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(54) **METHOD FOR COMBINED TRANSIENT AND FREQUENCY DOMAIN ELECTROMAGNETIC MEASUREMENTS**

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(52) **U.S. Cl.** **324/323**; 324/338; 324/339; 324/366; 324/371
(58) **Field of Classification Search** 324/323, 324/328, 329, 343, 366, 371, 338, 339, 347, 324/359, 354, 336; 702/2, 5, 6
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,704,581	A	11/1987	Clark et al.
6,541,975	B2	4/2003	Strack
6,603,313	B1	8/2003	Srnka
6,628,119	B1	9/2003	Eidesmo et al.
6,670,813	B2 *	12/2003	Strack 324/323
6,859,038	B2	2/2005	Ellingsrud et al.
7,203,599	B1 *	4/2007	Strack et al. 702/2
2006/0186887	A1	8/2006	Strack et al.

OTHER PUBLICATIONS

He et al., "Mapping reservoir boundary by borehole-surface TFEM, two case studies", The Leading Edge, Sep. 2005.

* cited by examiner

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(57) **ABSTRACT**

A method for interpreting transient electromagnetic survey data includes imparting an electromagnetic field in the Earth's subsurface by passing electric current through a transmitter antenna. The electric current includes switched direct current at a selected switching frequency. Voltages induced in a receiver corresponding to electromagnetic effects induced in the Earth's subsurface are detected. Frequency domain electromagnetic response of the Earth's subsurface is determined from the detected voltages and transient electromagnetic response of the Earth's subsurface is determined from the detected voltages.
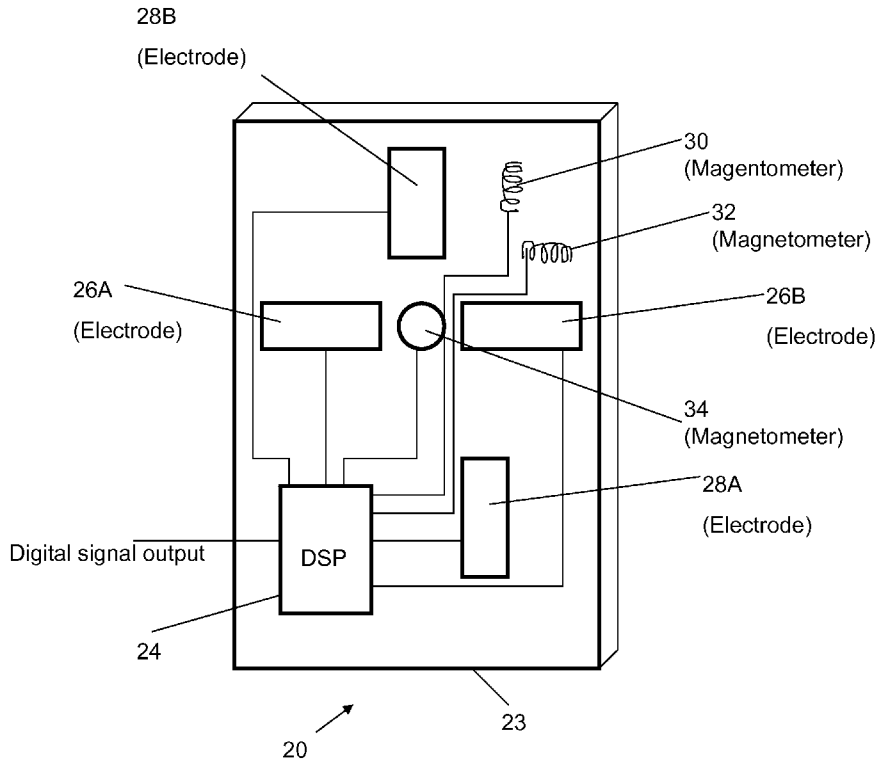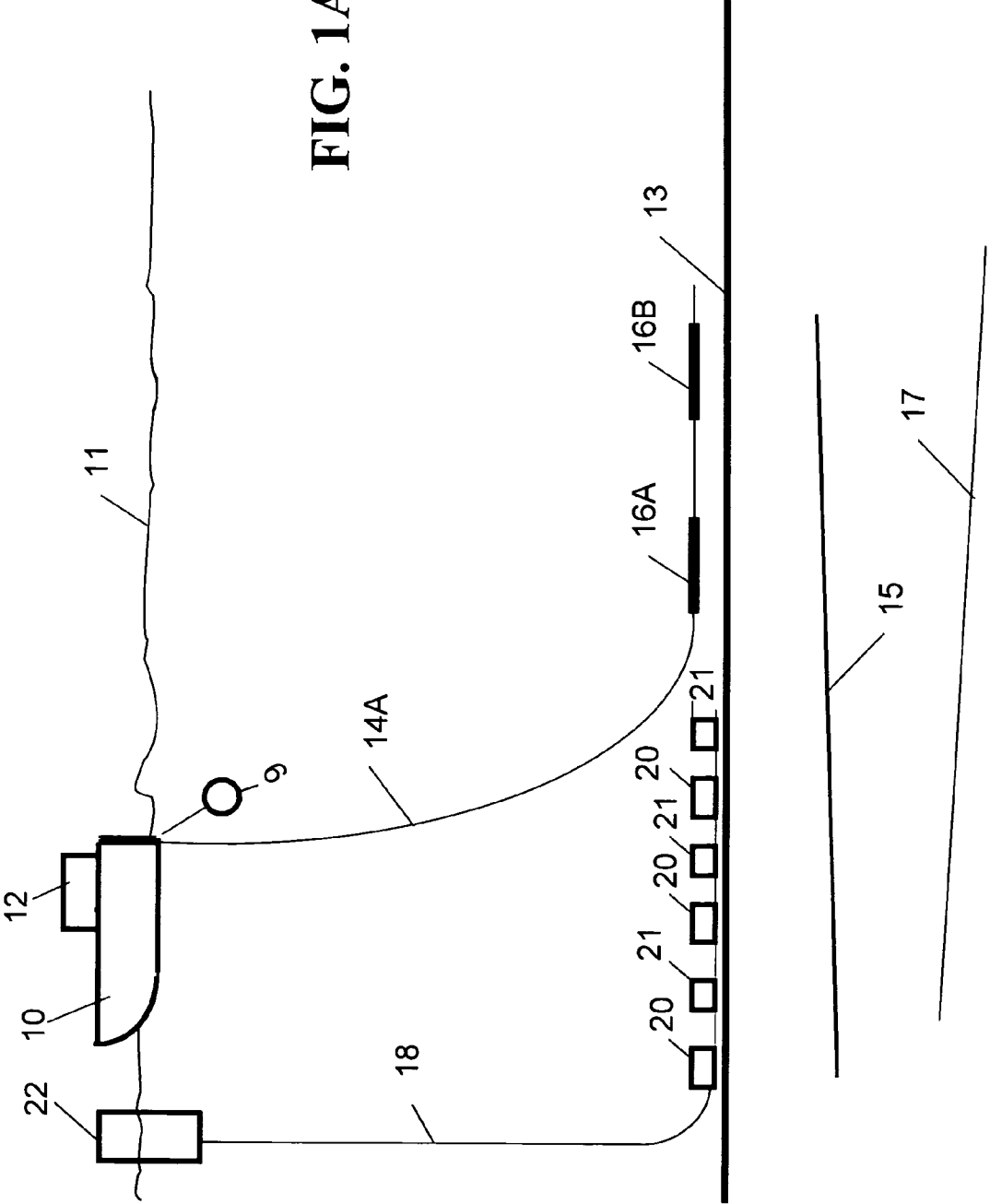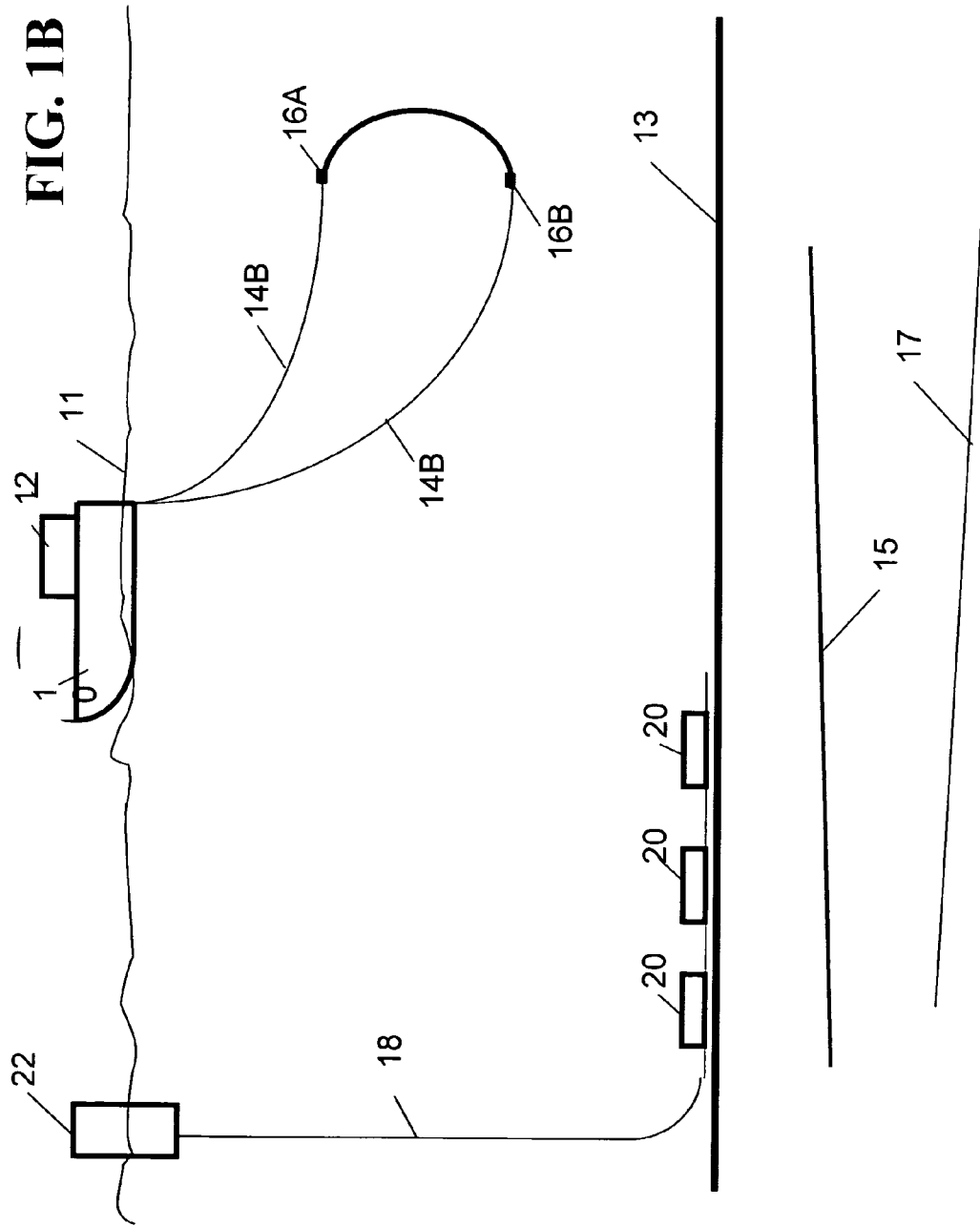
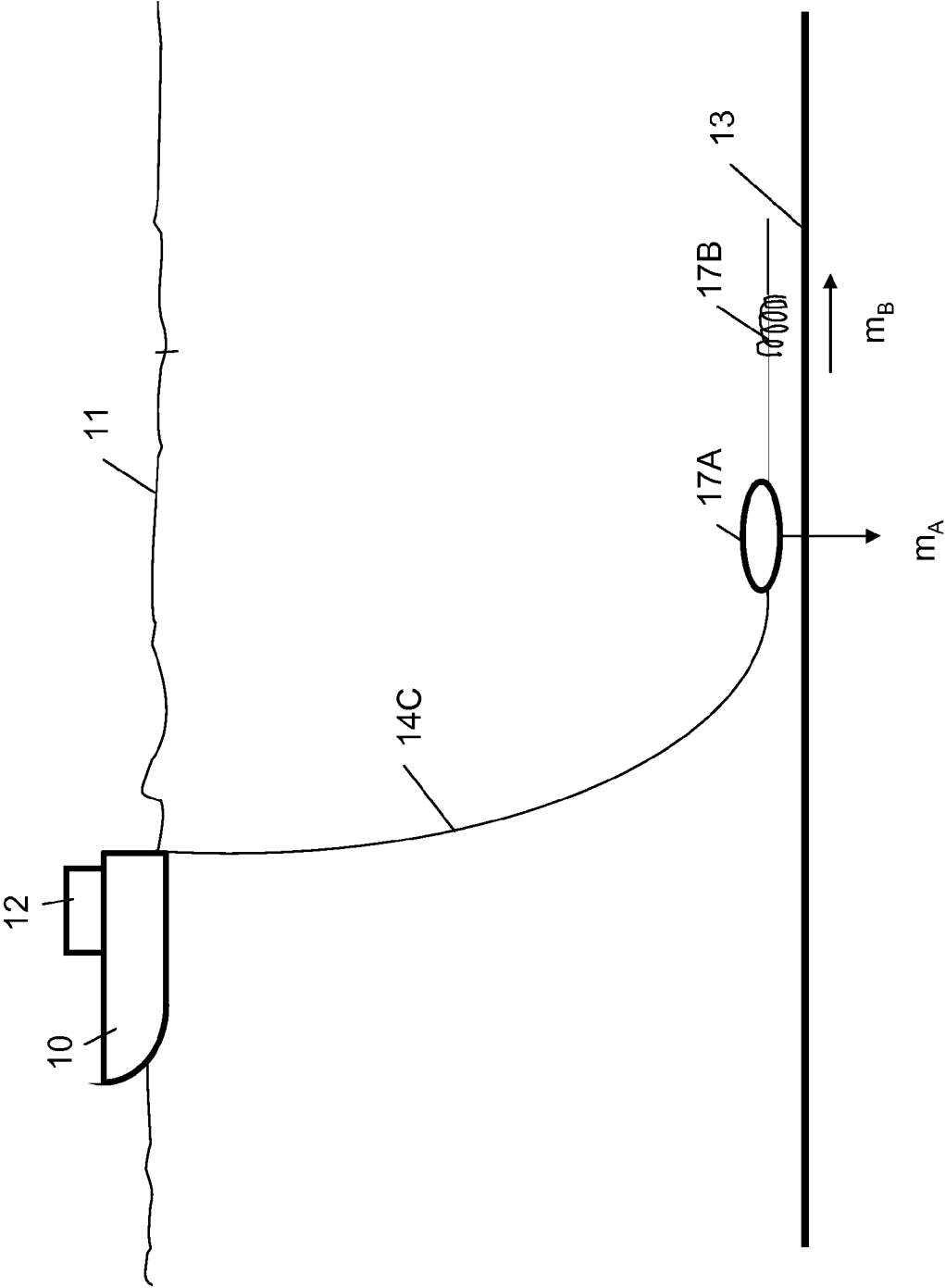**17 Claims, 6 Drawing Sheets**

FIG. 1A

FIG. 1B

FIG. 2

FIG. 3

30
(Magentometer)

32
(Magnetometer)

26B
(Electrode)

34
(Magnetometer)

28A
(Electrode)

28B
(Electrode)

26A
(Electrode)

DSP

Digital signal output

24

23

20

FIG. 4

GENERATE INITIAL EARTH MODEL——60

CALCULATE TRANSIENT RESPONSE——62
FOR 1ST SWITCHING EVENT

CALCULATE TRANSIENT RESPONSE
FOR PRIOR SWITCHING EVENT ⟋64

PRIOR RESPONSE BELOW ⟋66
SELECTED THRESHHOLD   NO

MOVE BACK IN TIME BY
ONE MORE SWITCHING EVENT ⟋68

YES

SUM RESPONSES   70⟍

COMPARE CALCULATED RESPONSE ⟋71
TO MEASURED RESPONSE
FOR FIRST SWITCHING EVENT

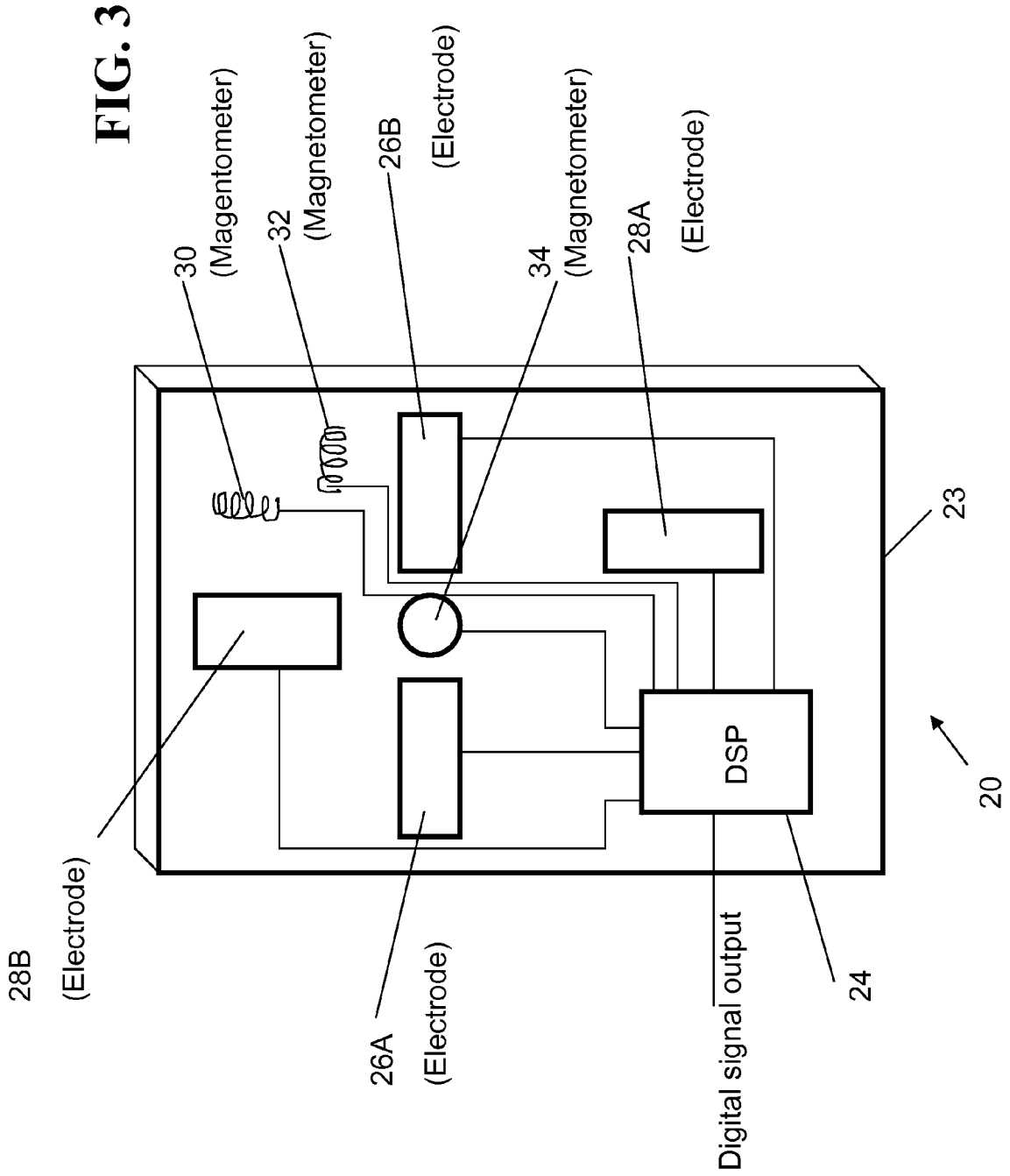DIFFERENCE BELOW THRESHHOLD? ⟋72   YES   END⟍74

NO

ADJUST MODEL   76 ⟋

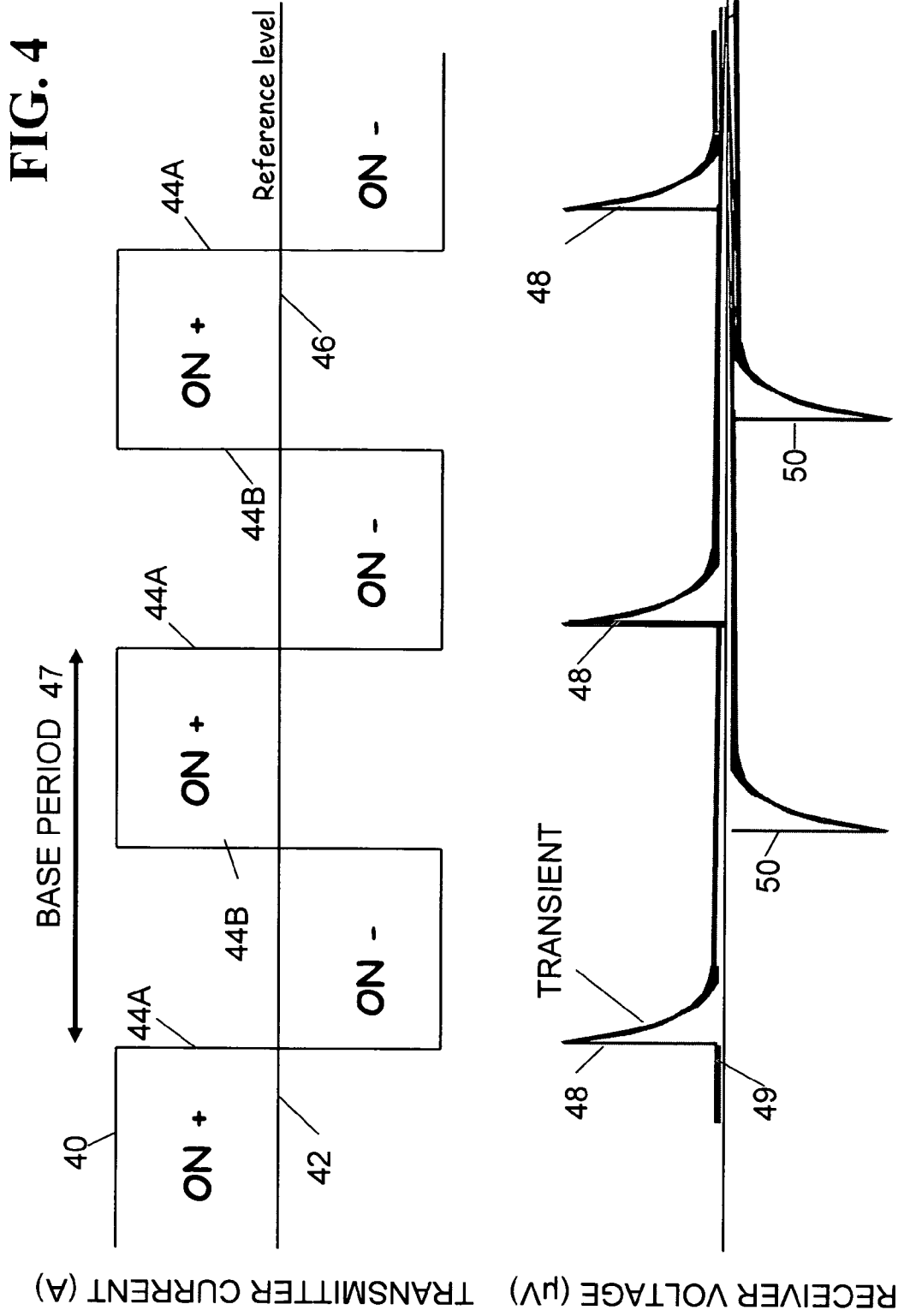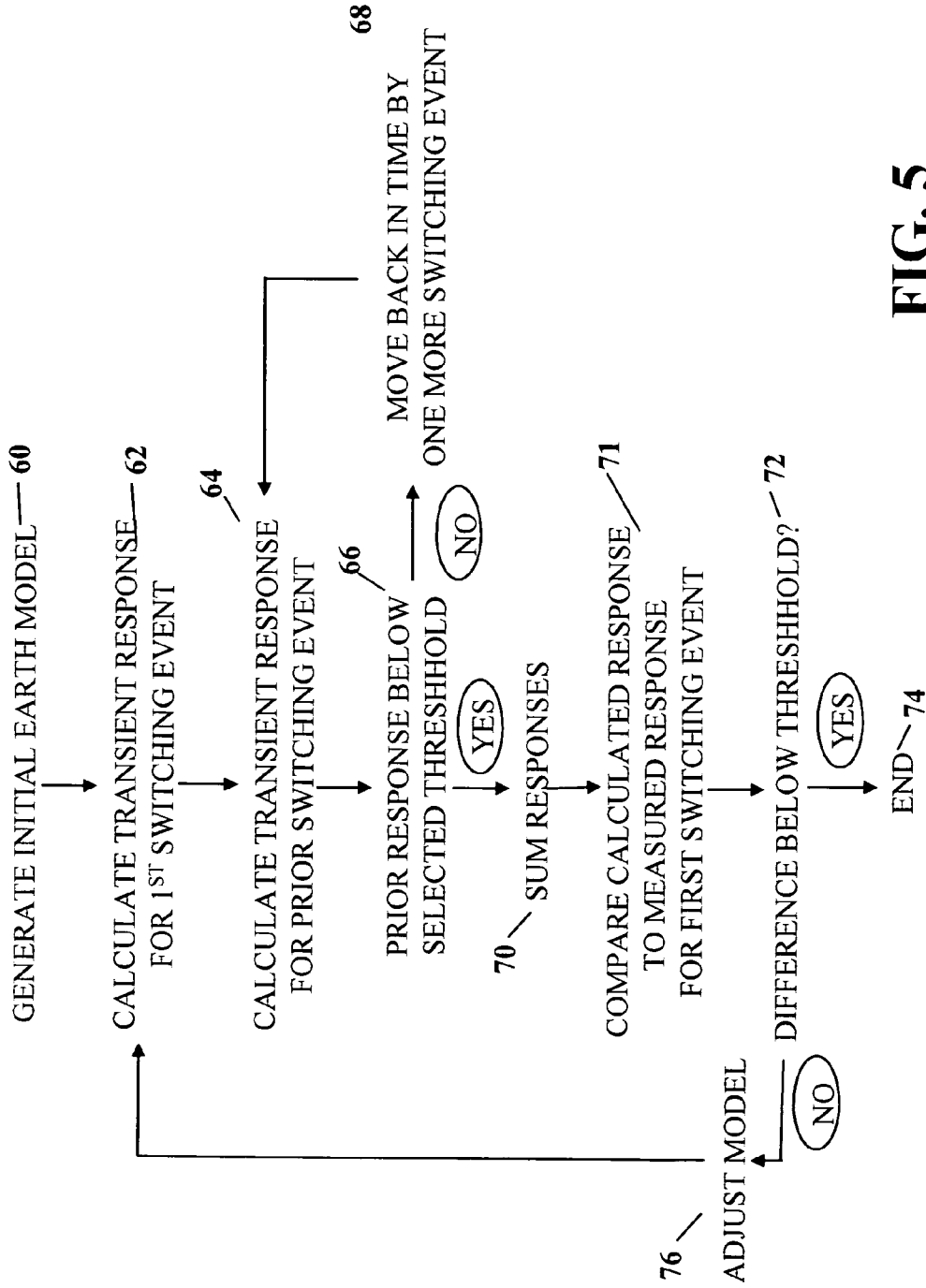**FIG. 5**

METHOD FOR COMBINED TRANSIENT AND FREQUENCY DOMAIN ELECTROMAGNETIC MEASUREMENTS

CROSS-REFERENCE TO RELATED APPLICATIONS

Not applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to the field of transient controlled-source electromagnetic conductivity measurement apparatus and methods subsurface Earth formations. More specifically, the invention relates to methods for acquiring and interpreting controlled-source electromagnetic measurements that account for so-called "run-on" effects. The invention can be used with but is not limited to marine electromagnetic and borehole electromagnetic surveying or geo-steering.

2. Background Art

Controlled source electromagnetic surveying includes imparting an electric current or a magnetic field into subsurface Earth formations, through the sea floor in marine surveying or through the borehole fluid in borehole surveying, and measuring voltages and/or magnetic fields induced in electrodes, antennas and/or magnetometers disposed near the Earth's surface or on the sea floor. The voltages and/or magnetic fields are induced in response to the electric current and/or magnetic field imparted into the Earth's subsurface.

Controlled source surveying known in the art typically includes imparting alternating electric current into the subsurface. The alternating current has one or more selected frequencies. Such surveying is known as frequency domain controlled source electromagnetic (f-CSEM) surveying. f-CSEM surveying techniques are described, for example, in Sinha, M. C. Patel, P. D., Unsworth, M. J., Owen, T. R. E., and MacCormack, M. G. R., 1990, *An active source electromagnetic sounding system for marine use*, Marine Geophysical Research, 12, 29-68. Other publications which describe the physics of and the interpretation of electromagnetic subsurface surveying include: Edwards, R. N., Law, L. K., Wolfgram, P. A., Nobes, D. C., Bone, M. N., Trigg, D. F., and DeLaurier, J. M., 1985, *First results of the MOSES experiment: Sea sediment conductivity and thickness determination, Bute Inlet, British Columbia, by magnetometric offshore electrical sounding*: Geophysics 50, No. 1, 153-160; Edwards, R. N., 1997, *On the resource evaluation of marine gas hydrate deposits using the sea-floor transient electric dipole-dipole method*: Geophysics, 62, No. 1, 63-74; Chave, A. D., Constable, S. C. and Edwards, R. N., 1991, *Electrical exploration methods for the seafloor*: Investigation in geophysics No 3, Electromagnetic methods in applied geophysics, vol. 2, application, part B, 931-966; and Cheesman, S. J., Edwards, R. N., and Chave, A. D., 1987, *On the theory of sea-floor conductivity mapping using transient electromagnetic systems*: Geophysics, 52, No. 2, 204-217. Typical borehole related applications are described in Strack (U.S. Pat. Nos. 6,541,975 B2, 6,670,813, and 6,739,165) and Hanstein et al., (U.S. Pat. No. 6,891,376). The proposed methodology is not limited to such applications because the array is moving along the survey area.

Following are described several patent publications which describe various aspects of electromagnetic subsurface Earth surveying. For the marine case, U.S. Pat. No. 5,770,945 issued to Constable describes a magnetotelluric (MT) system for sea floor petroleum exploration. The disclosed system includes a first waterproof pressure case containing a processor, AC-coupled magnetic field post-amplifiers and electric field amplifiers, a second waterproof pressure case containing an acoustic navigation/release system, four silver-silver chloride electrodes mounted on booms and at least two magnetic induction coil sensors. These elements are mounted together on a plastic and aluminum frame along with flotation devices and an anchor for deployment to the sea floor. The acoustic navigation/release system serves to locate the measurement system by responding to acoustic "pings" generated by a ship-board unit, and receives a release command which initiates detachment from the anchor so that the buoyant package floats to the surface for recovery. The electrodes used to detect the electric field are configured as grounded dipole antennas. Booms by which the electrodes are mounted onto a frame are positioned in an X-shaped configuration to create two orthogonal dipoles. The two orthogonal dipoles are used to measure the complete vector electric field. The magnetic field sensors are multi-turn, Mu-metal core wire coils which detect magnetic fields within the frequency range typically used for land-based MT surveys. The magnetic field coils are encased in waterproof pressure cases and are connected to the logger package by high pressure waterproof cables. The logger unit includes amplifiers for amplifying the signals received from the various sensors, which signals are then provided to the processor which controls timing, logging, storing and power switching operations. Temporary and mass storage is provided within and/or peripherally to the processor.

U.S. Pat. No. 6,603,313 B1 issued to Srnka discloses a method for surface estimation of reservoir properties, in which location of and average earth resistivities above, below, and horizontally adjacent to subsurface geologic formations are first determined using geological and geophysical data in the vicinity of the subsurface geologic formation. Then dimensions and probing frequency for an electromagnetic source are determined to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation, using the location and the average earth resistivities. Next, the electromagnetic source is activated at or near surface, approximately centered above the subsurface geologic formation and a plurality of components of electromagnetic response is measured with a receiver array. Geometrical and electrical parameter constraints are determined, using the geological and geophysical data. Finally, the electromagnetic response is processed using the geometrical and electrical parameter constraints to produce inverted vertical and horizontal resistivity depth images. Optionally, the inverted resistivity depth images may be combined with the geological and geophysical data to estimate the reservoir fluid and shaliness properties.

U.S. Pat. No. 6,628,110 B1 issued to Eidesmo et al. discloses a method for determining the nature of a subterranean reservoir whose approximate geometry and location are known. The disclosed method includes: applying a time varying electromagnetic field to the strata containing the reservoir; detecting the electromagnetic wave field response; and analyzing the effects on the characteristics of the detected field that have been caused by the reservoir, thereby determining the content of the reservoir, based on the analysis.

U.S. Pat. No. 6,541,975 B2 and U.S. Pat. No. 6,670,813 issued to Strack disclose a system for generating an image of

an Earth formation surrounding a borehole penetrating the formation. Resistivity of the formation is measured using a DC measurement, and conductivity and resistivity of the formations is measured with a time domain signal or AC measurement. Acoustic velocity of the formation is also measured. The DC resistivity measurement, the conductivity measurement made with a time domain electromagnetic signal, the resistivity measurement made with a time domain electromagnetic signal and the acoustic velocity measurements are combined to generate the image of the Earth formation.

U.S. Pat. No. 6,739,165 issued to Strack discloses a method where transient electromagnetic measurement are performed with a receiver or transmitter being placed in a borehole and the other being placed on the surface. Either is being moved and images of fluid content changes of the reservoir are obtained.

International Patent Application Publication No. WO 0157555 A1 discloses a system for detecting a subterranean reservoir or determining the nature of a subterranean reservoir whose position and geometry is known from previous seismic surveys. An n electromagnetic field is applied by a transmitter on the seabed and is detected by antennae also on the seabed. A refracted wave component is sought in the wave field response, to determine the nature of any reservoir present.

International Patent Application Publication No. WO 03048812 A1 discloses an electromagnetic survey method for surveying an area previously identified as potentially containing a subsea hydrocarbon reservoir. The method includes obtaining first and second survey data sets with an electromagnetic source aligned end-on and broadside relative to the same or different receivers. The invention also relates to planning a survey using this method, and to analysis of survey data taken in combination allow the galvanic contribution to the signals collected at the receiver to be contrasted with the inductive effects, and the effects of signal attenuation, which are highly dependent on local properties of the rock formation, overlying water and air at the survey area. This is very important to the success of using electromagnetic surveying for identifying hydrocarbon reserves and distinguishing them from other classes of structure.

U.S. Pat. No. 6,842,006 B1 issued to Conti et al. discloses a sea-floor electromagnetic measurement device for obtaining underwater magnetotelluric (MT) measurements of earth formations. The device includes a central structure with arms pivotally attached thereto. The pivoting arms enable easy deployment and storage of the device. Electrodes and magnetometers are attached to each arm for measuring electric and magnetic fields respectively, the magnetometers being distant from the central structure such that magnetic fields present therein are not sensed. A method for undertaking sea floor measurements includes measuring electric fields at a distance from the structure and measuring magnetic fields at the same location.

U.S. Patent Application Publication No. 2004 232917 relates to a method of mapping subsurface resistivity contrasts by making multichannel transient electromagnetic (MTEM) measurements on or near the Earth's surface using at least one source, receiving means for measuring the system response and at least one receiver for measuring the resultant earth response. All signals from the or each source-receiver pair are processed to recover the corresponding electromagnetic impulse response of the earth and such impulse responses, or any transformation of such impulse responses, are displayed to create a subsurface representation of resistivity contrasts. The system and method enable subsurface

fluid deposits to be located and identified and the movement of such fluids to be monitored.

U.S. Pat. No. 5,467,018 issued to Rueter et al. discloses a bedrock exploration system. The system includes transients generated as sudden changes in a transmission stream, which are transmitted into the Earth's subsurface by a transmitter. The induced electric currents thus produced are measured by several receiver units. The measured values from the receiver units are passed to a central unit. The measured values obtained from the receiver units are digitized and stored at the measurement points, and the central unit is linked with the measurement points by a telemetry link. By means of the telemetry link, data from the data stores in the receiver units can be successively passed on to the central unit.

U.S. Pat. No. 5,563,913 issued to Tasci et al. discloses a method and apparatus used in providing resistivity measurement data of a sedimentary subsurface. The data are used for developing and mapping an enhanced anomalous resistivity pattern. The enhanced subsurface resistivity pattern is associated with and an aid for finding oil and/or gas traps at various depths down to a basement of the sedimentary subsurface. The apparatus is disposed on a ground surface and includes an electric generator connected to a transmitter with a length of wire with grounded electrodes. When large amplitude, long period, square waves of current are sent from a transmission site through the transmitter and wire, secondary eddy currents are induced in the subsurface. The eddy currents induce magnetic field changes in the subsurface which can be measured at the surface of the earth with a magnetometer or induction coil. The magnetic field changes are received and recorded as time varying voltages at each sounding site. Information on resistivity variations of the subsurface formations is deduced from the amplitude and shape of the measured magnetic field signals plotted as a function of time after applying appropriate mathematical equations. The sounding sites are arranged in a plot-like manner to ensure that areal contour maps and cross sections of the resistivity variations of the subsurface formations can be prepared.

U.S. Pat. No. 7,038,456 issued to Ellingsrud et al. discloses an electric dipole transmitter antenna on or close to the sea floor used to induce electromagnetic (EM) fields and currents in the sea water and in the subsurface strata. In the sea water, the EM-fields are strongly attenuated due to the high conductivity in the saline environment, whereas the subsurface strata with less conductivity potentially can act as a guide for the EM-fields due to lower attenuation. If the frequency is low enough (on the order of 1 Hz), the EM-waves are able to penetrate deep into the subsurface, and deeply buried geological layers having higher electrical resistivity than the overburden (as e.g. a hydrocarbon filled reservoir) will affect the EM-waves. Depending on the angle of incidence and state of polarization, an EM wave incident upon a high resistive layer may excite a ducted (guided) wave mode in the layer. The ducted mode is propagated laterally along the layer and leaks energy back to the overburden and receivers positioned on the sea floor. The term "refracted" wave in this specification is intended to refer to this wave mode. Both theory and laboratory experiments show that the ducted mode is excited only for an incident wave with transverse magnetic (TM) polarization (magnetic field perpendicular to the plane of incidence) and at angles of incidence close to the Brewster angle and the critical angle (the angle of total reflection). For transverse electric (TE) polarization (electric field perpendicular to the plane of incidence) the ducted mode will not be excited. Since the induced current is proportional to the electric field, the current will be parallel to the layer interfaces for TE polarization but, for TM polarization, there is an appre-

ciable current across the layer interfaces. A horizontal dipole source on the sea floor will generate both TE and TM waves, but by varying the orientation of the receiver antennae, it is possible to vary the sensitivity to the two modes of polarization. It appears that an in-line orientation (source and receiver dipoles in-line) is more sensitive to the TM mode of polarization, whereas a parallel orientation (source and receiver dipoles in parallel) is more sensitive to the TE mode of polarization. The TM mode is influenced by the presence of buried high resistive layers, whereas the TE mode is not. By measuring with the two antenna configurations and exploiting the difference between the two sets of measurements, it is possible to identify deeply buried high resistivity zones, i.e. a hydrocarbon reservoir.

U.S. Pat. No. 6,717,411 issued to Ellingsrud et al. discloses a method of investigating subterranean strata which includes deploying an electric dipole transmitter antenna, deploying an electric dipole receiver antenna at a predetermined offset distance from the transmitter, applying an electromagnetic (EM) field to the strata using the transmitter, detecting the EM wave field response using the receiver, extracting phase information from the wave response, repeating the procedure with the transmitter and/or receiver in different locations for a plurality of transmissions, and using the phase information from the wave response for the plurality of transmissions in order to determine the presence and/or nature of the reservoir.

Thus, the offset can be varied by moving the receiver; or indeed the transmitter, or even both. Alternatively, the predetermined offset can be kept constant by moving both the transmitter and receiver. Thus, the horizontal boundaries of the reservoir may be found by analyzing the slope and/or slope change of the curve(s) of phase and/or magnitude as a function of source-receiver offset distance or position, or by analyzing the variation in phase and/or magnitude for a fixed source-receiver offset at several locations. The most useful source-receiver offset is typically larger than the "critical offset". In this part of the curve, the change in slope may indicate the reservoir boundary. Both the source and the receiver are preferably inside the reservoir area to achieve the smallest slope (or gradient). This is true for both the phase and the magnitude curves. Soon after either the source or the receiver leaves the reservoir area, the slopes increases rapidly. From the position where this change occurs, the reservoir boundary may be mapped. The true reservoir boundary will probably lie closer the centre of the reservoir compared to the location where the slope change occurred, typically 10 to 20% of the reservoir depth. The detailed position may be calculated using the measured data and forward modeling.

A typical f-CSEM marine survey can be described as follows. A recording vessel includes cables which connect to electrodes disposed on the sea floor. An electric power source on the vessel charges the electrodes such that a selected magnitude of current flows through the sea floor and into the Earth formations below the sea floor. At a selected distance ("offset") from the source electrodes, receiver electrodes are disposed on the sea floor and are coupled to a voltage measuring circuit, which may be disposed on the vessel or a different vessel. The voltages imparted into the receiver electrodes are then analyzed to infer the structure and electrical properties of the Earth formations in the subsurface.

Another technique for electromagnetic surveying of subsurface Earth formations known in the art is transient controlled source electromagnetic surveying (t-CSEM). In t-CSEM, electric current is imparted into the Earth at the Earth's surface, in a manner similar to f-CSEM. The electric current may be direct current (DC) and slowly varying alternating current (AC) typically in the form of square waves. At a selected time, the electric current is switched off, and induced voltages and/or magnetic fields are measured, typically with respect to time over a selected time interval, at the Earth's surface. Structure of the subsurface is inferred by the time distribution of the induced voltages and/or magnetic fields. t-CSEM techniques are described, for example, in Strack, K.-M., 1992, *Exploration with deep transient electromagnetics*, Elsevier, 373 pp. (reprinted 1999).

Each of f-CSEM methods and t-CSEM methods has particular advantages and disadvantages in any particular application. Performing both methods sequentially on any particular portion of the Earth's subsurface that is to be surveyed can be time consuming and expensive. Further, it is difficult to obtain both types of surveys on precisely the same portion of the Earth's subsurface when surveys are operated sequentially because of inherent limitations in ability to position the acquisition equipment at precisely the same geodetic positions each time, particularly in the case of marine surveys.

SUMMARY OF THE INVENTION

One aspect of the invention is a method for interpreting transient electromagnetic survey data. A method according to this aspect of the invention includes imparting an electromagnetic field in the Earth's subsurface by passing electric current through a transmitter antenna. The electric current includes switched direct current at a selected switching frequency. Voltages induced in a receiver corresponding to electromagnetic effects induced in the Earth's subsurface are detected. Frequency domain electromagnetic response of the Earth's subsurface is determined from the detected voltages and transient electromagnetic response of the Earth's subsurface is determined from the detected voltages.

Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A shows a marine electromagnetic survey system using a horizontal electric dipole current source and a seismic source.

FIG. 1B shows a marine electromagnetic survey system using a vertical electric dipole current source.

FIG. 2 shows an alternative way to energize the Earth using magnetic fields.

FIG. 3 shows one embodiment of an electromagnetic sensor.

FIG. 4 shows the current wave form used for a combination time and frequency domain excitation in one embodiment of a method according to the invention.

FIG. 5 is a flow chart of one embodiment of removing "run-on" effect from transient electromagnetic response measurements.

DETAILED DESCRIPTION

FIG. 1A shows one embodiment of a marine controlled source electromagnetic (CSEM) survey system for use with methods according to various aspects of the invention. The system includes a survey vessel 10 that moves in a predetermined pattern along the surface of a body of water 11 such as a lake or the ocean. The vessel 10 includes thereon source actuation, recording and navigation equipment, shown generally at 12 and referred to herein as the "recording system." The recording system 12 includes a controllable source of electric current used to energize electrodes 16A 16B towed in

the water **11** near the bottom **13** thereof to impart an electric field in the subsurface formations **15**, **17** below the bottom **13** of the water.). The recording system **12** includes instrumentation to determine the geodetic position of the vessel **10** at any time, such as can be performed using global positioning system (GPS) receivers or the like. The recording system **12** includes equipment to transfer signals from one or more recording buoys **22**. The recording buoys **22** receive and store signals from each of a plurality of electromagnetic sensors **20** positioned on the water bottom **13**. The sensors **20** may be disposed along a cable **18**. The cable **18** may be of a type used in connection with seismic sensors deployed on the water bottom known in the art as "ocean bottom cables."

The sensors **20** detect various electric and/or magnetic fields that result from electric fields induced in the Earth's subsurface by current passing through the electrodes **16A**, **16B**. The recording buoys **22** may include telemetry devices (not shown separately) to transmit data from the received signals to the vessel **10**, and/or may store the signals locally for later interrogation by the recording system **12** or by another interrogation device.

The current source (not shown separately) on the vessel **10** is coupled to the electrodes **16A**, **16B** by a cable **14A**. The cable **14A** is configured such that the electrodes **16A**, **16B** can be towed essentially horizontally near the water bottom **13** as shown in FIG. **1A**. In the present embodiment, the electrodes can be spaced apart about 50 meters, and can be energized such that about 1000 Amperes of current flows through the electrodes **16A**, **16B**. This is an equivalent source moment to that generated in typical electromagnetic survey practice known in the art using a 100 meter long transmitter dipole, and using 500 Amperes current. In either case the source moment can be about 5×10^4 Ampere-meters. The electric current used to energize the transmitter electrodes **16A**, **16B** can include switched direct current (DC). The current may be switched on and off, or, preferably, may be switched to alternate polarity across the electrodes **16A**, **16B**. As will be further explained, the DC used to energize the electrodes **16A**, **16B** may be switched so as to have a switching frequency on the order of 0.01 to 1 Hz.

The vessel may also tow a seismic source **9** for contemporaneous seismic and electromagnetic surveying. In such embodiments, the water bottom cable **18** may include seismic sensors **21** of any type known in the art.

In the present embodiment, as the current through the transmitter electrodes **16A**, **16B** is switched, a time-indexed recording of electric and/or magnetic fields detected by the various sensors **20** is recorded, either in the recording buoys **22** and/or in the recording system **12**, depending on the particular configuration of recording and/or telemetry equipment in the recording buoys **22** and in the recording system **12**. The time indexed recording is indexed to the time at which the current is switched, so as to record transient electromagnetic response of the subsurface Earth formations **15**, **17**. In addition, a recording of the signals detected by the various sensors **20** is made over a length of time intended to include a selected number of switching events, typically on the order of 1,000 to 2,000 switching events. Such recordings will include signals having characteristics related to the frequency domain response of the subsurface Earth formations to the electromagnetic fields induced by the switched DC imparted to the electrodes **16A**, **16B**. As will be readily appreciated by those skilled in the art, such response will include equivalent responses to the fundamental switching frequency, which is as explained above preferably on the order of 0.01 to 1 Hz, and odd harmonics thereof.

FIG. **1B** shows an alternative implementation of signal generation and recording, in which the transmitter electrodes **16A**, **16B** are arranged such that they are oriented substantially vertically along a cable **14B** configured to cause the electrodes **16A**, **16B** to be oriented substantially vertically as shown in FIG. **1B**. Energizing the electrodes **16A**, **16B**, detecting and recording signals is performed substantially as explained above with reference to FIG. **1A**.

The embodiments of FIG. **1A** and FIG. **1B** use electric current applied to electrodes to impart an electric field into the Earth's subsurface. An alternative to electric fields is to use magnetic fields, and such will be explained with reference to FIG. **2**. In FIG. **2**, the vessel **10** tows a cable **14C** which is connected to two loop transmitters **17A** and **17B**. The first loop transmitter **17A** encloses and area perpendicular to the water bottom **13**. Periodically, the recording system **12** causes electric current to flow through the first loop transmitter **17A**. The current can be in any of the same forms as described with reference to FIG. **1A**, including switched DC, PRBS, and alternating polarity DC. When the current changes, a transient magnetic field having dipole moment along direction M_A is imparted into the Earth. At the same or at different times, current is applied to the second loop transmitter **17B**. The second loop transmitter may be in the form of a solenoid coil, having a magnetic moment along direction M_B.

The foregoing embodiments have been explained in the context of marine electromagnetic surveying. It should be clearly understood that the foregoing embodiments are equally applicable to surveys conducted on land at the surface of the Earth or in a borehole. When conducted on land at the surface of the Earth, the sensors can be deployed in substantially similar patterns to that shown in FIG. **1A**. The survey current source may be applied in the form of electric current, as shown in FIG. **1A**, at the Earth's surface, or in the form of magnetic fields, as shown in and described with reference to FIG. **2**. For purposes of defining the scope of the invention, the various survey devices can be said to be disposed at the top of an area of the Earth's subsurface to be surveyed. The top of the Earth's subsurface will be at the bottom of the water in a marine survey, and at the surface of the Earth in a land based survey, or on the top of a layer of floating ice where such surveys are to be conducted.

FIG. **3** shows one embodiment of a sensor **20** in more detail. The sensor **20** may be enclosed in a housing **23** made from a dense, electrically non conductive, non magnetic material such as high density plastic such that the sensor **20** will sink in the water and rest on the water bottom (**13** in FIG. **1A**). Electrodes **26A**, **26B**, **28A**, **28B** are positioned on the bottom of the housing **23** such that they contact the water bottom (**13** in FIG. **1A**). The electrodes are arranged in dipole pairs. One pair **26A**, **26B** can be oriented along the length of cable (**18** in FIG. **2A**), and measures voltages along the direction of the cable. The other electrode pair **28A**, **28B** can be oriented transversely to the cable (**18** in FIG. **2A**) and measures voltages induced transversely to the cable (**18** in FIG. **2A**). The electrode pairs may span a distance of about 1 to 10 meters. The electrode pairs **26A**, **26B** and **28A**, **28B** may be coupled to a combined amplifier/digital signal processor **24** for converting the detected voltages into digital words corresponding to the voltage amplitude at selected moments in time. The present embodiment of the sensor **20** may include one or more magnetometers **30**, **32**, **34** oriented along mutually orthogonal directions. In the present embodiment, two of the magnetometers **30**, **32** may be oriented such that their sensitive axes are oriented along the same direction as the dipole moment of a corresponding electrode pair **26A**, **26B** and **28A**, **28B**. The signal output of each magnetometer **30**, **32**

34 may be coupled to the digital signal processor 24. The digitized signal output of the signal processor 24 can be coupled to the recording buoy (22 in FIG. 2A) for transmission to the recording system (12 in FIG. 1A) or later interrogation by the recording system (12 in FIG. 1A).

FIG. 4 shows a graph of a simulation of electric current passed through a transmitter antenna (as explained above either coils or electrodes) in the upper graph at curve 40, and voltages induced in a receiver antenna (also as explained above either coils, magnetic field detectors or electrodes) in the lower graph at curve 49. The transmitter current may be switched, at negative-going switching events 44A, and at positive-going switching events 44B. The switching events 44A, 44B may cause the current to vary a substantially equal amount above, and correspondingly below, a reference current level, which may be zero or other value. A time duration between successive corresponding polarity switching events (negative-going 44A or positive-going 44B) is referred to as the "base period" and is inversely related to a base frequency of equivalent alternating current. Transient response in the induced voltages is visible after each current switching event, as shown at 48 for negative-going switching events and at 50 for positive-going switching events. In a method according to the invention, transient electromagnetic response of the water and the subsurface formations (15, 17 in FIG. 1A) may be determined, for example, using a method described in U.S. Patent Application Publication No. 20060186887 filed by Strack et al. and incorporated herein by reference. Such method uses the transient response 48, 50 from at least one switching event to determine spatial distribution of conductivity in the Earth's subsurface.

The switched current passing through the transmitter antenna will also introduce frequency domain electromagnetic effects in the water and in the Earth's subsurface. The effective frequency content of such effects will be related to the switching frequency (base period) and harmonics thereof. In a method according to the invention, frequency domain response of the Earth's subsurface may be interpreted to determine the presence of subsurface resistive features, such as hydrocarbon reservoirs, using an interpretation technique described, or examiner, in U.S. Pat. No. 7,038,456 issued to Ellingsrud et al. and incorporated herein by reference. In one embodiment, the response of the water may be determined such as described in the Strack et al. '887 publication cited above using the transient response of the Earth measured at one or more switching events. Such water response may be attenuated from, deconvolved from or otherwise subtracted form the frequency domain response determined or just used as explained above. The result can be a model of the spatial distribution of the resistivity in the Earth's subsurface substantially corrected for the effects of the body of water above the subsurface formations.

It will be appreciated by those skilled in the art that if the switching frequency is sufficiently high, and the base period is then relatively short, that so-called "run-on" may affect the quality of transient electromagnetic measurements made after one or more switching events. Run-on refers to residual transient effects from one switching event affecting subsequent transient measurements because the prior transient effects have not sufficiently decayed. Run-on generally increases in effect as the switching frequency increases. One embodiment of an acquisition and processing method according to the invention that is intended to deal with the run-on effect is shown in the form of a flow chart in FIG. 5. Transient electromagnetic data may be acquired substantially as explained above with reference to FIGS. 1A, 1B and 2. At 60, an initial model of the conductivity distribution in the Earth's

subsurface is made for a volume of the Earth's subsurface, typically that corresponds to the acquisition geometry at the time the CSEM measurements are made. The volume will depend on, among other factors, the positions of the various electrodes and/or loop antennas used during measurement acquisition. The initial model is used, at 62, to generate an expected transient response (whether in voltage or magnetic field amplitude) with respect to time for a first selected switching event. As previously explained, such switching event may be current switch on, current switch off or current polarity reversal. Current polarity reversal, in some embodiments, may include a short duration intervening current switch off, depending on the apparatus used to make the measurements. It will be appreciated by those skilled in the art that forward modeling programs known in the art for calculating transient response do not take account of any undecayed effects of prior current switching events.

In the present embodiment, at 64, a transient response for a switching event prior in time to the first switching event in the acquisition sequence is calculated, preferably using the same forward modeling procedure used to calculate the transient response for the first switching event, and using the same initial model of conductivity distribution. At 66, the calculated transient response of the prior switching event is evaluated with respect to a selected threshold. The selected threshold may be, for example, a predetermined fraction of the peak amplitude of the transient response of the first switching event. The selected threshold may be a predetermined peak amplitude value. If the peak amplitude of the calculated response of the prior switching event is below the threshold, at 70, the calculated responses of the prior event and the first switching event are summed. The threshold is selected such that the effect of a switching event having such transient response is believed to substantially not affect the measured response of the first switching event.

If the calculated response for the prior event is above the selected threshold, then at 68 the data are examined for a switching event back in time from the prior switching event. A transient response for such back in time switching event is calculated at 34, just as for the prior switching event. The foregoing process is repeated for successively earlier switching events until the peak amplitude of the calculated transient response for such switching event is below the selected threshold. At such time, the calculated transient responses for all such switching events are summed, at 70. The summed response is compared, at 71, to the voltage and/or magnetic field actually measured at the first switching event. At 72, if the difference between the summed calculated responses and the measured response exceeds a selected threshold, at least one parameter of the initial model is adjusted, at 66, and the process is repeated from 62 to 72. Such adjustment of the model, and repetition of the process continues until the difference between the calculated response and the measured response is below the selected threshold, at 74, at which point the process is completed with respect to the first switching event.

The foregoing procedure may be repeated for measurements corresponding to other volumes in the Earth's subsurface until the user has determine conductivity distribution over a desired total volume of the Earth's subsurface.

Alternatively, the measurements made are analyzed without reference to a model of the Earth's subsurface. In such alternative implementation, transient response of some portion of the Earth's subsurface or other medium is measured during a plurality of switching events. The response will include decaying amplitude of measured induced voltage and/or magnetic field. The transient response after a first one

of the switching events may then be modeled such as by curve fit or other mathematical representation, or by equivalent analog circuit analysis, for example. In the present embodiment, at **64**, a transient response for a switching event prior in time to the first switching event in the acquisition sequence is calculated, preferably using the same modeling procedure used to calculate the transient response for the first switching event. At **66**, the calculated transient response of the prior switching event is evaluated with respect to a selected threshold. The selected threshold may be, for example, a predetermined fraction of the peak amplitude of the transient response of the first switching event. The selected threshold may be a predetermined peak amplitude value. If the peak amplitude of the calculated response of the prior switching event is below the threshold, at **70**, the calculated responses of the prior event and the first switching event are summed. The threshold is selected such that the effect of a switching event having such transient response is believed to substantially not affect the measured response of the first switching event.

If the calculated response for the prior switching event is above the selected threshold, then at **68** the data are examined for a switching event back in time from the prior switching event. A transient response for such back in time switching event is calculated at **64**, just as for the prior switching event. The foregoing process can be repeated for successively earlier switching events until the peak amplitude of the calculated transient response for such switching event is below the selected threshold. At such time, the calculated transient responses for all such switching events are summed, at **70**. The summed response is compared, at **71**, to the voltage and/or magnetic field actually measured at the first switching event. At **72**, if the difference between the summed calculated responses and the measured response exceeds a selected threshold, at least one parameter of the model is adjusted, at **66**, and the process is repeated from **62** to **72**. Such adjustment of the model, and repetition of the process continues until the difference between the calculated response and the measured response is below the selected threshold, at **64**, at which point the process is completed with respect to the first switching event.

Embodiments of a method according to the various aspects of the invention may provide better interpretation of the resistivity distribution in surveyed areas of the Earth's subsurface, while keeping data acquisition time to a minimum.

While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

What is claimed is:

1. A method for interpreting transient electromagnetic survey data, comprising:

    imparting an electromagnetic field in subsurface formations by passing electric current through a transmitter antenna, the electric current comprising switched direct current at a selected switching frequency;

    detecting voltages induced in a receiver corresponding to electromagnetic effects induced in the-subsurface formations;

    determining frequency domain electromagnetic response of the subsurface formations from the detected voltages; and

    determining transient electromagnetic response of the subsurface formations from the detected voltages.

2. The method of claim **1** wherein the electric current is switched to exceed and fall substantially a same amount below a reference value.

3. The method of claim **2** wherein the reference value is substantially zero.

4. The method of claim **1** wherein the transmitter antenna comprises a dipole electrode.

5. The method of claim **1** wherein the transmitter antenna comprises a wire loop.

6. The method of claim **1** wherein the receiver comprises a dipole electrode.

7. The method of claim **1** wherein the receiver comprises a wire loop.

8. The method of claim **1** wherein the receiver comprises a magnetometer.

9. The method of claim **1** wherein at least one of the imparting an electromagnetic field and the detecting is performed so as to have magnetic dipole moment substantially vertical.

10. The method of claim **1** wherein at least one of the imparting an electromagnetic field and the detecting is performed so as to have magnetic dipole moment substantially horizontal.

11. The method of claim **1** wherein the determining frequency domain electromagnetic response comprises measuring a characteristic of the detected voltages over a plurality of cycles of the current switching.

12. The method of claim **1** wherein the determining transient electromagnetic response comprises:

    measuring transient electromagnetic response over a plurality of transmitter current switching events;

    modeling the measured transient response for a first one of the current switching events;

    calculating transient response to the model for at least one current switching event prior in time to the at least a first current switching event;

    summing the modeled prior event response with the first event response;

    comparing the summed transient responses to the electromagnetic survey measurements; and

    adjusting the model and repeating the calculating transient responses until a difference between the summed calculated responses and the survey measurements falls below a selected threshold.

13. The method of claim **12** further comprising:

    comparing peak amplitude of the calculated transient response of the at least one prior switching event to a selected threshold;

    if the peak amplitude exceeds a selected threshold, calculating a transient response for a switching event prior in time to the at least one prior switching event; and

    repeating the comparing peak amplitude and calculating transient response for successively prior in time switching events until the peak amplitude is below the selected threshold.

14. The method of claim **13** further comprising:

    summing the calculated transient responses for all the switching events;

    comparing the summed transient responses to the survey measurements; and

    adjusting the model and repeating the calculating all the transient responses until a difference between the summed calculated responses and the survey measurements falls below a selected threshold.

15. A method for interpreting transient electromagnetic survey data, comprising:

imparting an electromagnetic field in subsurface formations by passing electric current through a transmitter antenna, the electric current comprising switched direct current at a selected switching frequency;

detecting voltages induced in a receiver corresponding to electromagnetic effects induced in the subsurface formations;

determining frequency domain electromagnetic response of the subsurface formations from the detected voltages; and

determining transient electromagnetic response of the subsurface formations from the detected voltages, wherein the determining transient electromagnetic response comprises, measuring transient electromagnetic response over a plurality of transmitter current switching events, modeling the measured transient response for a first one of the current switching events; calculating transient response to the model for at least one current switching event prior in time to the at least a first current switching event; summing the modeled prior event response with the first event response, comparing the summed transient responses to the electromagnetic survey measurements and adjusting the model and repeating the calculating transient responses until a difference

between the summed calculated responses and the survey measurements falls below a selected threshold.

16. The method of claim 15 further comprising:

comparing peak amplitude of the calculated transient response of the at least one prior switching event to a selected threshold;

if the peak amplitude exceeds a selected threshold, calculating a transient response for a switching event prior in time to the at least one prior switching event; and

repeating the comparing peak amplitude and calculating transient response for successively prior in time switching events until the peak amplitude is below the selected threshold.

17. The method of claim 16 further comprising:

summing the calculated transient responses for all the switching events;

comparing the summed transient responses to the survey measurements; and

adjusting the model and repeating the calculating all the transient responses until a difference between the summed calculated responses and the survey measurements falls below a selected threshold.

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