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(71) Applicant (for all designated States except US): **BAKER HUGHES INCORPORATED** [US/US]; P. O. Box 4740, 2929 Allen Parkway, Suite 2100, Houston, TX 77019-2118 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **BESPALOV, Alexandre, N.** [RU/US]; 739 Cypresswood Cove, Spring, TX 77373 (US). **MERCHANT, Gulamabbas** [US/US]; 16011 Mission Village Drive, Houston, TX 77083 (US). **XUE, Cynthia, Dong** [CN/US]; 2350 Bagby Street, Apt. No. 9202, Houston, TX 77006 (US). **PELEGRI, Luis, M.** [AR/US]; 6106 Spruce Bough Ct., Humble, TX 77346 (US). **RABINOVICH, Michael, B.** [US/US]; 206 Heatherbrook Lane, Houston, TX 77094 (US).

PAINCHAUD, Stephen, V. [US/US]; 17703 Shady Canyon Lane, Tomball, TX 77373 (US). **CORLEY, Bill, H.** [US/US]; 639 South Rivershire, Conroe, TX 77304 (US). **FORGANG, Stanislav, W.** [US/US]; 18055 Somerset Knolls, Houston, TX 77094-1429 (US).

(74) Agents: **DONOUGHUE, Timothy, M.** et al.; Baker Hughes Incorporated, P.O. Box 4740, Houston, TX 77027-4740 (US).

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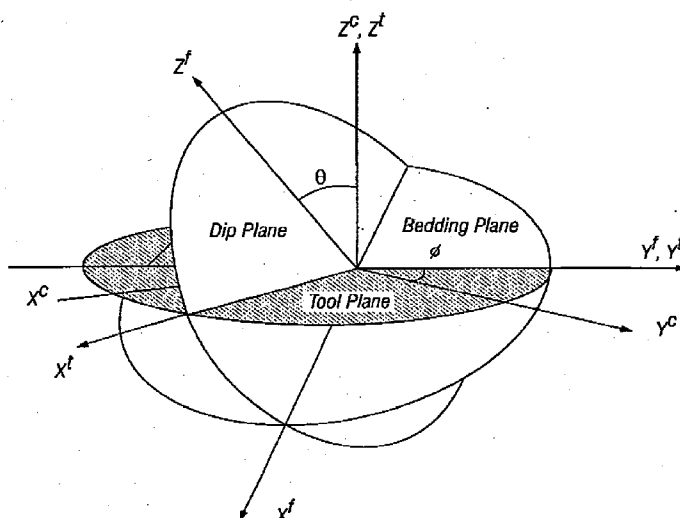


FIG. 9

(57) Abstract: Measurements made by a multi-component induction logging tool are corrected for tool eccentricity in a deviated borehole. The eccentricity angle is determined from single frequency skin-effect corrected data and is then used to correct multi-frequency data. Multifrequency focusing is then applied to the corrected multifrequency data. An inversion is then used to recover formation resistivity and relative dip and azimuth of the borehole.

WO 2009/018331 A1



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594-45936WO

**CORRECTION OF MULTI-COMPONENT MEASUREMENTS FOR TOOL
ECCENTRICITY IN DEVIATED WELLS**

**Alexandre N. Besspalov; Gulamabbas Merchant; Cynthia Dong Xue; Luis M.
Pelegri; Michael B. Rabinovich; Stephen V. Painchaud; Bill H. Corley; Stanislav
5 W. Forgang; Randy Gold**

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

[0001] The disclosure is related generally to the use of multi-component resistivity measurements for determination of properties of earth formations.

10 **2. Background of the Art**

[0002] Electromagnetic induction resistivity well logging instruments are well known in the art. Electromagnetic induction resistivity well logging instruments are used to determine the electrical conductivity, and its converse, resistivity, of earth formations penetrated by a borehole. Formation conductivity has been determined based on
15 results of measuring the magnetic field of eddy currents that the instrument induces in the formation adjoining the borehole. The electrical conductivity is used for, among other reasons, inferring the fluid content of the earth formations. Typically, lower conductivity (higher resistivity) is associated with hydrocarbon-bearing earth formations. The physical principles of electromagnetic induction well logging are
20 well described, for example, in, J. H. Moran and K. S. Kunz, *Basic Theory of Induction Logging and Application to Study of Two-Coil Sondes*, Geophysics, vol. 27, No. 6, part 1, pp. 829-858, Society of Exploration Geophysicists, December 1962. Many improvements and modifications to electromagnetic induction resistivity instruments described in the Moran and Kunz reference, supra, have been devised,
25 some of which are described, for example, in US 4,837,517 to Barber, in US 5157605 to Chandler et al., and in US 5,600,246 to Fanini et al.

[0003] Conventional induction well logging techniques employ an insulating pipe inside a coil mandrel. One or more transmitter coils are energized by an alternating current. The oscillating magnetic field produced by this arrangement results in the

594-45936WO

induction of currents in the formations which are nearly proportional to the conductivity of the formations. These currents, in turn, contribute to the voltage induced in one or more receiver coils. By selecting only the voltage component which is in phase with the transmitter current, a signal is obtained that is

5 approximately proportional to the formation conductivity. In conventional induction logging apparatus, the basic transmitter coil and receiver coil have axes which are aligned with the longitudinal axis of the well logging device. This arrangement tends to induce secondary current loops in the formations that are concentric with the vertically oriented transmitting and receiving coils. The resultant conductivity

10 measurements in a vertical well (one with its axis normal to bedding) are indicative of the horizontal conductivity (or resistivity) of the surrounding formations. There are, however, various formations encountered in well logging which have a conductivity that is anisotropic. Anisotropy results from the manner in which formation beds were deposited by nature. For example, "uniaxial anisotropy" is characterized by a

15 difference between the horizontal conductivity, in a plane parallel to the bedding plane, and the vertical conductivity, in a direction perpendicular to the bedding plane. When there is no bedding dip, horizontal resistivity can be considered to be in the plane perpendicular to the borehole, and the vertical resistivity in the direction parallel to the bore hole. Conventional induction logging devices, which tend to be sensitive

20 only to the horizontal conductivity of the formations, do not provide a measure of vertical conductivity or of anisotropy. Techniques have been developed to determine formation anisotropy. See, e.g. US 4,302,722 to *Gianzero et al.* Transverse anisotropy often occurs such that variations in resistivity occur in the azimuthal direction.

25 **[0004]** In the transverse induction logging tools the response of transversal coil arrays is determined by an average resistivity, however, the relatively lower conductivity of hydrocarbon-bearing sand layers dominates in this estimation. In general, the volume of shale/sand in the formation can be determined from gamma-ray or nuclear well logging measurements. Then a combination of the conventional induction logging

30 tool with transmitters and receivers oriented along the well axis and the transversal

594-45936WO

induction logging tool can be used for determining the conductivity of individual shale and sand fractions.

[0005] Multi-component signals can be used for interpreting formation resistivities and petrophysical parameters. The principles used for this interpretation have been discussed, for example, in U.S. 6,470,274 to *Mollison* et al., U.S. 6,643,589 to *Zhang* et al., U.S. 6,636,045 to *Tabarovsky* et al., the contents of which are incorporated herein by reference. Specifically, the parameters estimated may include horizontal and vertical resistivities (or conductivities), relative dip angles, strike angles, sand and shale content and water saturation. In addition, US Patent Application Ser. No. 11/125,530 of *Rabinovich* et al. teaches the use of multi-component measurements for analysis of fractured earth formations that may also have anisotropic layers.

[0006] Not discussed in the prior art is the effect of tool eccentricity on multi-component measurements. US Patent Application Ser. No. 11/400,548 of *Rabinovich* et al. having the same assignee as the present application addresses the problem of correcting for a disturbance such as tool eccentricity that affects the azimuthal response of a multicomponent logging tool. The teachings of *Rabinovich* are primarily directed towards a vertical borehole and demonstrate methods of processing to address the problem. The present disclosure is applicable to deviated boreholes and also presents hardware solutions to the problem of eccentricity.

SUMMARY OF THE DISCLOSURE

[0007] Another embodiment of the disclosure is a method of determining a resistivity property of an earth formation. The method includes positioning a logging tool in a borehole with the tool displaced from a center of the borehole in a first direction. Multicomponent measurements are made at a plurality of frequencies indicative of the resistivity property. The multicomponent measurements are used to estimate the resistivity property of the earth formation, and the estimated resistivity property is recorded on a suitable medium. The multicomponent measurements may be obtained using a transmitter antenna on the logging tool with an axis substantially along the first direction. Estimating the resistivity property may be done performing an inversion in which at least one of the multicomponent measurements is excluded.

594-45936WO

Estimating the resistivity property may include a multifrequency focusing. The method may further include using the estimated resistivity property to determine a horizontal resistivity, a vertical resistivity, a relative dip angle, an azimuthal angle, a sand fraction, a water saturation, and/or a permeability. The method may further

5 include conveying the logging tool into the borehole on a wireline. The method may further include obtaining the multicomponent measurements by using an additional transmitter antenna on a logging tool with an axis substantially orthogonal to the first direction. The transmitter antenna may be extended from a body of the logging tool.

[0008] Another embodiment of the disclosure is an apparatus for determining a

10 resistivity property of an earth formation. The apparatus includes a logging tool configured to be positioned in a borehole with the tool displaced from a center of the borehole in a first direction and make multicomponent measurements at a plurality of frequencies indicative of a resistivity property of the earth formation. A processor is configured to estimate from the measurements the resistivity property of the earth

15 formation, and record the estimated resistivity property on a suitable medium. The logging tools may be configured to obtain the multicomponent measurements by using a transmitter antenna on the logging tool with an axis substantially along the first direction. The processor may be further configured to estimate the resistivity property by performing an inversion in which at least one of the measurements is

20 excluded. The processor may be configured estimate resistivity property by applying a multifrequency focusing. The processor may be further configured to use the estimated resistivity property to determine a horizontal resistivity, a vertical resistivity, a relative dip angle, an azimuthal angle, a sand fraction, a water saturation, and/or a permeability. The apparatus may include a wireline configured to convey the

25 logging tool into the borehole. The logging tool may include an additional transmitter antenna within axis substantially orthogonal to the first direction. The transmitter antenna may be extendable from a body of the logging tool.

[0009] Another embodiment of the disclosure is a computer-readable medium for use with an apparatus for evaluating an earth formation. The apparatus includes a logging

30 tool configured to be positioned in a borehole with the tool displaced from a center of

594-45936WO

the borehole in a first direction and make multicomponent measurements indicative of a resistivity property of the earth formation. The medium includes instructions which enable a processor to estimate from the measurements the resistivity property, and record the estimated property on a suitable medium. The medium may include a

5 ROM, (i) an EPROM, (ii) an EEPROM, (iii) a flash memory, and (iv) an optical disk

BRIEF DESCRIPTION OF THE FIGURES

[0010] The present disclosure is best understood with reference to the following figures in which like numbers refer to like components and in which:

10 **FIG. 1** illustrates an induction instrument disposed in a wellbore penetrating an earth formation;

FIG. 2 (prior art) illustrates the arrangement of transmitter and receiver coils in multi-component induction logging tool marketed under the name 3DExplorer™;

FIG. 3 illustrates an eccentric logging tool inside a borehole;

15 **FIG. 4** illustrates a logging tool inside a borehole with a fracture direction indicated thereon;

FIG. 5 illustrates a model used for simulating fractures in the subsurface;

FIG. 6 illustrates simulation results for vertical resistive fractures of different length on HDIL and skin effect corrected (SEC) 3DEX measurements;

20 **FIGS. 7a-7d** show simulated current flows in a horizontal plane intersected by a vertical fracture;

FIG. 8 is a flow chart illustrating different embodiments of the present disclosure;

FIG. 9 shows the different angles of interest in a deviated borehole;

25 **FIG. 10a-10c** show a centered tool and two possible directions of eccentricity of the tool in the borehole;

FIG. 11 illustrates the determined rotation angle from single-frequency measurements for different eccentricities for a model with an eccentricity angle of 30°;

30 **FIG. 12** illustrates the determined rotation angle from single frequency

594-45936WO

measurements for different eccentricities for a model with an eccentricity angle of 45°;

FIG. 13 illustrates a flow chart of an embodiment of the disclosure used in deviated boreholes;

5 **FIGS. 14a, 14b** shows an embodiment of the disclosure in which bowsprings are used to maintain a transverse coil oriented along a borehole diameter;

FIG. 15 shows an arrangement in which transmitter and receiver coils are mounted on two mandrels maintained at substantially 90° to each other;

10 **FIG. 16** shows an arrangement in which two mandrels are extended from a central housing in one embodiment of the present disclosure; and

FIG. 17 shows an arrangement in which two mandrels at 90° to each other are spaced apart vertically.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0011] Referring now to **FIG. 1**, an electromagnetic induction well logging
15 instrument **10** is shown disposed in a wellbore **2** drilled through earth formations. The earth formations are shown generally at **4**. The instrument **10** can be lowered into and withdrawn from the wellbore **2** by use of an armored electrical cable **6** or similar conveyance known in the art. The instrument **10** can be assembled from three subsections: an auxiliary electronics unit **14** disposed at one end of the instrument **10**;
20 a coil mandrel unit **8** attached to the auxiliary electronics unit **14**; and a receiver/signal processing/telemetry electronics unit **12** attached to the other end of the coil mandrel unit **8**, this unit **12** typically being attached to the cable **6**.

[0012] The coil mandrel unit **8** includes induction transmitter and receiver coils, as will be further explained, for inducing electromagnetic fields in the earth formations **4**
25 and for receiving voltage signals induced by eddy currents flowing in the earth formations **4** as a result of the electromagnetic fields induced therein.

[0013] The auxiliary electronics unit **14** can include a signal generator and power amplifiers (not shown) to cause alternating currents of selected frequencies to flow through transmitter coils in the coil mandrel unit **8**. A processor which controls the
30 operation of the tool and processing acquired data may be part of the electronics unit.

594-45936WO

Alternatively, some or all of the processing and control may be done by a surface processor.

[0014] The receiver/signal processing/telemetry electronics unit **12** can include receiver circuits (not shown) for detecting voltages induced in receiver coils in the coil mandrel unit **8**, and circuits for processing these received voltages (not shown) into signals representative of the conductivities of various layers, shown as **4A** through **4F** of the earth formations **4**. As a matter of convenience the receiver/signal processing/telemetry electronics unit **12** can include signal telemetry to transmit the conductivity- related signals to the earth's surface along the cable **6** for further processing, or alternatively can store the conductivity related signals in an appropriate recording device (not shown) for processing after the instrument **10** is withdrawn from the wellbore **2**.

[0015] The example in **FIG. 1** shows a vertical well. This is not to be construed as a limitation to the disclosure, and the method of the present disclosure may be used for analyzing data acquired in a deviated well.

[0016] Referring to **FIG. 2**, the configuration of transmitter and receiver coils in the 3DEXTM multi-component induction logging instrument of Baker Hughes is shown. This is for exemplary purposes only and any multi-component tool may be used. Three orthogonal transmitters **101**, **103** and **105** that are referred to as the T_x , T_z , and T_y transmitters are shown (the z - axis is the longitudinal axis of the tool). Corresponding to the transmitters **101**, **103** and **105** are associated receivers **107**, **109** and **111**, referred to as the R_x , R_z , and R_y receivers, for measuring the corresponding magnetic fields. It should be noted that the method of the present disclosure may also be used with non-orthogonal configurations of transmitters and receivers. Well known coordinate rotation methods may be used with such non-orthogonal measurements to rotate them into the desired orientation. For the purposes of the present disclosure, all such measurements (orthogonal and non-orthogonal) will be referred to as multi-component measurements.

[0017] We first discuss the teachings of US Patent Application Ser. No. 11/400,548 of *Rabinovich et al.* having the same assignee as the present application. The

594-45936WO

Rabinovich '548 application addresses the problem of correcting for a disturbance such as tool eccentricity that affects the azimuthal response of a multicomponent

logging tool. The method includes making at least one multi-component measurement using a logging tool in a borehole in the earth formation. The multi-

5 component measurements are indicative of a resistivity property of the earth formation and are affected by a disturbance in the azimuthal direction. The method further comprises applying a correction to the multi-component measurements that corrects for the disturbance. The discussion in *Rabinovich* '548 is primarily directed towards vertical boreholes (borehole axis normal to the bedding plane). It serves as
10 the background for the present disclosure which deals with similar problems in deviated boreholes.

[0018] Turning now to **FIG. 3**, a top view of an eccentric logging tool **125** is shown within a circular borehole **127**. The tool coordinate system is defined by the (x,y) axes **121**, **123**. The eccentricity direction is defined by the direction **121'**. This

15 defines a new coordinate system (x', y') **121'**, **123'**. It can be shown that when a multi-component tool is oriented such that X-coils of the tool are aligned with the eccentricity direction, the $H_{x'x'}$ measurement (coils oriented with magnetic moments parallel to the eccentricity direction) is substantially unaffected by eccentricity. The remaining borehole effect changes very little with eccentricity due to the large spacing
20 between transmitter and receivers. In Table 1 we present results for the numerical eccentricity modeling of XX component in 12.25" hole with 0.05 Ω -m mud for 1.6 m main coil spacing and frequency 20 KHz:

Table 1. Apparent resistivities for XX component for different tool eccentricities in X-direction.

25

Eccentricity (in)	Apparent Resistivity (ohm.m)	
	Rt=Rv=5 Ohm.m	Rt=Rv=25 Ohm.m
0	7.68	24.4
0.5	7.69	24.5
1.0	7.69	24.5
1.5	7.69	24.6
2.0	7.70	24.7

594-45936WO

In Table 1, the eccentricity is defined as the distance from the center of the borehole to the center of the logging tool.

[0019] The multi-component induction tool of **FIG. 2** acquires, among other measurements, H_{xx} , H_{yy} and H_{xy} components that are oriented at unknown angle φ with respect to the eccentricity direction and corresponding coordinate system (x', y') . Below we illustrate how from measured H_{xx} , H_{yy} , and H_{xy} components from an eccentric tool **125** we can determine the orientation of the eccentricity (angle φ). By using a rotation technique, this makes it possible to extract the unaffected corresponding component $H_{x'x'}$. This unaffected component can then be used in subsequent processing for resistivity anisotropy.

[0020] For the eccentric tool the measured H_{xx} , H_{yy} , and H_{xy} components can be expressed through the principal components $H_{x'x'}$ and $H_{y'y'}$ using the known rotation equation:

$$\begin{pmatrix} H_{xx} \\ H_{yy} \\ H_{xy} \end{pmatrix} = \begin{pmatrix} \cos^2 \varphi & \sin^2 \varphi \\ \sin^2 \varphi & \cos^2 \varphi \\ -\cos \varphi \sin \varphi & \cos \varphi \sin \varphi \end{pmatrix} \begin{pmatrix} H_{x'x'} \\ H_{y'y'} \end{pmatrix} \quad (1).$$

15

When $\varphi \neq 45^\circ$, this relationship allows us immediately determine the angle φ :

$$\varphi = \frac{1}{2} \tan^{-1} \left(\frac{2H_{xy}}{H_{yy} - H_{xx}} \right). \quad (2).$$

Consequently, we can calculate the principal $H_{x'x'}$ component itself:

$$H_{x'x'} = \frac{H_{xx} \cos^2 \varphi - H_{yy} \sin^2 \varphi}{\cos^2 \varphi - \sin^2 \varphi} \quad (3).$$

When $\varphi = 45^\circ$, the full set of **eqns. (1)** must be solved.

594-45936WO

[0021] Those versed in the art and having the benefit of the present disclosure would recognize that given knowledge of the borehole diameter and the mud resistivity (or equivalently, the mud conductivity) the amount of eccentricity of the logging tool can be estimated. From a practical standpoint, this requires the use of a caliper such as an acoustic caliper to give measurements from which the borehole diameter can be estimated, and a mud resistivity measuring device. In one embodiment of the disclosure, an acoustic caliper is provided, and a mud resistivity device such as that disclosed in U.S. 6,801,039 to *Fabris et al.*, (having the same assignee as the present disclosure and the contents of which are incorporated herein by reference) may be used.

[0022] A similar problem is encountered in the presence of fractures. As discussed in US Patent Application Ser. No. 11/125,530 of *Rabinovich et al.*, resistive and conductive fractures may significantly affect the measurements of induction tools. The basic geometry is illustrated in **FIG. 4** where a 3DEX tool **145** is shown in a circular borehole **147**. The tool (x, y) coordinate system is indicated by **141**, **143**. A fracture plane is indicated by **141'** and the normal to the fracture plane is **143'**. We consider a rotated coordinate system defined by the directions **141'**, **143'**.

[0023] When a multi-component tool is oriented such that X-coils of the tool are aligned with the fracture plane, the $H_{y'y'}$ measurement (coils oriented with magnetic moments perpendicular to the fracture plane) is not affected if the fracture is resistive, *i.e.*, has a higher resistivity than the surrounding medium. This lack of sensitivity is due to the fact that the primary electric field generated by y' -transmitter (at 90° to the fracture plane) and secondary electric field inducing a magnetic field into y' -receiver are parallel to the fracture. It is well known that a thin resistive layer parallel to electric currents does not affect induction measurements.

[0024] If, on the other hand, the fracture is conductive, *i.e.*, is has a higher conductivity than the surrounding medium, the $H_{x'x'}$ measurement is not affected by the fracture due to the fact that the primary and secondary electrical currents for this component are perpendicular to the fracture and when they cross it they are not changed by a very narrow conductive interval.

594-45936WO

[0025] The multi-component induction tool of **FIG. 2** acquires, among other component, H_{xx} , H_{yy} and H_{xy} components that are oriented at unknown angle ϕ with respect to the fracture and corresponding coordinate system (x', y') . Below we illustrate how from measured H_{xx} , H_{yy} , and H_{xy} components in the presence of a

5 fracture we can determine the orientation of the fracture (angle ϕ) and consequently by using a rotation technique we can extract unaffected corresponding component $H_{x'x'}$ (for a conductive fracture) or $H_{y'y'}$ (for resistive fracture). This unaffected component then will be used in subsequent processing for resistivity anisotropy.

[0026] In the presence of fracture the measured H_{xx} , H_{yy} , and H_{xy} components can be

10 expressed through the principal components $H_{x'x'}$ and $H_{y'y'}$ using the known rotation equation, the same as **eqn. (1)**:

$$\begin{pmatrix} H_{xx} \\ H_{yy} \\ H_{xy} \end{pmatrix} = \begin{pmatrix} \cos^2 \phi & \sin^2 \phi \\ \sin^2 \phi & \cos^2 \phi \\ -\cos \phi \sin \phi & \cos \phi \sin \phi \end{pmatrix} \begin{pmatrix} H_{x'x'} \\ H_{y'y'} \end{pmatrix} \quad (4),$$

15

When $\phi \neq 45^\circ$, this relationship allows us immediately determine the angle ϕ :

$$\phi = \frac{1}{2} \tan^{-1} \left[\frac{2H_{xy}}{H_{yy} - H_{xx}} \right] \quad (5).$$

Consequently, we can calculate the principal components themselves:

594-45936WO

$$H_{x'x'} = \frac{H_{xx} \cos^2 \varphi - H_{yy} \sin^2 \varphi}{\cos^2 \varphi - \sin^2 \varphi}$$

$$H_{y'y'} = \frac{H_{xx} \sin^2 \varphi - H_{yy} \cos^2 \varphi}{\sin^2 \varphi - \cos^2 \varphi} \quad (6).$$

The principal components are in a plane transverse to the longitudinal axis of the tool. When $\varphi = 45^\circ$, the full set of **eqns. (4)** must be solved.

- 5 [0027] The two effects discussed above (eccentering and fracturing) are examples in which the response of the 3DEX tool is affected by the orientation of the tool. The correction given by **eqns. (1) - (6)** is referred to as an azimuthal correction. The azimuthal correction corrects for the effect of a disturbance in the azimuthal direction of the multi-component measurements by causes such as eccentering and fracturing.
- 10 [0028] We next discuss the effect of a vertical fracture on the H_{zz} component. **FIG. 5** shows a model that was used for simulating the effect of a vertical fracture. A fracture of radial extend $2L$ and width W intersects a vertical wellbore. **FIG. 6** depicts the results of numerical simulation for the High Definition Induction Log (HDIL), (focused curves) and 3DEX (skin-effect corrected) curves. The HDIL is an
- 15 array induction tool with transmitter and receiver coils parallel to the tool axis. Presented are twelve different fracture radii - from 0 (no fracture) to 10 feet and infinite fracture (**421, 423, 425, 427, 429, 431, 433, 435, 435, 437, 439, 441 and 443**) - for 3 different vertical resistivities: with anisotropy ratios of 1, 2, and 4 (a total of 36 cases). The length of the fracture increases in the Z direction (presented in the
- 20 track **401** by the discontinuous line **402**). For each fracture radius 100 ft of data are generated where the tools rotate from 0 to 360 degrees. The tool rotation is depicted schematically by **404**. The HDIL focused curves are in track **403**. In the next three pairs of tracks (**405a-405b**), (**407a-407b**) and (**409a-409b**), we depict 3DEX SEC curves for three anisotropy values ($\lambda = 1, 2$ and 4 with two tracks for each). The first

594-45936WO

track in each pair is the XY component while the second track in each pair shows the ZZ, XX and YY components.

- [0029] Several observations may be made on this figure. It is seen that the HDIL response is similar to that of resistive invasion - shallow focused curves read higher resistivity than the deep ones. This behavior of the focused curves is easy to explain: a shallow resistive fracture is an obstacle for the shallow induced currents that contribute mostly to the short subarrays. Note that in the top interval **421** there is no visible separation between the different curves in track **403** that correspond to the different transmitter-receiver spacing in the HDIL, while at the largest fracture length (interval **443**), the shallow curve **450** reads higher resistivities than the deep curve **452**. The induced currents with a large radius (that mostly contribute to the deep curves) are not affected at all or affected very little by shallow fractures. It is noted that a 120 in. (3.048m) depth of investigation curve does not change unless the length of the fracture becomes greater than 4 ft (1.219m).
- [0030] **FIGS. 7a-7d** show the simulated current flow in a horizontal plane for a coil with its axis parallel to the borehole. **FIG. 7a** is for $L=0$ and shows undisturbed current flowing around the borehole. **FIG. 7d** is for $L=9$ in (22.86cm) and shows the significant disruption of current flow around the borehole. **FIGS. 7b** and **7c** (which correspond to fracture radial extents of 3 in (.076m) and 6 in (1.52m) respectively) show results that are intermediate to those in **FIG. 7a** and **7d**.
- [0031] The modeling results above show that a multi-array induction tool such as the HDIL has a good sensitivity to the radial extent of a vertical resistivity fracture. A simple inversion algorithm has been developed for estimation of the radial extent of a fracture using the array induction data. At every depth, we have 6 measurements and 2 unknowns – the formation resistivity and the radial extent of the fracture. For simplicity, vertical variations in resistivity are not presently accounted for, though they could be. A look-up table of HDIL responses for different formation resistivities and different radial extent of the fractures enables the use of basic interpolation techniques to recover the formation resistivity and the radial extent of the fracture.
- [0032] A table lookup can also be done for different formation resistivities for

594-45936WO

different borehole sizes and different mud conductivities. This enables the determination of the recovery of the formation resistivity using measurements made with an eccentric tool.

[0033] The use of H_{zz} measurements in conjunction with various combinations of H_{xx} and H_{yy} measurements is discussed, for example, in US6,636,045 to *Tabarovsky et al.*, having the same assignee as the present disclosure and the contents of which are incorporated herein by reference. In the present disclosure, once the corrected H_{zz} measurement is obtained, then it is possible to estimate the horizontal and vertical formation resistivities using $H_{x'x'}$ or $H_{y'y'}$, or an average of $H_{x'x'}$ and $H_{y'y'}$ measurements as discussed above.

[0034] FIG. 8 illustrates some of the possible embodiments of the disclosure discussed in *Rabinovich* '548.. 3DEX measurements are obtained **505** where the measurements are affected by azimuthal variations. Examples of these azimuthal variations that have been discussed above include the effects of eccentricity or the effect of a fracture. These measurements are processed to correct the orientation effects **511** as discussed above. In one embodiment of the disclosure, conventional LWD resistivity measurements are obtained **503**. The conventional LWD measurements are used to estimate R_h , and as long as there are no pre-existing fractures in the earth formation, can be used in combination with the corrected measurement from **511** to estimate horizontal and vertical formation resistivity **509**. As noted above, the corrected measurement may be $H_{x'x'}$ or $H_{y'y'}$, or an average of $H_{x'x'}$ and $H_{y'y'}$, and the estimation may be done using, for example, the method of *Tabarovsky*.

[0035] As an alternative to using LWD resistivity measurements for getting R_h , array resistivity measurements may be used **501**. The array resistivity measurements may be inverted to determine the fracture length **507** (as discussed above) and get an estimate of R_h . Optionally, R_h from LWD measurements may be used as part of the inversion **507**. The estimate of R_h from **507** may then be used in conjunction with the corrected measurement from **511** to get the horizontal and vertical resistivity of the formation **509**.

594-45936WO

[0036] Those versed in the art and having the benefit of the present disclosure would recognize that in a vertical borehole, multifrequency-focused data (MFF data) can be rotated. In a deviated borehole, as discussed below, it is preferable to rotate single frequency data and then apply the rotation.

- 5 [0037] FIG. 9 shows the geometry and the angles involved in a deviated borehole. The z -axis of the formation coordinate system, Z^f , is normal to the bedding plane, while X^f and Y^f are on the bedding plane. The tool coordinate system is described by (X^t, Y^t, Z^t) in FIG. 9. The z -axis of the tool system is normal to the tool plane and X^t and Y^t are on the tool plane. The two formation angles, θ and ϕ , are to be recovered from our inversion processing, as well as the horizontal and vertical resistivities R_h and R_v .

- 10 [0038] The MFF works very well in oil-based and fresh mud systems. In salty muds with R_t/R_m contrast over 50-100 and eccentricity 1-2 inches (2.54-5.08cm) the eccentricity effect on some of the 3DEX components can reach hundreds and thousands per cent. In such extreme conditions application of MFF technique requires very high accuracy of the data (0.01%), which is difficult to achieve in real measurements.

- 15 [0039] In the wells with no relative dip a simple rotation of multi-frequency focused xx , yy , and xy components allows us to extract unaffected $x'x'$ component which can be used in the subsequent processing for electrical anisotropy as discussed above. However in the presence of relative dip, this technique may not be reliable, because formation dip and azimuth also affect the measurements.

- 20 [0040] We conducted a 3-D numerical simulation study to evaluate the eccentricity effects on the 3DEX data in deviated wells. We discovered that if the tool was eccentric exactly in the direction of XX component, the only component that cannot be properly corrected by MFF technique is YY . The other components after MFF show no or very little dependence on eccentricity (See Tables 2 and 3).

- 25 Table 2. Eccentricity effects in Model 1. $R_m=0.05\Omega\text{-m}$, $BHD=12.25$ in, $R_h=2.5\Omega\text{-m}$, $R_v=5\Omega\text{-m}$, Relative Dip = 45° . Relative Rotation= 30° . Tool is eccentric in the direction of XX component.

594-45936WO

Eccentricity (in)	Apparent conductivities for 9 components (mS/m)								
	XX	YY	ZZ	XY	XZ	YX	YZ	ZX	ZY
0.0	338	310	344	-76	119	-74	-82	121	-84
0.5	339	303	348	-77	119	-74	-81	121	-84
1.0	339	284	344	-78	119	-74	-82	121	-84
1.5	338	248	347	-79	119	-73	-82	121	-85
2.0	338	201	347	-80	119	-74	-81	120	-84
No borehole	341	313	348	-76	124	-76	-82	124	-82

Table 3. Eccentricity effects in Model 2. $R_m=0.05 \Omega\text{-m}$, $BHD=12.25$ in, $R_h=25 \Omega\text{-m}$,
 5 $R_v=50 \Omega\text{-m}$, Relative Dip = 45° . Relative Rotation= 45° . Tool is eccentric in the direction of XX component.

Eccentricity (in)	Apparent conductivities for 9 components (mS/m)								
	XX	YY	ZZ	XY	XZ	YX	YZ	ZX	ZY
0.0	33	33	34	-8	10	-8	-10	10	-11
0.5	33	14	34	-9	10	-9	-10	10	-11
1.0	33	-50	34	-9	10	-8	-10	9	-11
1.5	32	-95	35	-9	11	-8	-10	8	-11
2.0	32	-147	36	-10	10	-9	-10	9	-11
No borehole	33	33	35	-8.4	10.5	-8.4	-10.5	10.5	-10.5

10 [0041] The reason for the ability to recover the xx components can be seen with reference to **FIGS. 10a–10c**. Shown in **FIG. 10a** is a centered tool in a circular borehole. In **FIG. 10b**, the tool is displaced in the x -direction but with the x -coil oriented along a diameter of the borehole. When this happens, it can be seen that the eddy currents in the fluid due to a transmitter oriented in the x -direction will be
 15 symmetric with respect to the x -axis. On the other hand, the eddy currents in the fluid due to a y -transmitter which is not oriented along a borehole diameter will be asymmetric with respect to the y -axis. The situation is reversed in **FIG. 10c**, i.e., when the tool is displaced along the y -axis, the eddy currents are symmetric about the y -axis and the eddy currents are not symmetric about the x -axis. The imbalance
 20 affects some components and not others.

[0042] Referring back to Tables 2 and 3, it means that all components except the yy component can be still used for conventional 3DEX processing for formation dip and

594-45936WO

azimuth, R_h and R_v . When the tool is eccentered in an arbitrary direction with respect to the tool's x-axes (which is most likely the case for the real logging environment), we expect four components xx , yy , xy , and yx to be affected by tool eccentricity. That leaves us with only 3 independent MFF components zz , xz , and yz (5 $zx=xz$, $zy=yz$) which are not sufficient to resolve four unknowns R_h , R_v , θ and ϕ .

[0043] The present disclosure may use one of two different approaches to address this problem. The first approach is based on the fact that the eccentricity effect on single frequency measurements in conductive deviated boreholes is significantly stronger than the effect of formation dip and azimuth. Our numerical experiments show that we can neglect the effect of the formation dip in single frequency measurements and use the same equations to determine the eccentricity direction we use in case of vertical wells discussed above.

[0044] FIG. 11 shows the results of determining the rotation angle from single frequency measurements for a model in which the eccentricity angle is 30° . The abscissa is the frequency used for determination of the rotation angle. The curve 601 is for an eccentricity of 1 inch (2.54 cm), the curve 603 is for an eccentricity of 1.5 inches (3.81 cm) while 605 is for an eccentricity of 2 inches (5.08 cm). The point at f_0 corresponds to the skin-effect corrected data. As can be seen, the skin-effect corrected measurement gives an accurate estimation of the eccentricity angle.

[0045] FIG. 12 shows corresponding results for the case where the eccentricity angle is 45° . The curves 621, 623 and 625 are the estimated eccentricity angles from single frequency measurements for eccentricities 0.1 in, 1.5 inches and 2 inches (2.54 cm, 3.81 cm and 5.07 cm) respectively. Again, skin-effect corrected measurement gives the best estimate of the eccentricity angle.

[0046] Turning now to FIG. 13, an embodiment of the present disclosure for the determination of formation horizontal and vertical resistivities using multi-frequency 3DEX measurements in a deviated borehole is illustrated. At each depth, the eccentricity direction is determined 641 using the skin-effect corrected 3DEX measurements. This estimated eccentricity angle is then used to rotate 643 the 3DEX data at all the frequencies. With this rotation, as discussed above, the $y'y'$ data will be

594-45936WO

unreliable. A multifrequency focusing of the rotated data is performed **645**. MFF of the $y'y'$ data may be omitted due to its unreliability. The focused and rotated data are then inverted **647** to give the formation resistivities, relative dip angle and azimuth angle without use of the $y'y'$ data. The data may be interpreted according to the

5 principles enunciated in U.S. 6,470,274 to *Mollison et al.*, U.S. 6,643,589 to *Zhang et al.*, U.S. 6,636,045 to *Tabarovsky et al.*, and U.S. 6,686,736 to *Schoen et al.*, the contents of which are incorporated herein by reference. This includes the determination of R_h and R_v , the relative dip angle, the azimuth angle, the sand and shale fractions, the water saturation, and the permeability of the formation.

10 **[0047]** Another embodiment of the disclosure makes use of the current symmetry for an eccentric tool as shown in **FIGS. 10a-10c**. The mechanical arrangement is illustrated in **FIGS. 14a, 14b**. A wireline **651** conveys a logging tool **653** into the borehole **661**. Bowspring devices **655, 655'** are oriented parallel to the axis of the x coil of the longitudinal tool. This positions the tool within the borehole in the

15 configuration shown in **FIG. 14b** wherein the tool is eccentric in the direction of the x axis. Standoffs **661, 661'** are provided to avoid strong borehole effects on the z coil. Using the tool shown in **FIGS. 14a, 14b**, it is possible to bypass the steps **641** and **643** in **FIG. 13** and proceed directly to the multi-frequency focusing and inversion.

[0048] The hardware configuration shown in **FIG. 14** is one of many arrangements

20 that may be used to ensure that the currents circulating in the mud near the receiver coils cancel each other out. This may be accomplished by having the tool perfectly centralized. Achieving accurate centralization is particularly difficult in horizontal or highly deviated wells. The configuration shown in **FIG. 14** has one of the transverse coils oriented along a borehole diameter. In the embodiment of the disclosure shown

25 in **FIG. 15**, this is carried further and both x - and y - coils are oriented along a borehole diameter.

[0049] Shown in **FIG. 15** are two mandrels **701, 711**. Mandrel **701** is provided with an x transmitter coil **707**, and x receiver coil **703** and an x bucking coil **705**. Similarly, mandrel **711** is provided with a y transmitter coil **717**, a y receiver coil **713** and a y

30 bucking coil **715**. The use of bucking coils would be known to those versed in the art

594-45936WO

and is not discussed further here.

[0050] Each of the mandrels **701**, **711** may be provided with its own set of bowsprings and standoffs. This is not shown in **FIG. 15** but has been discussed above with reference to **FIGS. 14a, 14b**. An appropriate mechanical arrangement (not
5 shown) is provided to maintain the two mandrels oriented at 90° to each other. With such an arrangement, each of the coils can be maintained close to the borehole wall and also be oriented along a borehole diameter.

[0051] The desired configuration of the mandrels illustrated in **FIG. 15** can be obtained by modifying a conventional pad-mounted imaging tool such as that
10 disclosed in U.S. 6,714,014 to *Evans* et al., having the same assignee as the present disclosure and the contents of which are incorporated herein by reference. This is schematically shown in **FIG. 16**. The two mandrels **701'**, **711'** are extendable from a central housing **721** by extension arms **725**. The extension arms provide electrical communication between the antenna coils on the mandrels and the electronics in the
15 housing. The mandrels are maintained at the required 90° orientation. Extension devices **723** (of which one is shown), possibly bowsprings, are provided opposite the two extendable mandrels to maintain the central housing in the necessary position in the borehole.

[0052] In another embodiment of the disclosure, the two mandrels are not at the same
20 horizontal position. This is illustrated in **FIG. 17** where each of the mandrels **801**, **811** is provided with its own coils and bowsprings. This arrangement has the disadvantage of not having the coils at the same depth.

[0053] Some or all of the processing may be done by a downhole processor, a processor at the surface, or a processor at a remote location. Implicit in the control
25 and processing of the data is the use of a computer program on a suitable machine readable medium that enables the processor to perform the control and processing. The machine readable medium may include ROMs, EPROMs, EEPROMs, Flash Memories and Optical disks. The disclosure may also be implemented in conjunction with a measurement-while-drilling arrangement in which the multi-component and
30 multi-array measurements are made using a suitable device on a bottomhole assembly

594-45936WO

conveyed on a drilling tubular such as a drillstring.

[0054] While the foregoing disclosure is directed to the preferred embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope of the appended claims be embraced by

5 the foregoing disclosure.

594-45936WO

CLAIMS

What is claimed is:

- 1 1. A method of determining a resistivity property of an earth formation, the
2 method comprising:
3 (a) positioning a logging tool in a borehole with a center of the tool
4 displaced from a center of the borehole in a first direction;
5 (b) making, at a plurality of frequencies, multi-component measurements
6 indicative of a resistivity property of the earth formation;
7 (c) estimating from the multi-component measurements at the plurality of
8 frequencies the resistivity property of the earth formation; and
9 (d) recording the estimated resistivity property on a suitable medium.
10
- 1 2. The method of claim 1 wherein obtaining the multi-component measurements
2 further comprises using a transmitter antenna on the logging tool with an axis
3 substantially along the first direction.
4
- 1 3. The method of claim 1 wherein estimating the resistivity property further
2 comprises performing an inversion in which at least one of the multi-
3 component measurements is excluded.
4
- 1 4. The method of claim 1 wherein estimating the resistivity property further
2 comprises applying a multifrequency focusing.
3
- 1 5. The method of claim 1 further comprising using the estimated resistivity
2 property to determine at least one of: (i) a horizontal resistivity, (ii) a vertical
3 resistivity, (iii) a relative dip angle, (iv) an azimuthal angle, (v) a sand
4 fraction, (vi) a water saturation, and (vii) a permeability.
5
- 1 6. The method of claim 1 further comprising conveying the logging tool into the
2 borehole on a wireline.

594-45936WO

3

1 7. The method of claim 2 further comprising obtaining the multi-component
2 measurements by using an additional transmitter antenna on the logging tool
3 with an axis substantially orthogonal to the first direction.

4

1 8. The method of claim 2 further comprising extending the transmitter antenna
2 away from a body of the logging tool.

3

1 9. An apparatus for determining a resistivity property of an earth formation, the
2 apparatus comprising:

3 (a) a logging tool configured to be positioned in a borehole with the tool
4 displaced from a center of the borehole in a first direction, the logging
5 tool further configured to obtain, at a plurality of frequencies, multi-
6 component measurements indicative of the resistivity property of the
7 earth formation; and

8 (b) a processor configured to:

9 (A) estimate from the multi-component measurements at the
10 plurality of frequencies a resistivity property of the earth
11 formation; and
12 (B) record the estimated resistivity property on a suitable medium.

13

1 10. The apparatus of claim 9 wherein logging tool is configured to obtain the
2 multi-component measurements by using a transmitter antenna on the logging
3 tool with an axis substantially along the first direction.

4

1 11. The apparatus of claim 9 wherein the processor is further configured to
2 estimate the resistivity property by performing an inversion in which at least
3 one of the multi-component measurements is excluded.

4

1 12. The apparatus of claim 9 wherein the processor is further configured to

594-45936WO

2 estimate the resistivity property by applying a multifrequency focusing.

3

1 13. The apparatus of claim 9 further wherein the processor is further configured to
2 use the estimated resistivity property to determine at least one of: (i) a
3 horizontal resistivity, (ii) a vertical resistivity, (iii) a relative dip angle, (iv) an
4 azimuthal angle, (v) a sand fraction, (vi) a water saturation, and (vii) a
5 permeability.

6

1 14. The apparatus of claim 9 further comprising a wireline configured to convey
2 the logging tool into the borehole.

3

1 15. The apparatus of claim 10 wherein logging tool is configured to obtain the
2 multi-component measurements by using an additional transmitter antenna on
3 the logging tool with an axis substantially orthogonal to the first direction.

4

1 16. The apparatus of claim 10 wherein the transmitter antenna is extendable from
2 a body of the logging tool.

3

1 17. A computer readable medium for use with an apparatus for determining a
2 resistivity property of an earth formation, the apparatus comprising:

3 (a) a logging tool configured to be positioned in a borehole with the tool
4 displaced from a center of the borehole in a first direction, the logging
5 tool further configured to obtain, at a plurality of frequencies, multi-
6 component measurements indicative of a resistivity property of the
7 earth formation;

8 the medium comprising instructions which enable a processor to:

9 (b) estimate from the multi-component measurements at the plurality of
10 frequencies a resistivity property of the earth formation; and

11 (c) record the estimated resistivity property on a suitable medium.

12

594-45936WO

- 1 18. The medium of claim 17 further comprising at least one of: (i) a ROM, (ii) an
2 EPROM, (iii) an EEPROM, (iv) a flash memory, and (v) an optical disk.
3

1/16

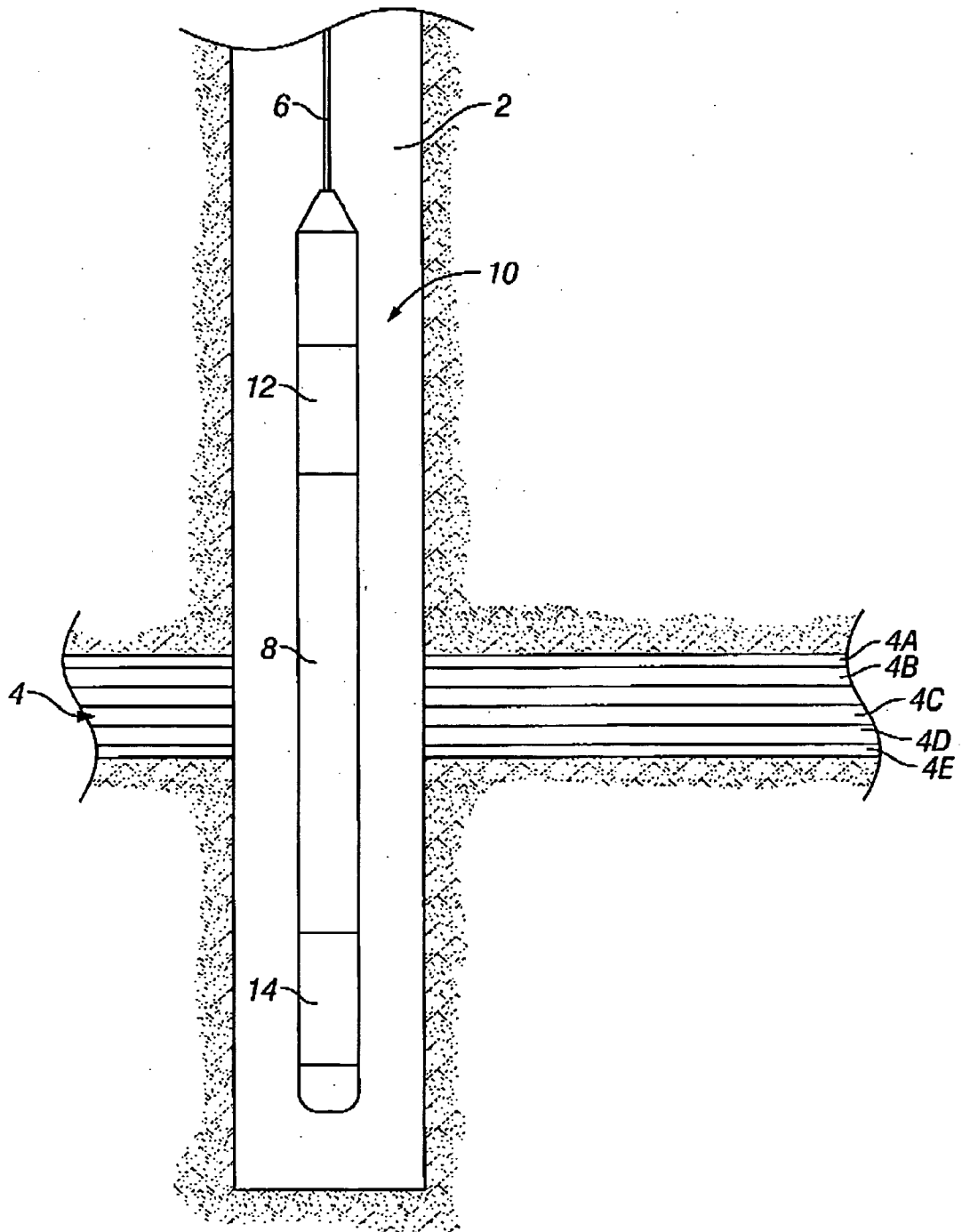


FIG. 1

2/16

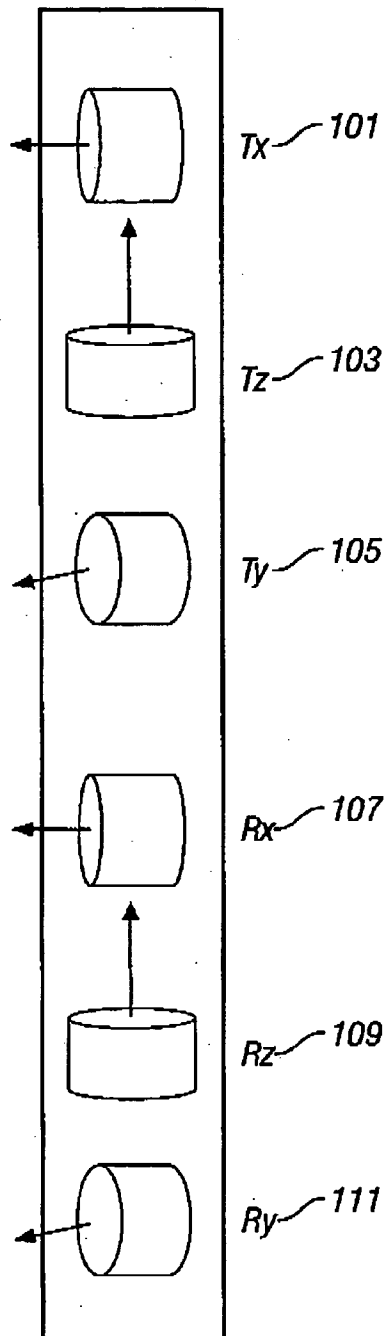
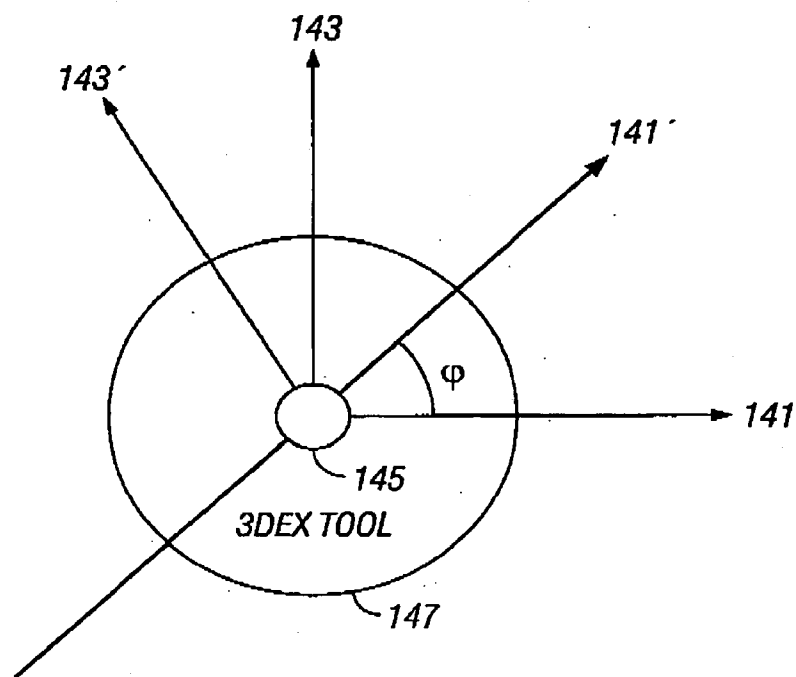
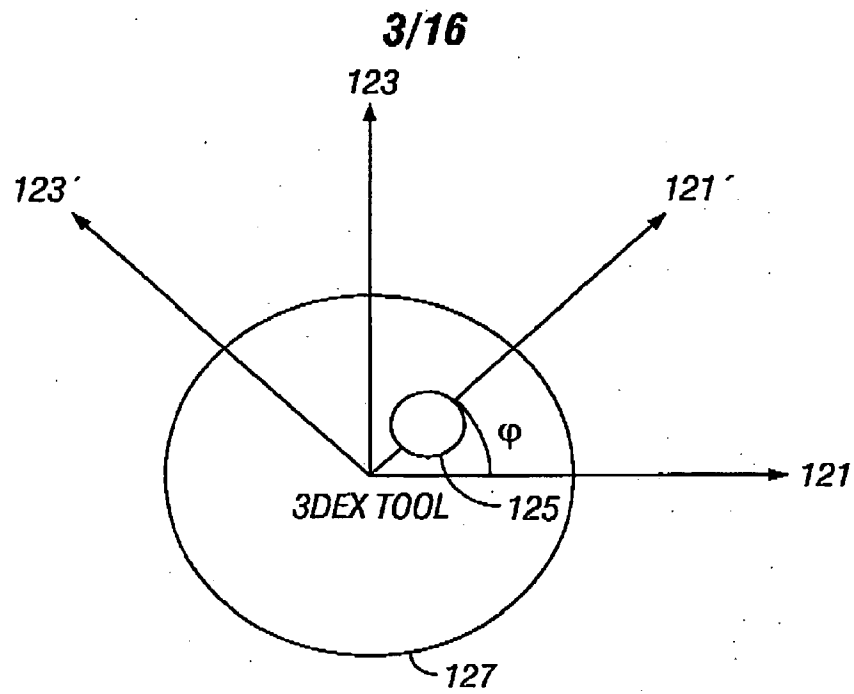


FIG. 2
(Prior Art)



4/16

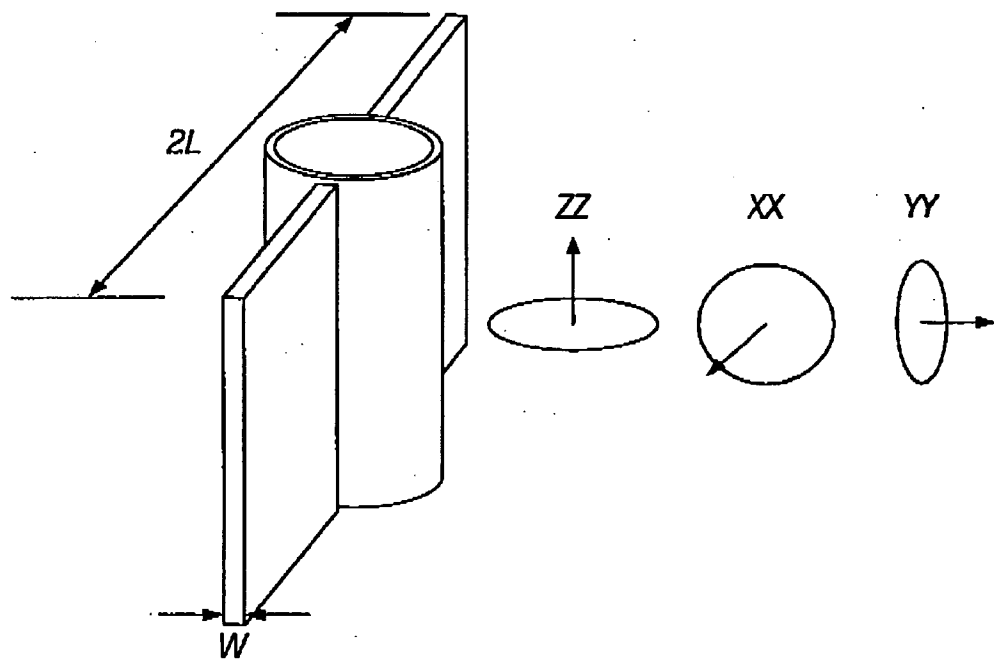
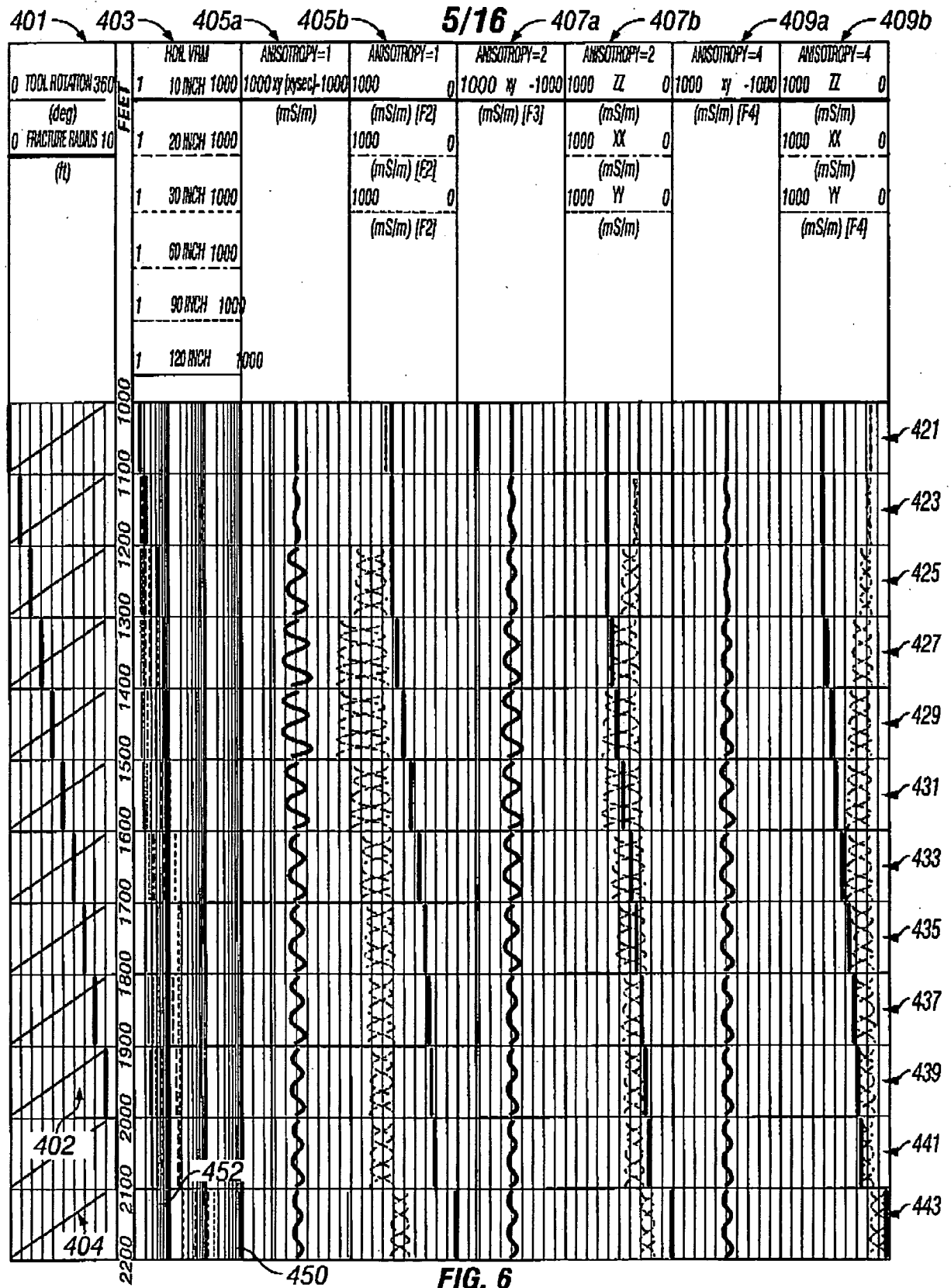


FIG. 5



6/16

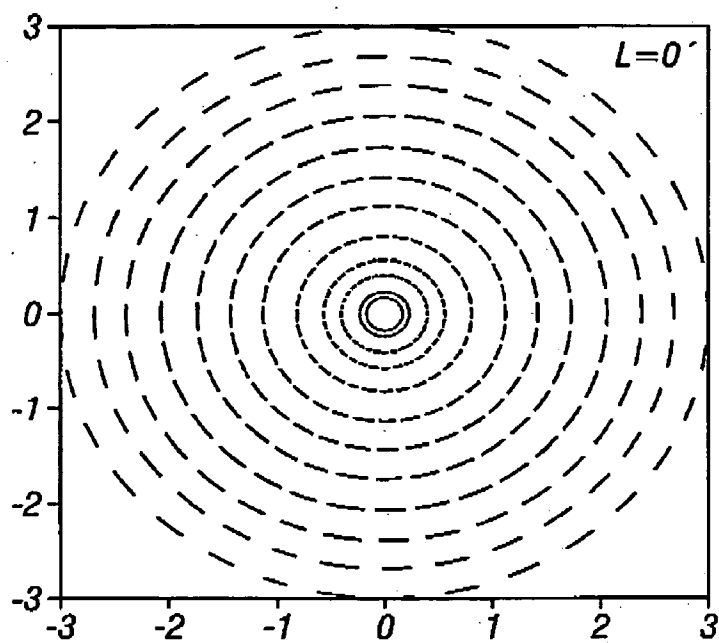


FIG. 7a

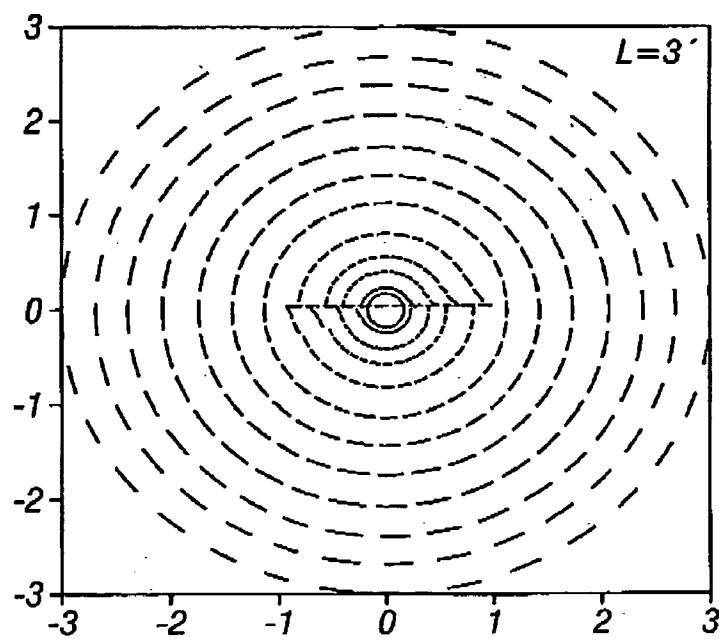


FIG. 7b

7/16

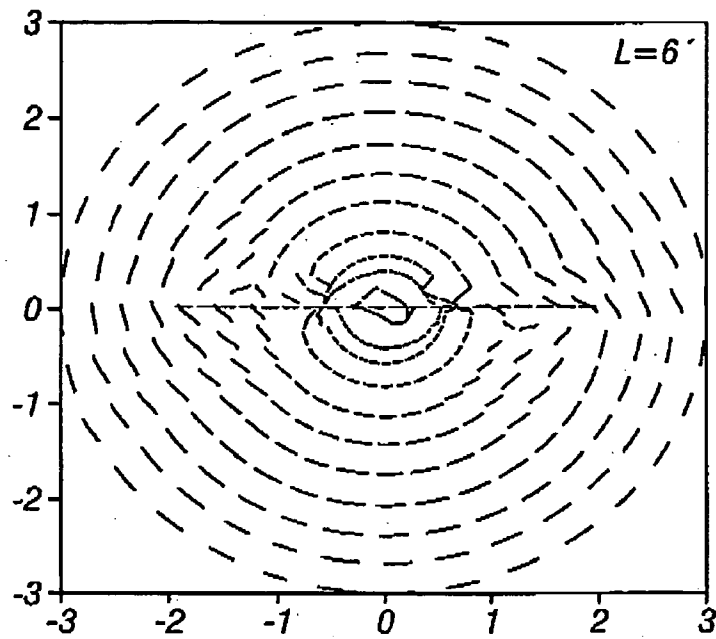


FIG. 7c

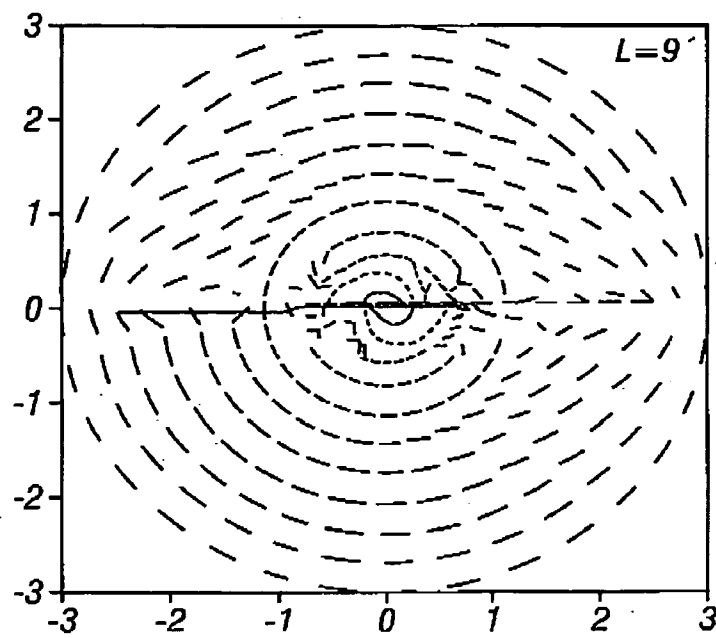


FIG. 7d

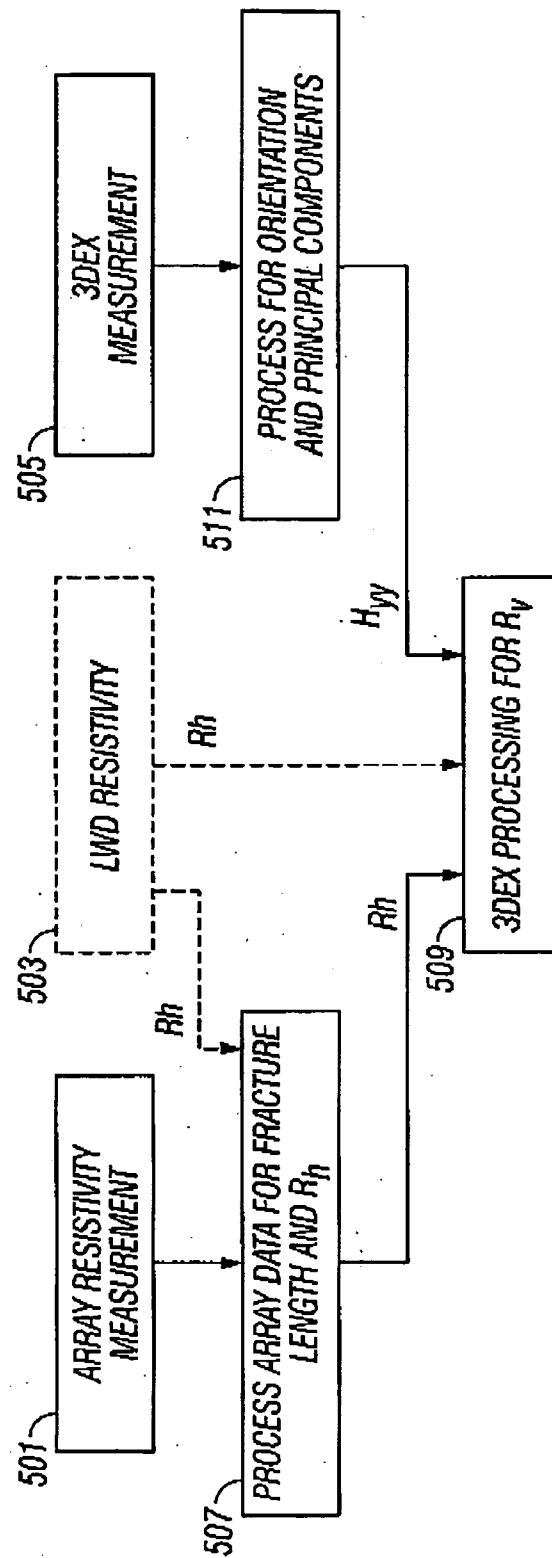


FIG. 8

9/16

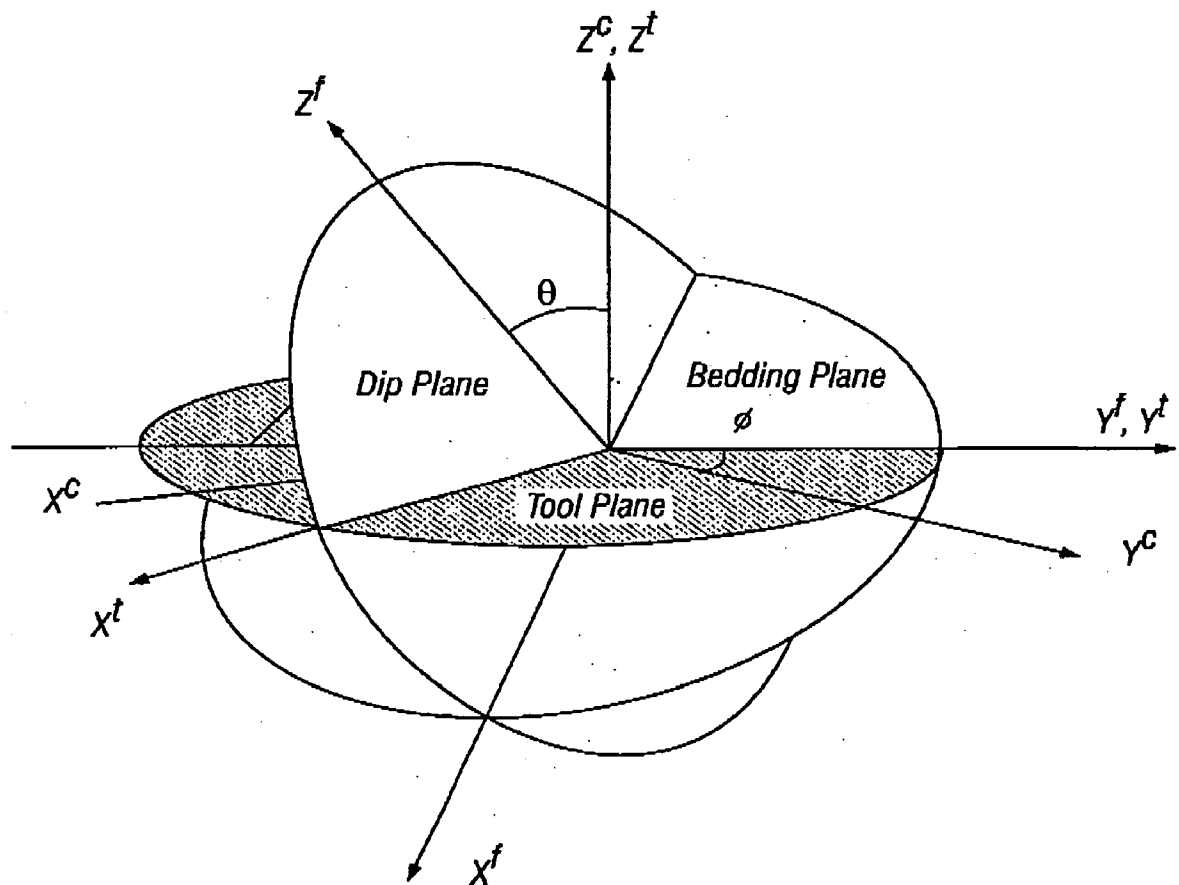


FIG. 9

10/16

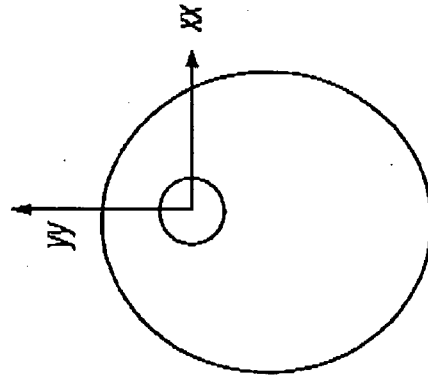


FIG. 10c

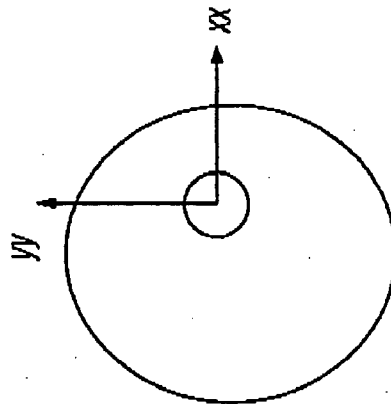


FIG. 10b

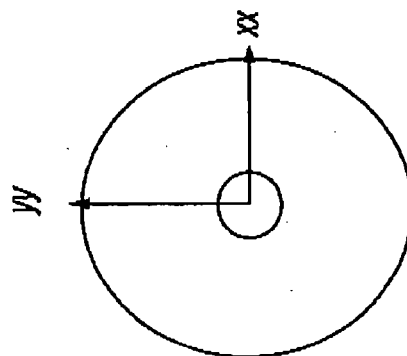


FIG. 10a

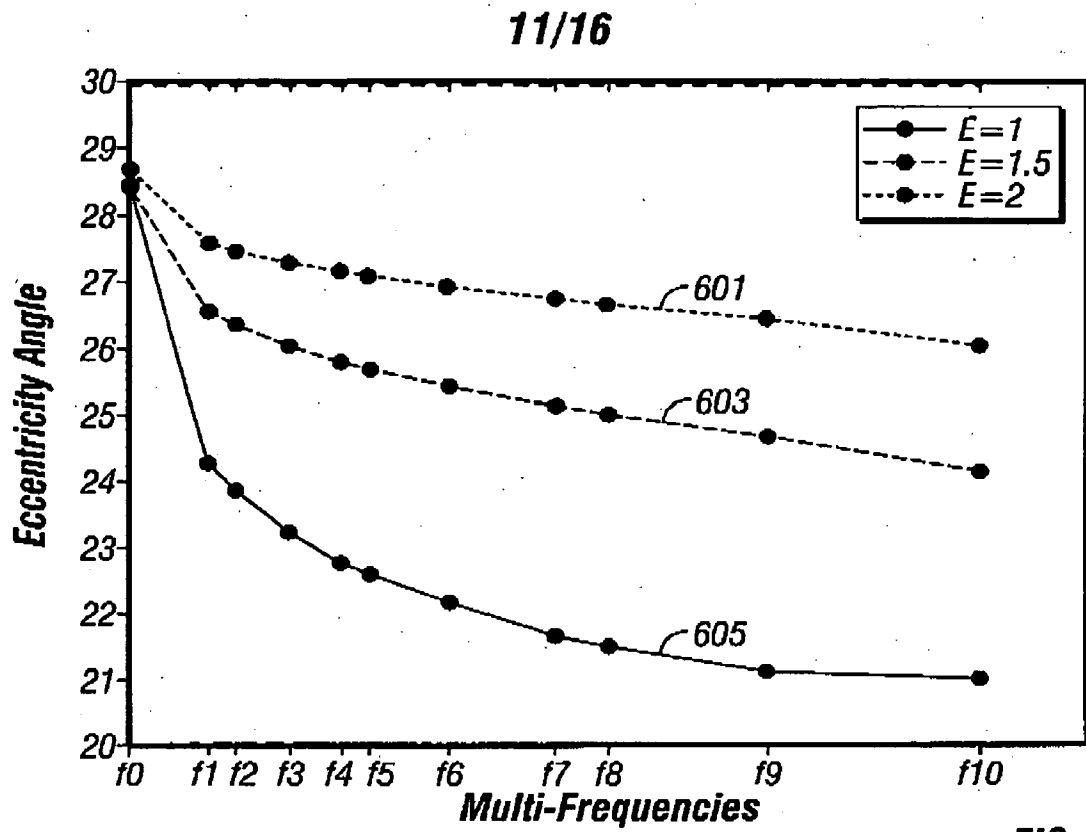


FIG. 11

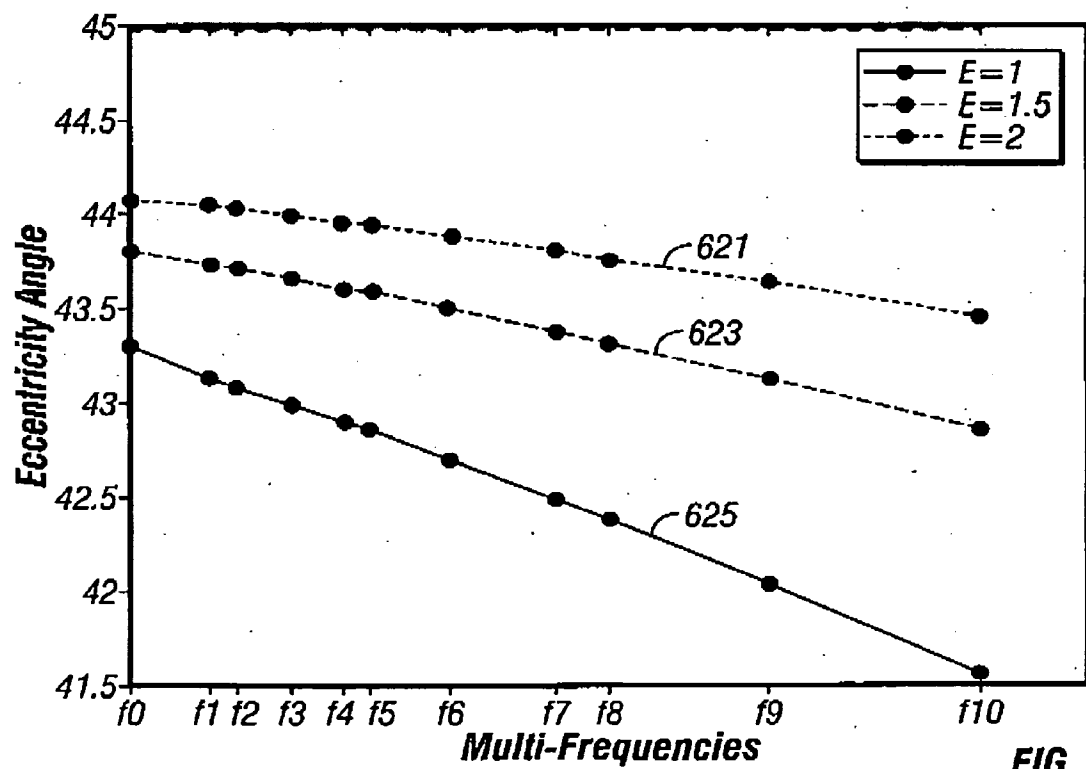
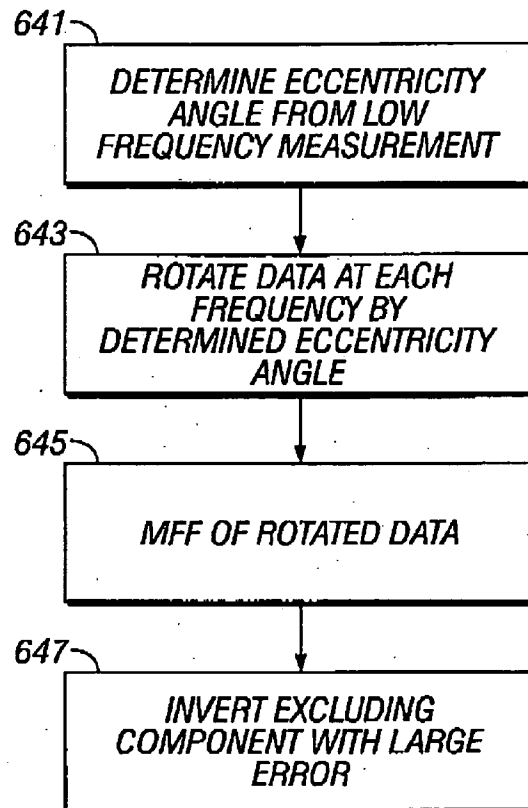


FIG. 12

12/16**FIG. 13**

13/16

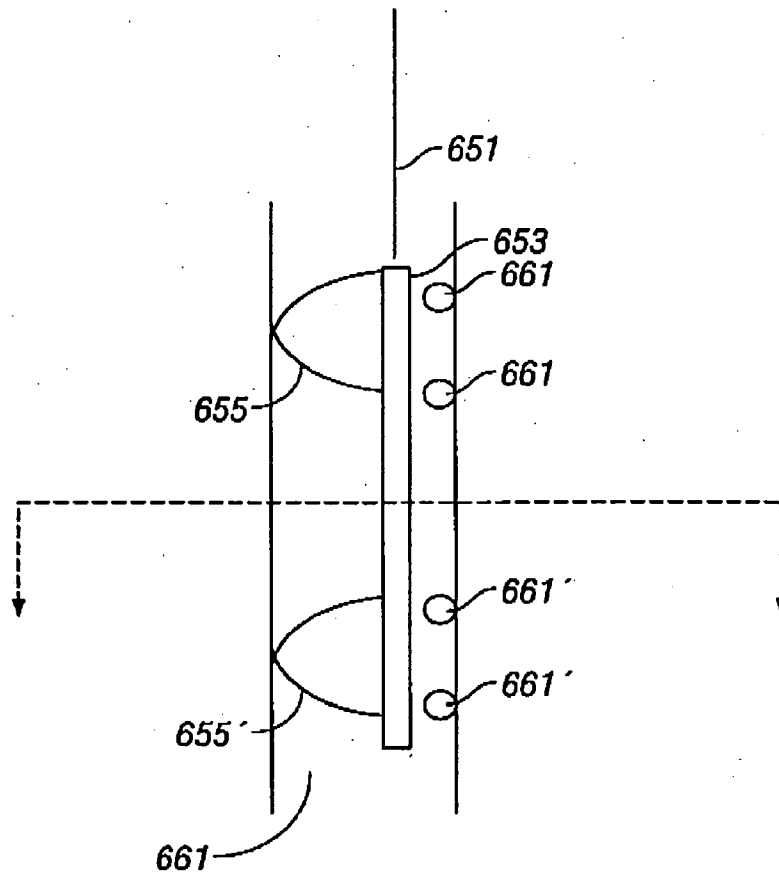


FIG. 14a

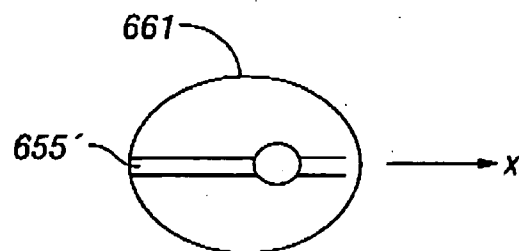


FIG. 14b

14/16

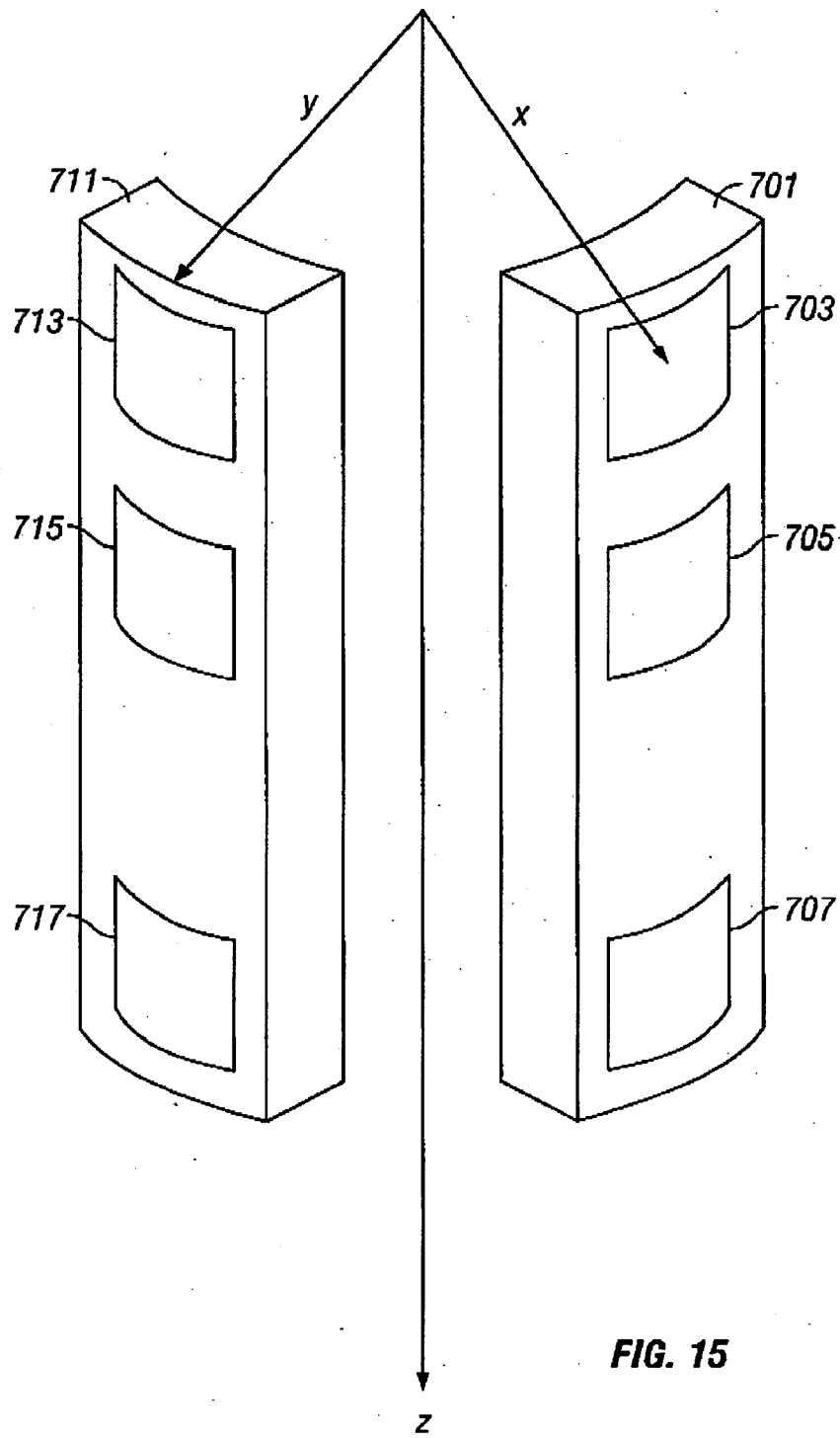


FIG. 15

15/16

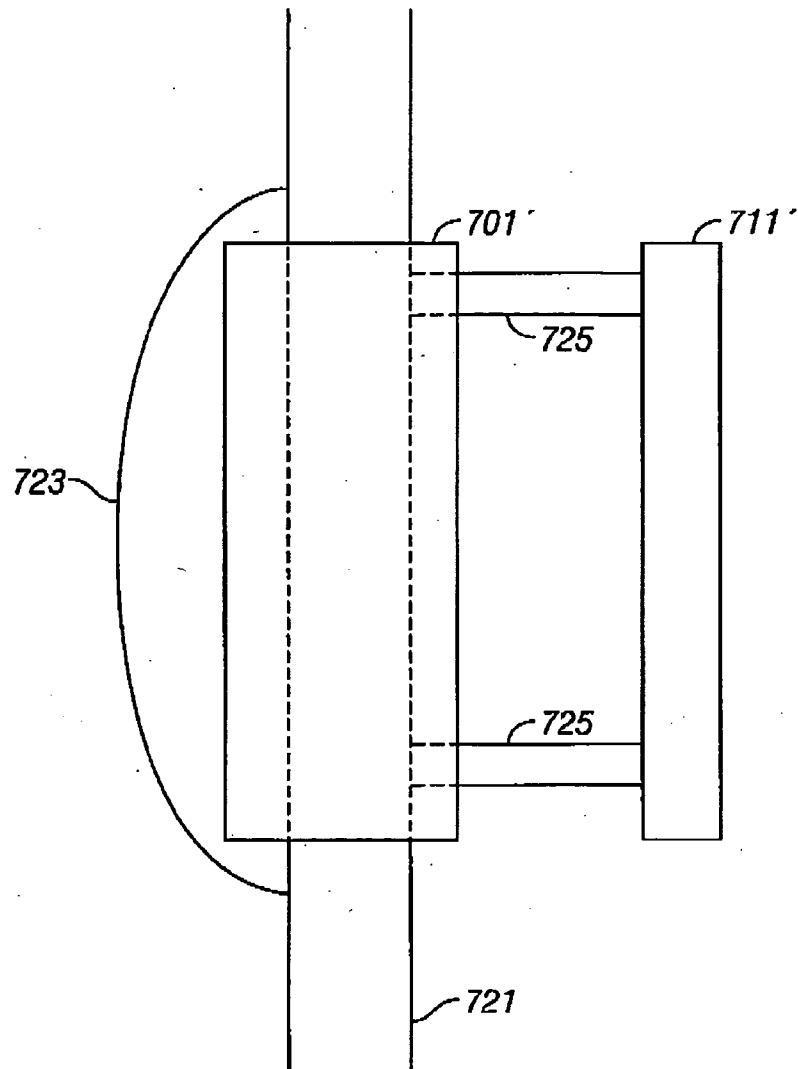


FIG. 16

16/16

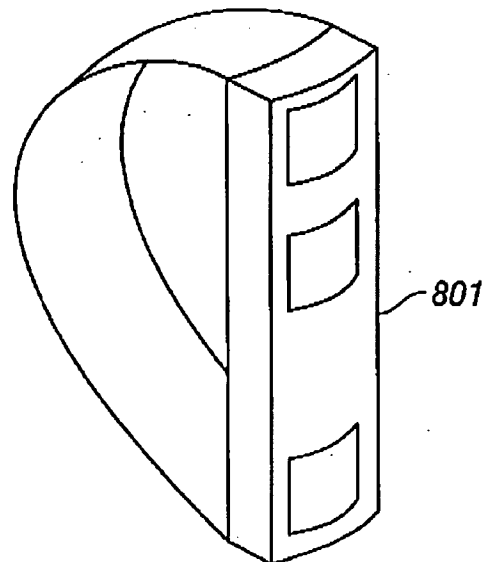
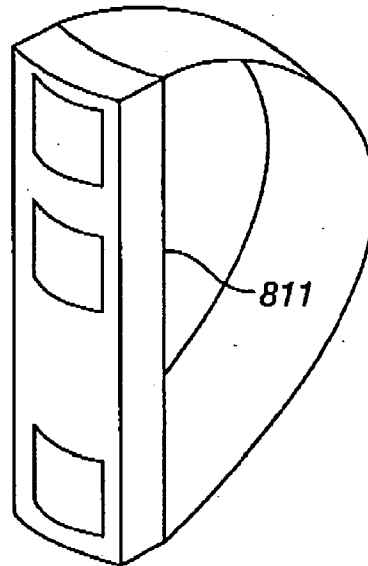


FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 08/71575

A. CLASSIFICATION OF SUBJECT MATTER IPC(8) - G01V 1/40 (2008.04) USPC - 702/7 According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) USPC: 702/7 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched US: 702/6, 7, 85 (keyword limited - see terms below) Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) PubWEST (PGPB, USPT, USOC, EPAB, JPAB); GOOGLE Search Terms: resistivity, earth, tool, logging, borehole, frequencies, estimation, near3 measurement, axis near2 direction, dip angle, azimuth, sand fraction, water saturation, permeability, transmitter, antenna, orthogonal, multifrequency focusing		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2004/0196047 A1 (Fanini et al.) 07 October 2004 (07.10.2004), entire document, especially; abstract, para. [0003], [0014], [0016], [0079], [0103], [0116], [0143]	1 - 18
Y	US 2005/0256645 A1 (Rabinovich et al.) 17 November 2005 (17.11.2005), entire document, especially; abstract, para. [0022], [0031], [0034]	1 - 18
☐ Further documents are listed in the continuation of Box C. ☐		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 16 October 2008 (16.10.2008)		Date of mailing of the international search report 10 NOV 2008
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201		Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774