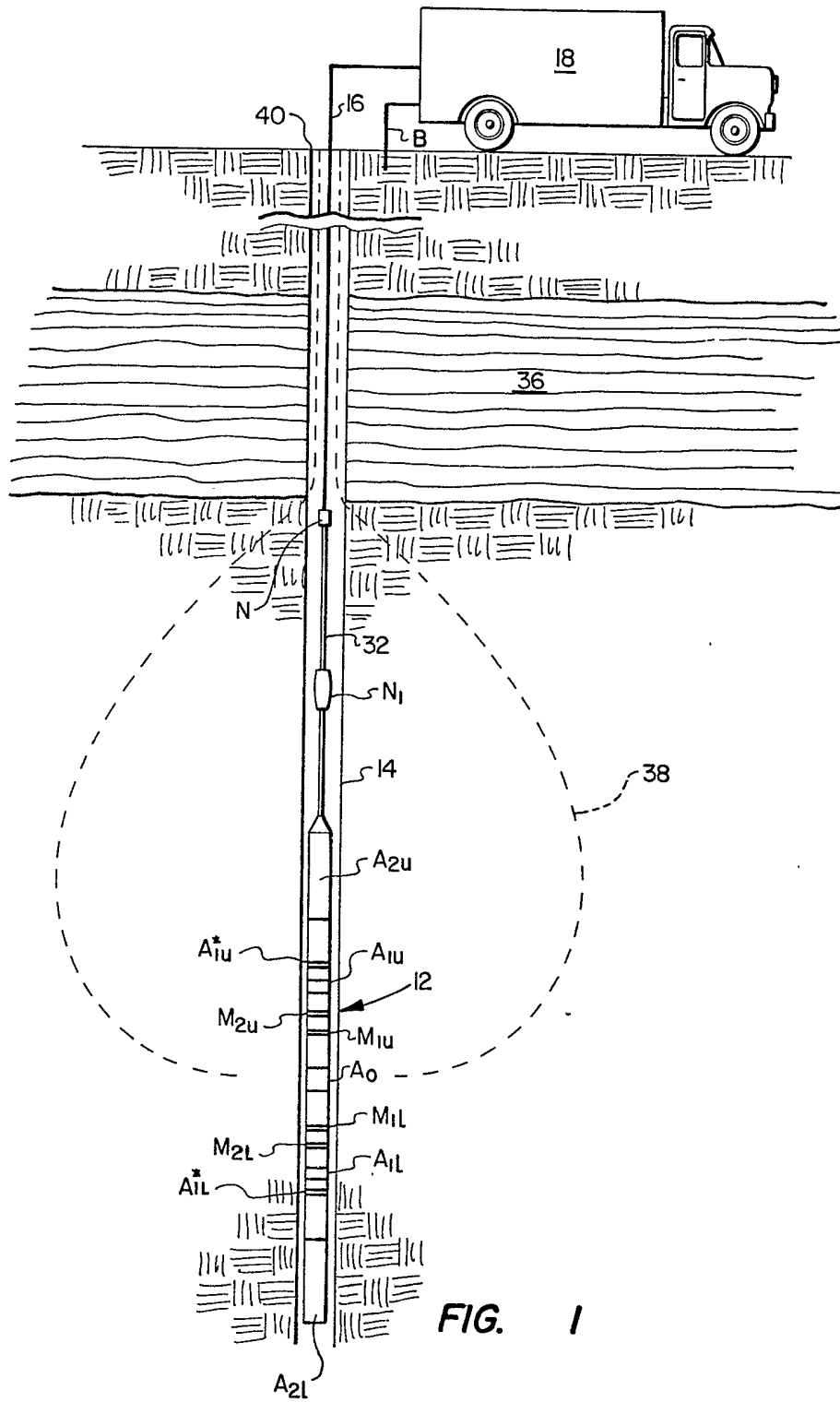


FIG. 1. A



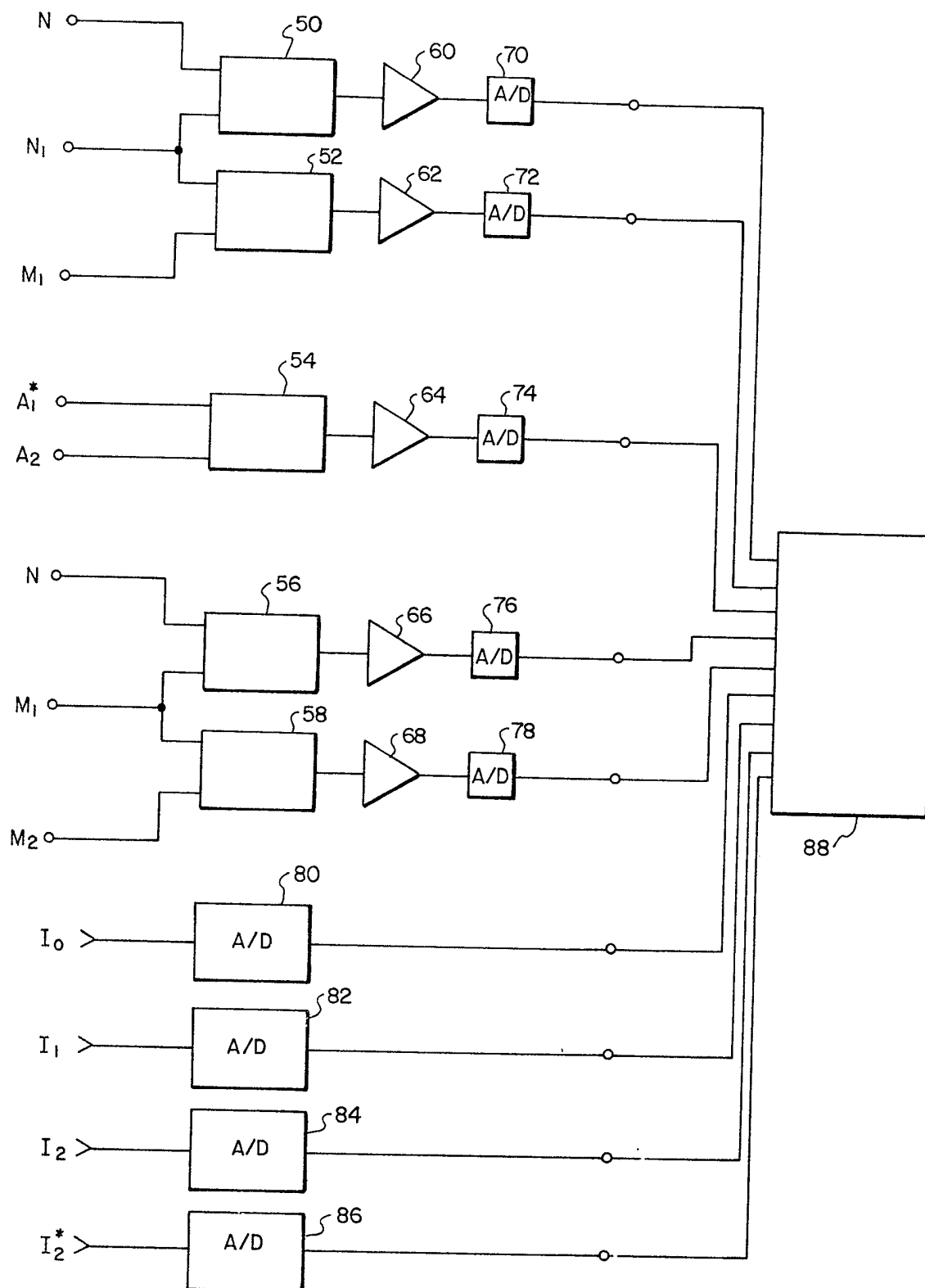


FIG. 2

SPECIFICATION

Method and apparatus for reducing Groeningen effect errors in resistivity measurements of an earth formation

- 5 This invention relates to geological formation exploration in general and in particular to the utilization of resistivity measurements in the exploration of geological formations. More particularly, this invention relates to a method and apparatus for reducing anomaly induced errors in such resistivity measurements of geological formations.
- 10 It is well known in the prior art that the sedimentary portion of the earth's surface is generally comprised of successive layers or beds which generally do not have a constant thickness. Each of these beds will typically exhibit a certain resistivity characteristic which can be highly useful in the evaluation of a particular borehole with regard to the presence of hydrocarbon deposits. The resistivity characteristics of a particular formation are generally investigated by introducing a resistivity measurement sonde into the borehole. Such sondes
- 15 are generally lowered into a borehole on a cable utilizing a section of insulated cable generally known as the "bridle" which is generally disposed between the cable and the sonde.
- While disposed in the borehole, the resistivity measuring sonde is utilized to generate a survey current and generally one or more focusing or "bucking" currents which are utilized to obtain deeper lateral penetration of the formation by the survey current. In previously known resistivity measurement sondes, voltage
- 20 measurements taken between electrodes disposed on the sonde are utilized to constantly adjust the amount of focusing current necessary to optimize the penetration of the survey current into the formation. A return electrode is utilized at the surface to provide a return for the various currents and permit the current measurements necessary to determine formation resistivity. A voltage reference electrode is also generally utilized and is generally located at a point between the lower part of the conductive cable and the sonde.
- 25 While this system has worked well for many years, certain field conditions have been encountered which cause errors in the calculated or apparent resistivity of the formation. One such error is induced due to an anomaly in the resistance of a formation above the sonde which causes variations in the return path of the survey and focusing currents to the return electrode. When attempting resistivity measurements in a low resistance earth formation below a highly resistive bed, the survey and focusing currents tend to return
- 30 along the well casing or cable and induce a greater than normal voltage at the reference electrode disposed above the sonde. This results in an error in calculation due to the fact that the voltage differential between the sonde and the reference electrode will not be equal to the voltage differential between the sonde and the theoretical point at infinity utilized in these calculations.
- This particular error, sometimes referred to as the "Groeningen" effect or "casing" effect is particularly distressing in that the resultant resistivity measurements are similar in nature to those associated with
- 35 petrochemical deposits when such deposits are not present. The expense associated with drilling and testing these wellbores makes it desirable that a method and apparatus be defined to correct for or reduce the errors induced by such resistive anomalies. One method of correcting for this error involves the utilization of very low frequency currents; however, since several cycles of current are necessary to complete a single
- 40 resistivity measurement, the speed at which the sonde must be operated in this method is quite slow. The expense associated with these wells and equipment dictates that these measurements be taken as rapidly as possible, thereby eliminating this approach as a viable alternative.
- It is therefore one object of the present invention to provide an improved apparatus for reducing anomaly induced errors in resistivity measurements of earth formations.
- 45 It is another object of the present invention to provide an improved method for reducing anomaly induced errors in resistivity measurements of earth formations.
- It is yet another object of the present invention to provide an improved method for reducing anomaly induced errors in resistivity measurements of earth formations which permits the resistivity measurement device to be operated at normal speeds.
- 50 It is another object of the present invention to provide an improved method for reducing anomaly induced errors in resistivity measurements of earth formations which can be utilized in conjunction with known resistivity measurement sondes.
- The present invention provides a method for reducing anomaly induced errors in resistivity measurements of an earth formation traversed by a borehole in which the resistivity measurement is accomplished
- 55 utilizing a sonde suspended in said borehole from a conductive cable in the borehole, said sonde having a plurality of voltage measuring electrodes and current emitting electrodes disposed thereon and a first reference electrode disposed above said sonde, comprising:
- emitting a survey current from a selected one of said plurality of current emitting electrodes and measuring the voltage induced by said survey current at at least a selected one of said voltage measuring
- 60 electrodes;
- disposing a second reference electrode between said first reference voltage electrode and said sonde;
- emitting a first focusing current at a first selected frequency from a selected one of said plurality of current emitting electrodes and measuring the voltage induced by said first focusing current between said sonde and said second reference electrode;
- 65 emitting a second focusing current at a frequency substantially below said first selected frequency from a

selected one of said plurality of current emitting electrodes and measuring the voltage induced by said second focusing current between said second reference electrode and said first reference electrode; and combining the voltage induced by said first focusing current and the voltage induced by said second focusing current to obtain a resultant total voltage measurement between said sonde and said first reference electrode wherein said resultant total voltage measurement has a reduced anomaly induced error.

The various voltages induced by the survey and focusing currents may be utilized to calculate a corresponding set of transfer impedances for that current. By utilizing the calculated transfer impedances, the relationships of focusing currents to survey current which is necessary to properly focus the sonde may be calculated. With the relationship of the survey current and focusing currents thus defined, the apparent resistivity of the formation may be expressed as a function of the transfer impedances and the currents without the necessity of actually altering the amounts of focusing current.

In an embodiment of the invention, one of the focusing currents is operated at a very low frequency to minimize the effect of a resistive anomaly and, by measuring the voltages induced by that current between widely spaced electrodes, the sonde may be operated at a faster rate than would otherwise be possible.

The present invention further provides apparatus for correcting anomaly induced errors in resistivity measurements of an earth formation traversed by a borehole in which the resistivity measurement is accomplished utilizing voltage measurements between a sonde suspended in said borehole from a conductive cable and a first reference electrode disposed above said sonde, comprising:

means for emitting a first focusing current from said sonde at a selected frequency;

a second reference electrode disposed between said first reference electrode and said sonde;

means for measuring a first voltage induced by said first focusing current between said sonde and said second reference electrode;

means for emitting a second focusing current from said sonde at a frequency substantially below said selected frequency;

means for measuring a second voltage induced by said second focusing current between said second reference electrode and said first reference electrode; and

means for combining said first voltage and said second voltage wherein said resultant voltage is a corrected measurement of the voltage measurement between said sonde and said first reference electrode.

By way of example, an embodiment of the invention will now be described with reference to the

accompanying drawings, wherein:

Figure 1 is a partially schematic, partially diagrammatic view of resistivity measuring apparatus of the present invention; and

Figure 2 is a block diagram of the circuitry of resistivity measuring apparatus of the present invention.

With reference now to the Figures, and in particular with reference to *Figure 1*, there is depicted a partially schematic, partially diagrammatic view of the resistivity measuring apparatus of the present invention.

The method and apparatus disclosed herein will find application with many different types of resistivity measuring devices; however, for purposes of explanation, the embodiment disclosed herein is described with respect to a so-called "deep laterolog". The "deep laterolog" is designed to measure formation resistivities at greater distances from the borehole and, in particular, beyond the "invaded zone" where the presence of drilling fluids may alter the formation resistivity.

As in most typical installations of this type, the system includes a sonde 12 suspended in a borehole 14 by means of a wireline cable 16. Electrical conductors (not shown) disposed within wireline cable 16 are coupled to various electronic processing devices contained in van 18. Sonde 12 includes a plurality of voltage measuring electrodes M_{1L} and M_{1U} , M_{2L} and M_{2U} , and A_{1L}^* and A_{1U}^* which are disposed on the surface of sonde 12 on either side of a survey current emitting electrode A_0 . The subscripts U and L signify the upper and lower of each pair of a pair of symmetrical electrodes. Sonde 12 also includes a plurality of focus current emitting electrodes A_{1L} , A_{1U} , A_{2L} and A_{2U} .

Also depicted in *Figure 1* is a voltage reference electrode or torpedo N which is separated from sonde 12 by a length of insulated cable 32, typically referred to as a "bridle." Located between sonde 12 and torpedo N is an additional voltage measuring electrode N_1 . Electrode N_1 is particularly useful in the method disclosed herein for reducing errors in the formation resistivity measurements which may be caused by resistive anomalies such as zone 36.

As is depicted in *Figure 1*, a typical path of return for survey current 38 is altered by the highly resistive nature of zone 36. Rather than proceeding radially outward to return electrode B, the path of survey current is altered by the presence of wireline cable 16 and well casing 40. Those skilled in the art will appreciate that the electromagnetic phenomena known as "skin effect" will enhance this alteration of return path and induce a greater than normal voltage at electrode N. This error may be minimized by utilizing very low frequency currents (typically less than one hertz); however, since it is generally acknowledged that three cycles of current are necessary for each resistivity reading, a resistivity log of several thousand feet of borehole could become very time consuming.

Fortunately, the "Groeningen" effect varies very slowly with depth and may be compensated for by utilizing this novel technique of independent voltage and current measurements which permits sonde 12 to be operated at normal logging speeds while simultaneously measuring and computing a "focused" condition which is corrected for the errors induced by the effect.

In order to understand the novel method and apparatus being described it is necessary to understand the

operation of a conventional deep laterolog system.

Generally, a survey current I_0 is emitted by the central electrode A_0 and a plurality of focusing currents are emitted from electrodes A_{1L} , A_{1U} , A_{2L} and A_{2U} . The ratios between focusing currents and survey current are constantly adjusted to maintain a zero or null voltage gradient between electrode pairs M_1 and M_2 and A_1^* and A_2 . 5

In order to simplify the notation utilized herein, the average voltage of symmetrical electrode pairs, without U and L subscripts, is written utilizing the rule expressed in equation (1):

$$V_{M_1} = \frac{V_{M_{1U}} + V_{M_{1L}}}{2} \quad (1) \quad 10$$

Similarly, the sum of currents flowing from (or to) symmetrical electrodes will be written without the U and L subscript as follows:

$$I_1 = (I_{1U} + I_{1L}) \quad (2) \quad 15$$

When the aforementioned zero voltage gradient is achieved and the sonde is "focused," the apparent resistivity of a formation can be expressed by:

$$Ra = \frac{K [V_{M_1} - V_{N_0}]}{I_0} \quad (3) \quad 20$$

Where N_0 is a remote electrode which is ideally at electrical infinity. In actual practice, the voltage measurement is taken with respect to torpedo N. In general, torpedo N is far enough away from sonde 12 that no error occurs. However, as depicted in Figure 1, measurements taken beneath a zone of high resistivity can be perturbed by the presence of the current flowing down wireline cable 16 to sonde 12. 25

The method of the present invention utilizes four nominal value currents which are emitted from sonde 12. A survey current I_0 is emitted from electrode A_0 . Three separate focusing currents are also utilized. Current I_1 is emitted from electrodes A_{1U} and A_{1L} ; current I_2 is emitted from electrodes A_{2U} and A_{2L} ; and, current I_2^* is also emitted from electrodes A_{2U} and A_{2L} . 30

Each of these currents is emitted independently which, as those skilled in the art will appreciate, can be accomplished by alternately emitting each current or by continuously emitting all currents at various different frequencies. No attempt is made during this process to alter the amount of focusing current being emitted to actually balance sonde 12. In the preferred mode of the present invention, currents I_0 and I_1 are alternately emitted at several hundreds of hertz, current I_2 is emitted at less than 100 hertz and current I_2^* at a very low frequency (less than one hertz). 35

Preferably, during the period of time that each current is emitted, a series of five voltage potentials are measured:

40	Voltage	Measuring Point	40
	V_1	between M_1 and N	
	V_2	between M_1 and M_2	
	V_3	between A_1^* and A_2	
45	V_4	between M_1 and N_1	45
	V_5	between N_1 and N	

Each of these voltages is utilized in conjunction with each current to generate five transfer impedances for sonde 12 for each current source. In this manner, the principle of superposition in linear circuitry permits the amounts of various currents necessary to achieve a desired voltage level to be simply and easily computed utilizing the transfer impedances. The matrix of thus calculated transfer impedances is as follows:

55		V_1	V_2	V_3	V_4	V_5	55
	I_0	a_{01}	a_{02}	a_{03}	a_{04}	a_{05}	
	I_1	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	
	I_2	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}	
	I_2^*	a_{31}	a_{32}	a_{33}	a_{34}	a_{35}	(4)
60							60

By now setting I_0 equal to unity and writing the conditions necessary to balance sonde 12, the theoretical amount of focusing currents necessary to balance the tool may be derived. The balance conditions are:

$$I_0 = 1 \quad (5)$$

5

$$V_2 = V_{M_1} - V_{M_2} = a_{02}I_0 + a_{12}I_1 + a_{22}I_2 = 0 \quad (6)$$

$$V_3 = V_{A_1^*} - V_{A_2} = a_{03}I_0 + a_{13}I_1 + a_{23}I_2 = 0 \quad (7)$$

10

By solving equations (5), (6) and (7) we can determine the exact amount of focusing current necessary to balance sonde 12 without the limitations generally imposed by physical constraints in existing systems.

15

$$I_0 = 1 \quad (8)$$

$$I_1 = \frac{a_{02}a_{23} - a_{03}a_{22}}{a_{22}a_{13} - a_{12}a_{23}} \quad (9)$$

20

$$I_2 = \frac{a_{02}a_{13} - a_{03}a_{12}}{a_{12}a_{23} - a_{22}a_{13}} \quad (10)$$

25

Given the precise amount of focusing current needed to balance sonde 12, the apparent resistivity of sonde 12 can be expressed as follows:

30

$$R_a = K(a_{01}I_0 + a_{11}I_1 + a_{21}I_2) / I_0 \quad (11)$$

As those skilled in the art will appreciate, by substituting equations (9) and (10) into equation (11) the apparent resistivity of the formation may be expressed as a function of transfer impedances with I_0 being constrained to unity.

35

This expression of the apparent resistivity of the formation is not corrected for the resistive anomaly of zone 36. This error can be seen to be an error in transfer impedance a_{21} due to the spurious voltage induced between electrodes M_1 and N by the altered current path. In order to reduce this error it is only necessary to replace transfer impedance a_{21} by a combination of two different transfer impedances, only one of which can be measured at a very low frequency. Indeed, since the voltage difference between electrodes M_1 and N is equal to the voltage difference between electrodes M_1 and N_1 plus the voltage difference between electrodes N_1 and N , transfer impedance a_{21} can be replaced by a combination of transfer impedances a_{24} and a_{35} , where a_{24} is measured at a less than one hundred hertz and a_{35} is measured at a very low frequency. By having measured the voltage induced between electrodes N_1 and N at a very low frequency, this measurement can be combined with the voltage induced between electrodes M_1 and N_1 at normal survey frequencies to generate a corrected voltage measurement as expressed in equation (12):

$$R_a = K[a_{01}I_0 + a_{11}I_1 + (a_{24} + a_{35})I_2] / I_0 \quad (12)$$

50

Those ordinarily skilled in the art will appreciate that the physical distances between electrodes M_1 , N_1 and N are much greater than the distances between electrodes disposed on sonde 12, and this physical separation will permit the measurement of the voltage between electrode N_1 and N to be accomplished at a very low frequency.

55

A block diagram of the circuitry necessary to perform this method is depicted in Figure 2. As can be seen, the voltages at each electrode on sonde 12 are coupled to appropriate band pass filters 50, 52, 54, 56 and 58, in those embodiments in which differing frequencies are utilized. The outputs of each band pass filter are then amplified by amplifiers 60, 62, 64, 66 and 68 and coupled to analog-to-digital converters 70, 72, 74, 76 and 78. Similarly, the amount of current emitted from each electrode is coupled to an appropriate

60

analog-to-digital converter 80, 82, 84 and 86. The outputs of each analog-to-digital converter are then coupled to an appropriately programmed digital processing device 88 which is utilized, in a preferred embodiment of the present invention, to calculate the necessary transfer impedances and to control the selective application of various survey and focusing currents in a manner well known in the art.

CLAIMS

1. A method for reducing anomaly induced errors in resistivity measurements of an earth formation traversed by a borehole in which the resistivity measurement is accomplished utilizing a sonde suspended in
5 said borehole from a conductive cable in the borehole, said sonde having a plurality of voltage measuring electrodes and current emitting electrodes disposed thereon and a first reference electrode disposed above said sonde, comprising: 5
- emitting a survey current from a selected one of said plurality of current emitting electrodes and measuring the voltage induced by said survey current at at least a selected one of said voltage measuring
10 electrodes; 10
- disposing a second reference electrode between said first reference voltage electrode and said sonde;
emitting a first focusing current at a first selected frequency from a selected one of said plurality of current
emitting electrodes and measuring the voltage induced by said first focusing current between said sonde
and said second reference electrode;
- 15 emitting a second focusing current at a frequency substantially below said first selected frequency from a 15
selected one of said plurality of current emitting electrodes and measuring the voltage induced by said
second focusing current between said second reference electrode and said first reference electrode; and
combining the voltage induced by said first focusing current and the voltage induced by said second
focusing current to obtain a resultant total voltage measurement between said sonde and said first reference
20 electrode wherein said resultant total voltage measurement has a reduced anomaly induced error. 20
2. The method for reducing anomaly induced errors in resistivity measurements of an earth formation according to Claim 1 further including the step of calculating a first set of transfer impedances for said sonde by means of measuring said survey current and said voltage induced by said survey current.
3. The method for reducing anomaly induced errors in resistivity measurements of an earth formation
25 according to Claim 2 further including the step of calculating a second set of transfer impedances for said 25
sonde by means of measuring said first focusing current and said voltage induced by said first focusing
current.
4. The method for reducing anomaly induced errors in resistivity measurements of an earth formation according to Claim 3 further including the step of calculating a third set of transfer impedances for said
30 sonde by means of measuring said second focusing current and the voltage induced by said second focusing 30
current.
5. The method for reducing anomaly induced errors in resistivity measurements of an earth formation according to Claim 4 further including the step of calculating the amount of focusing current needed to properly focus said sonde by utilizing said first, second and third sets of transfer impedances.
- 35 6. The method for reducing anomaly induced errors in resistivity measurements of an earth formation 35
according to Claim 5 further including the step of calculating the resistivity of an earth formation transversed
by said sonde as a function of said survey current, said first focusing current, said second focusing current
and said first, second and third sets of transfer impedances.
7. Apparatus for correcting anomaly induced errors in resistivity measurements of an earth formation
40 traversed by a borehole in which the resistivity measurement is accomplished utilizing voltage measure- 40
ments between a sonde suspended in said borehole from a conductive cable and a first reference electrode
disposed above said sonde, comprising:
- means for emitting a first focusing current from said sonde at a selected frequency;
- a second reference electrode disposed between said first reference electrode and said sonde;
- 45 means for measuring a first voltage induced by said first focusing current between said sonde and said 45
second reference electrode;
- means for emitting a second focusing current from said sonde at a frequency substantially below said
selected frequency;
- means for measuring a second voltage induced by said second focusing current between said second
50 reference electrode and said first reference electrode; and 50
- means for combining said first voltage and said second voltage wherein said resultant voltage is a
corrected measurement of the voltage measurement between said sonde and said first reference electrode.
8. The apparatus for correcting anomaly induced errors in resistivity measurements of an earth
formation according to Claim 7 further including an elongate insulated cable disposed between said sonde
55 and said first reference electrode. 55
9. The apparatus for correcting anomaly induced errors in resistivity measurements of an earth
formation according to Claim 8 wherein said second reference electrode is disposed on said elongated
insulated cable.
10. The apparatus for correcting anomaly induced errors in resistivity measurements of an earth
60 formation according to Claim 7 wherein said sonde includes a plurality of current emitting electrodes and 60
wherein said survey current is emitted from a first selected current emitting electrodes and wherein said first
and second focusing currents are emitted from a second selected current emitting electrode.
11. A method for reducing anomaly induced errors in resistivity measurements of an earth formation
traversed by a borehole, in which the resistivity measurement is accomplished utilizing a sonde suspended
65 in said borehole from a conductive cable in said borehole, said sonde having a plurality of voltage measuring 65

- electrodes and current emitting electrodes disposed thereon, comprising:
 suspending said sonde from said conductive cable utilizing a length of insulated cable;
 disposing a first reference electrode above said sonde;
 disposing a second reference electrode on said insulated cable at a point between said first reference
- 5 electrode and said sonde; 5
 emitting a survey current from a selected one of said current emitting electrodes;
 measuring the voltages induced by said survey current at at least one of said voltage measuring
 electrodes;
 computing at least a first set of transfer impedances utilizing said voltages induced at at least one of said
- 10 voltage measuring electrodes and said survey current; 10
 emitting a first focusing current from a selected one of said current emitting electrodes;
 measuring the voltages induced by said first focusing current between said sonde and said second
 reference electrode;
 computing at least a second set of transfer impedances utilizing said voltages induced between said sonde
- 15 and said second reference electrode and said first focusing current; 15
 emitting a second focusing current from a selected one of said current emitting electrodes at a frequency
 substantially below the frequency of said first focusing current;
 measuring the voltages induced by said second focusing current between said second reference electrode
 and said first reference electrode;
- 20 computing at least a third set of transfer impedances utilizing said voltages induced between said second 20
 reference electrode and said first reference electrode and said second focusing current; and
 determining the resistivity of the earth formation as a function of said first, second and third sets of
 transfer impedances.
12. A method according to any one of claims 1 to 6 and 11, substantially as described herein with
- 25 reference to the accompanying drawings. 25
 13. Apparatus for correcting anomaly induced errors in resistivity measurements of an earth formation
 traversed by a borehole, the apparatus being substantially as described herein with reference to, and as
 illustrated by the accompanying drawings.