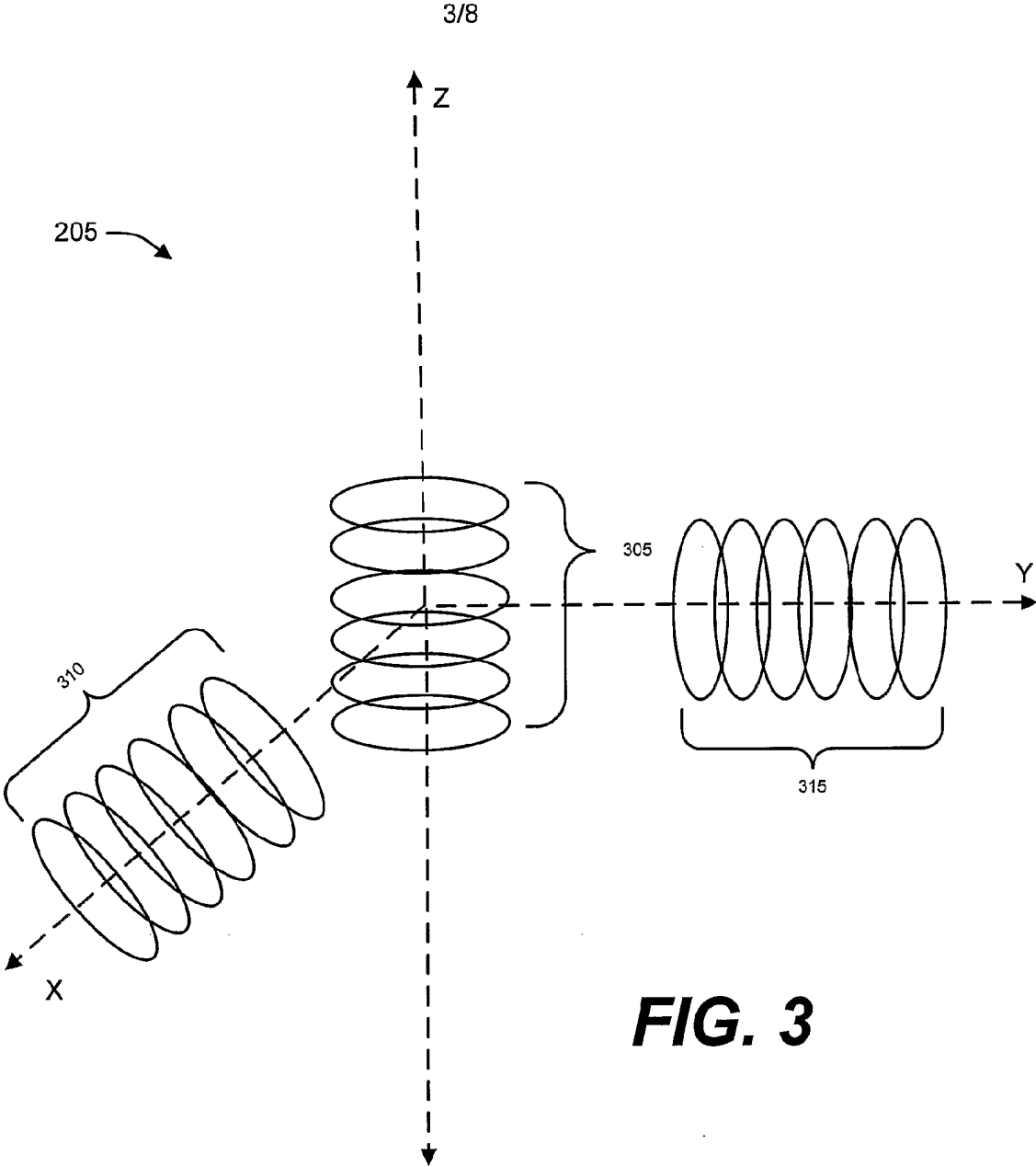
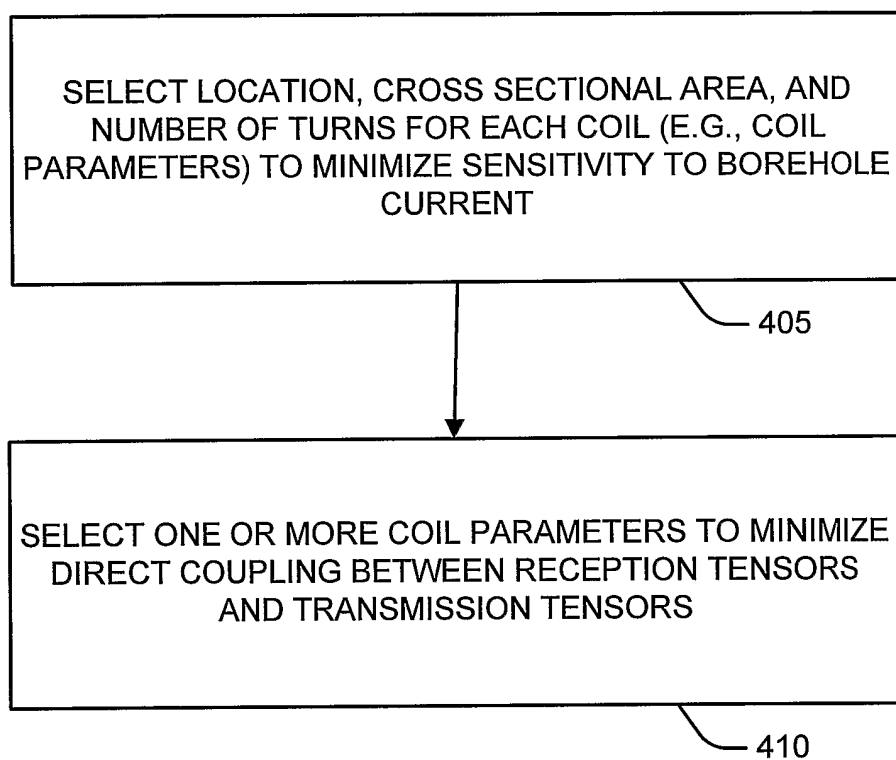
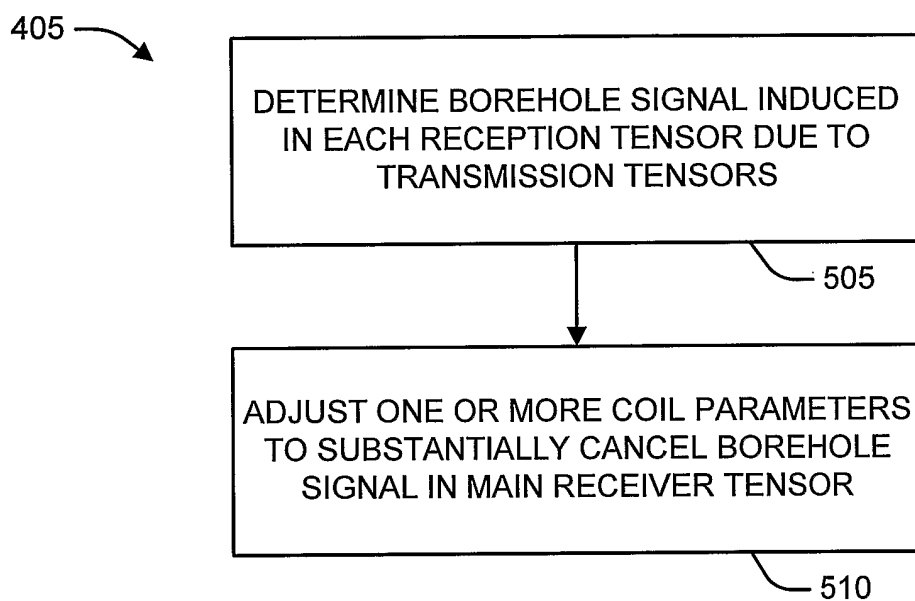


FIG. 3

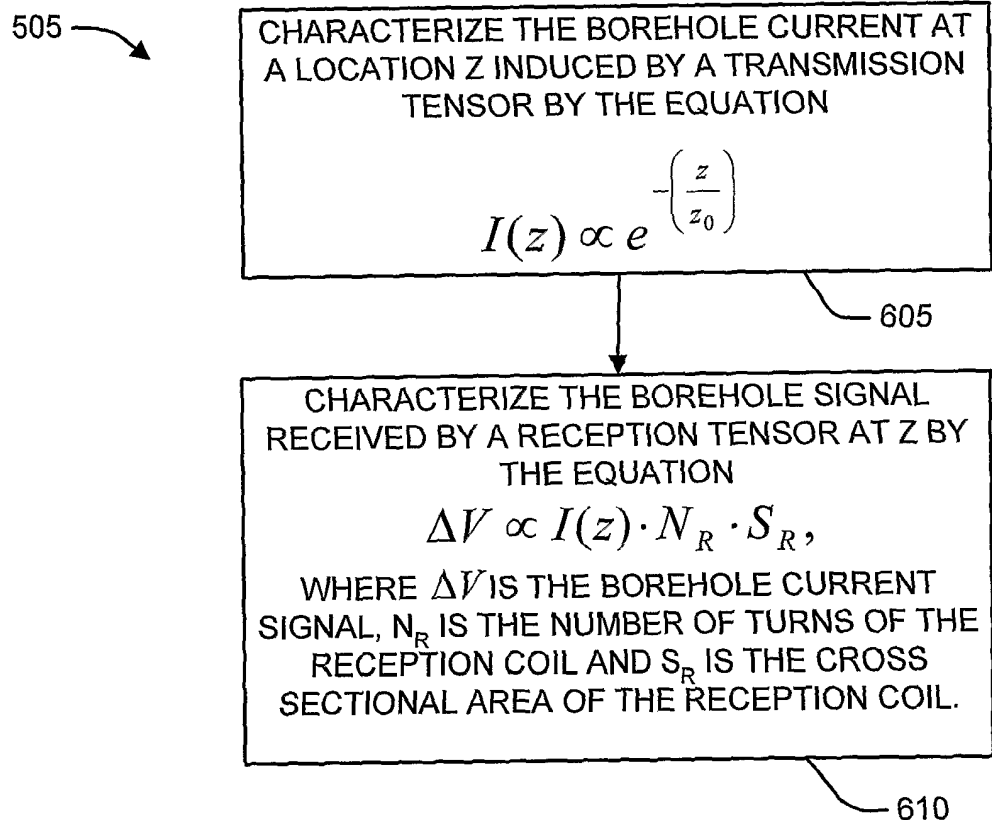
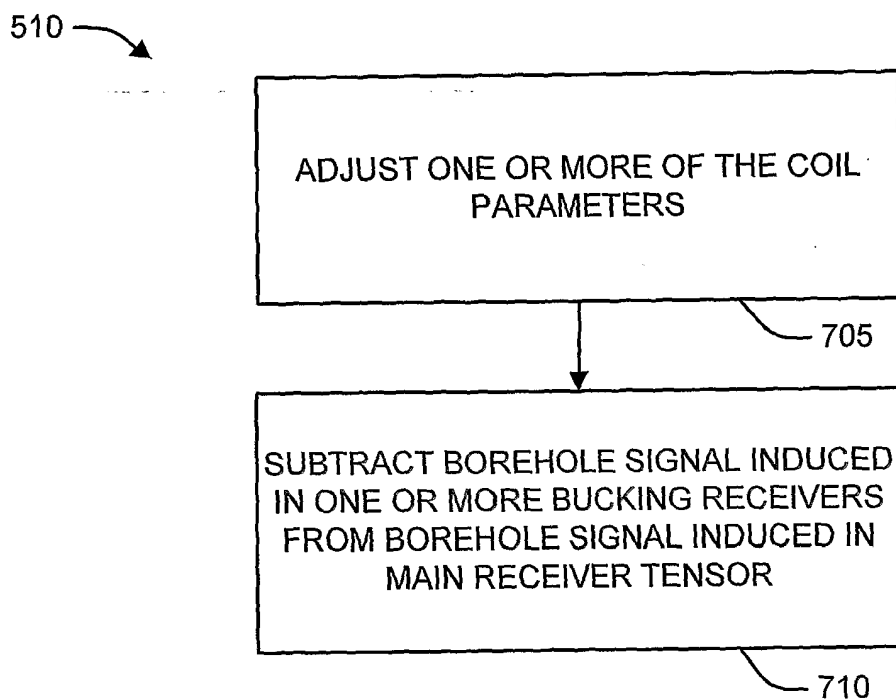
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**FIG. 4**

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**FIG. 5**

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**FIG. 6****FIG. 7**

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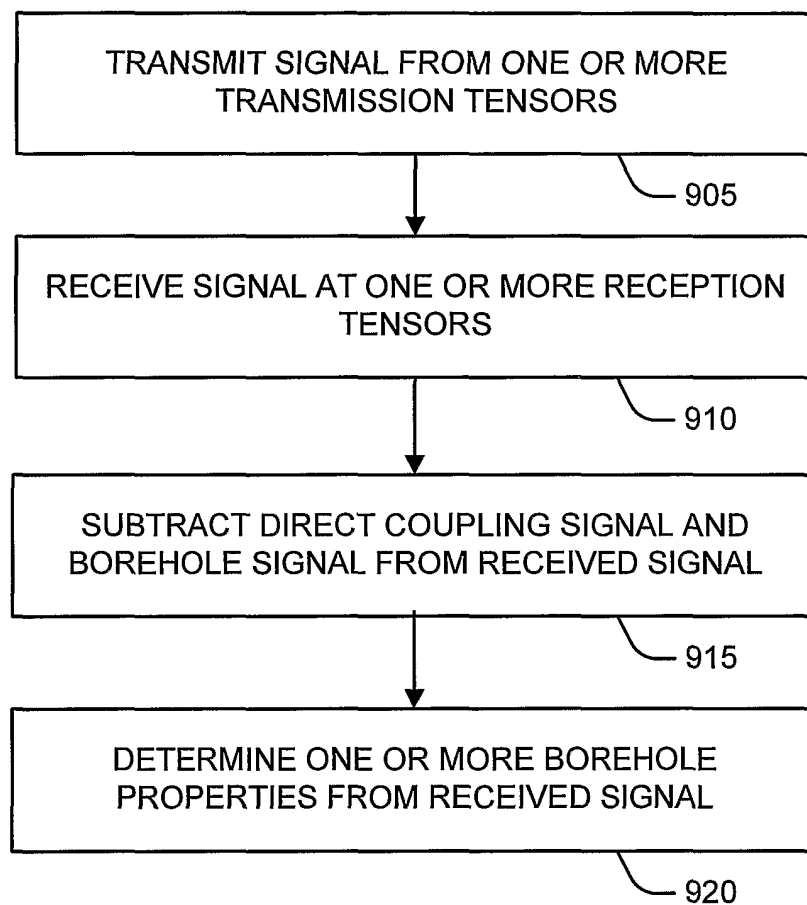
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ADJUST ONE OR MORE COIL PARAMETERS TO SATISFY THE EQUATION:

$$\frac{N_m \cdot S_m}{Z_m^3} - \left(\frac{N_{b1} \cdot S_{b1}}{Z_{b1}^3} + \frac{N_{b2} \cdot S_{b2}}{Z_{b2}^3} + \dots + \frac{N_{bQ} \cdot S_{bQ}}{Z_{bQ}^3} \right) = 0$$

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**FIG. 9**