US007705599B2

US 7,705,599 B2

(12) **United States Patent**
Strack et al.

(10) **Patent No.:** **US 7,705,599 B2**
(45) **Date of Patent:** **Apr. 27, 2010**

(54) **BUOY-BASED MARINE ELECTROMAGNETIC SIGNAL ACQUISITION SYSTEM**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/774,748**

(22) Filed: **Jul. 9, 2007**

(65) **Prior Publication Data**

US 2009/0015262 A1   Jan. 15, 2009

(51) **Int. Cl.**
G01V 3/00 (2006.01)
G01V 3/08 (2006.01)
(52) **U.S. Cl.** **324/348**; 324/323
(58) **Field of Classification Search** 324/348,
324/359, 354, 323; 702/2, 5, 16
See application file for complete search history.

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(57)   **ABSTRACT**

A sensor cable system for measuring electromagnetic response of the Earth's subsurface includes a sensor cable deployable on the bottom of a body of water. The sensor cable has a plurality of electromagnetic sensing devices thereon at spaced apart locations. A system control unit is in signal communication with the sensing elements. The system control unit includes a transceiver for communicating signals to and from a corresponding sensor cable system. The system control unit includes a global positioning system signal receiver. The system control unit includes a processor configurable to receive signals detected by sensing elements in the corresponding sensor cable system. The processor is configurable to compute stacked signals from the sensing elements in the sensor cable and from sensing elements in the corresponding system. The processor is configurable to calculate a statistical measure of the stacked signals. The system control unit is disposed in a flotation device.
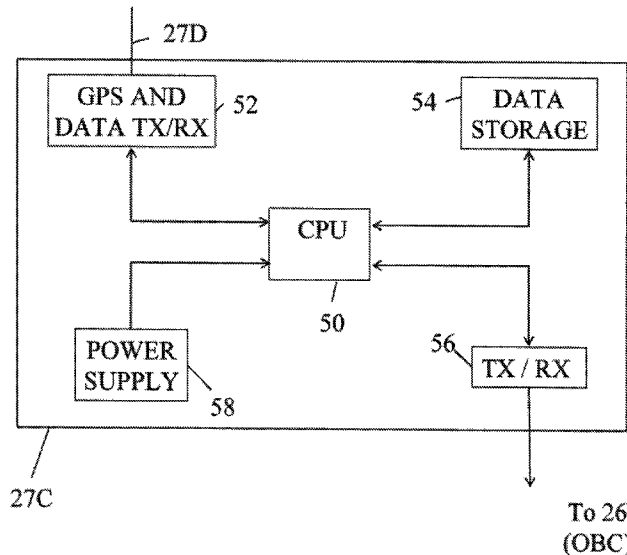
21 Claims, 8 Drawing Sheets

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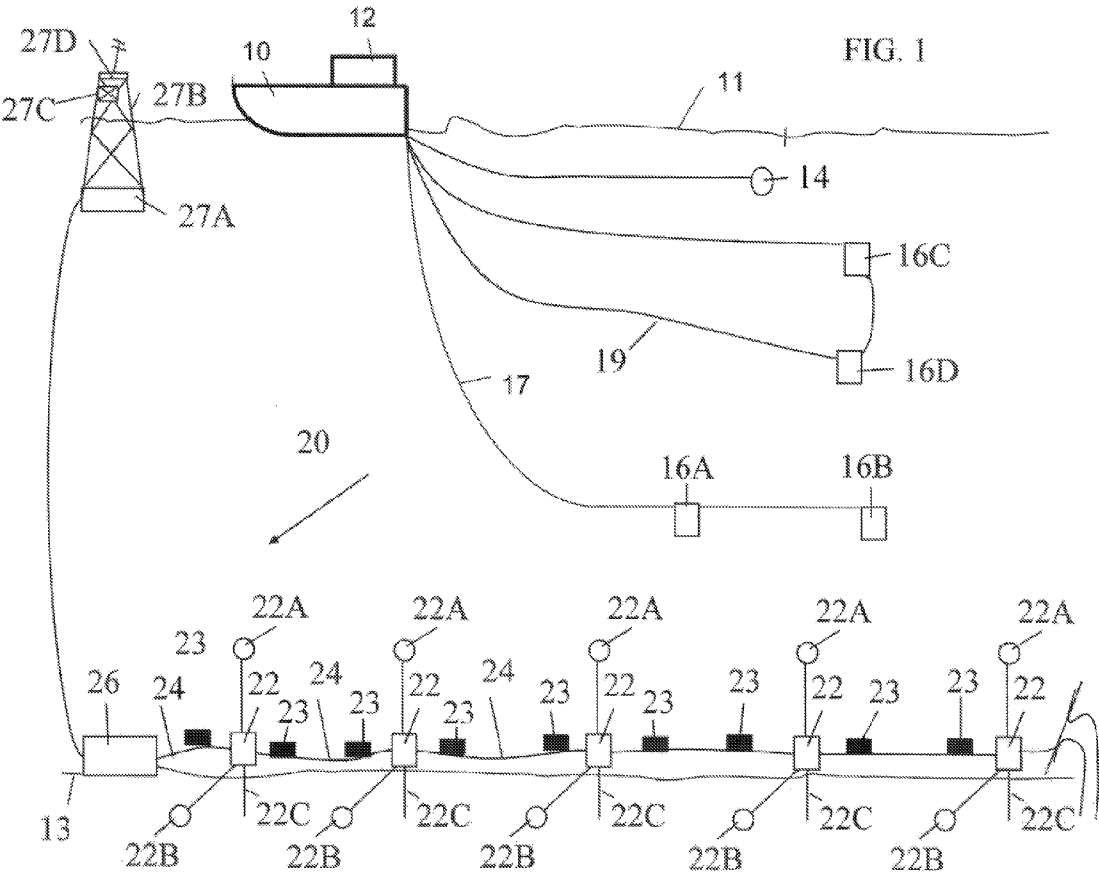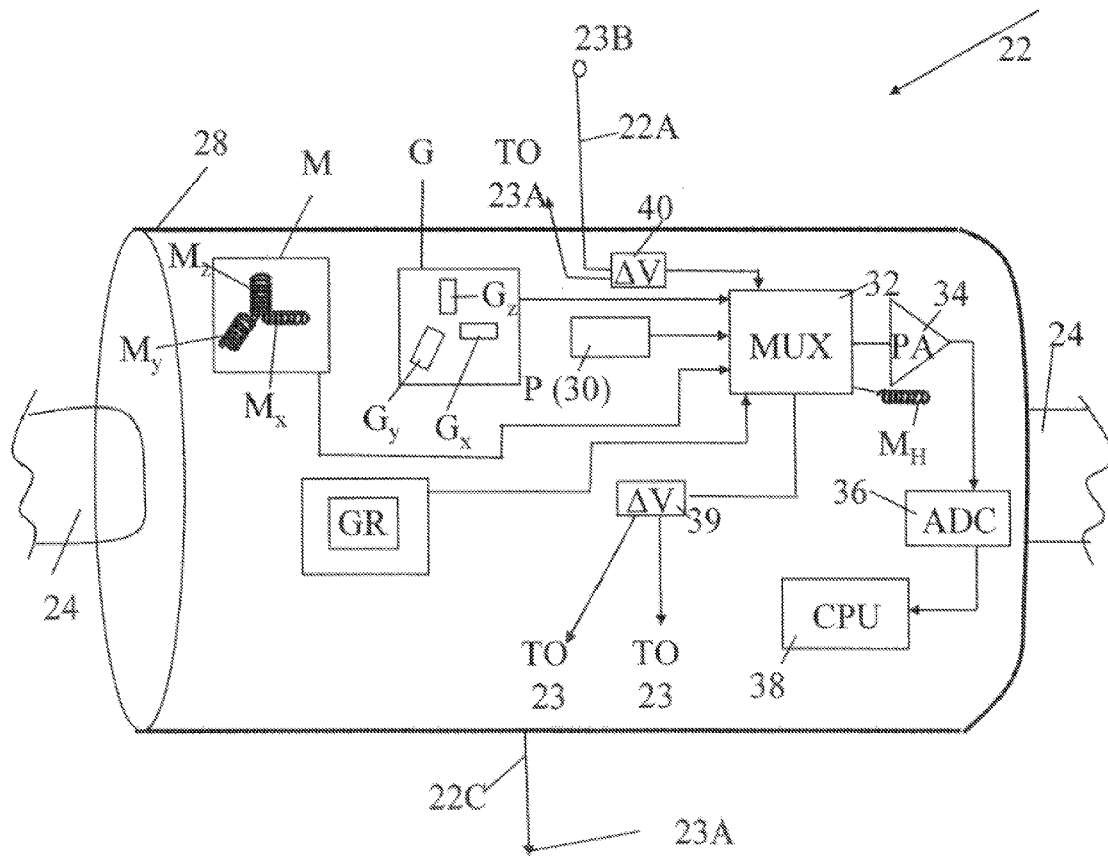
FIG. 1

FIG. 2
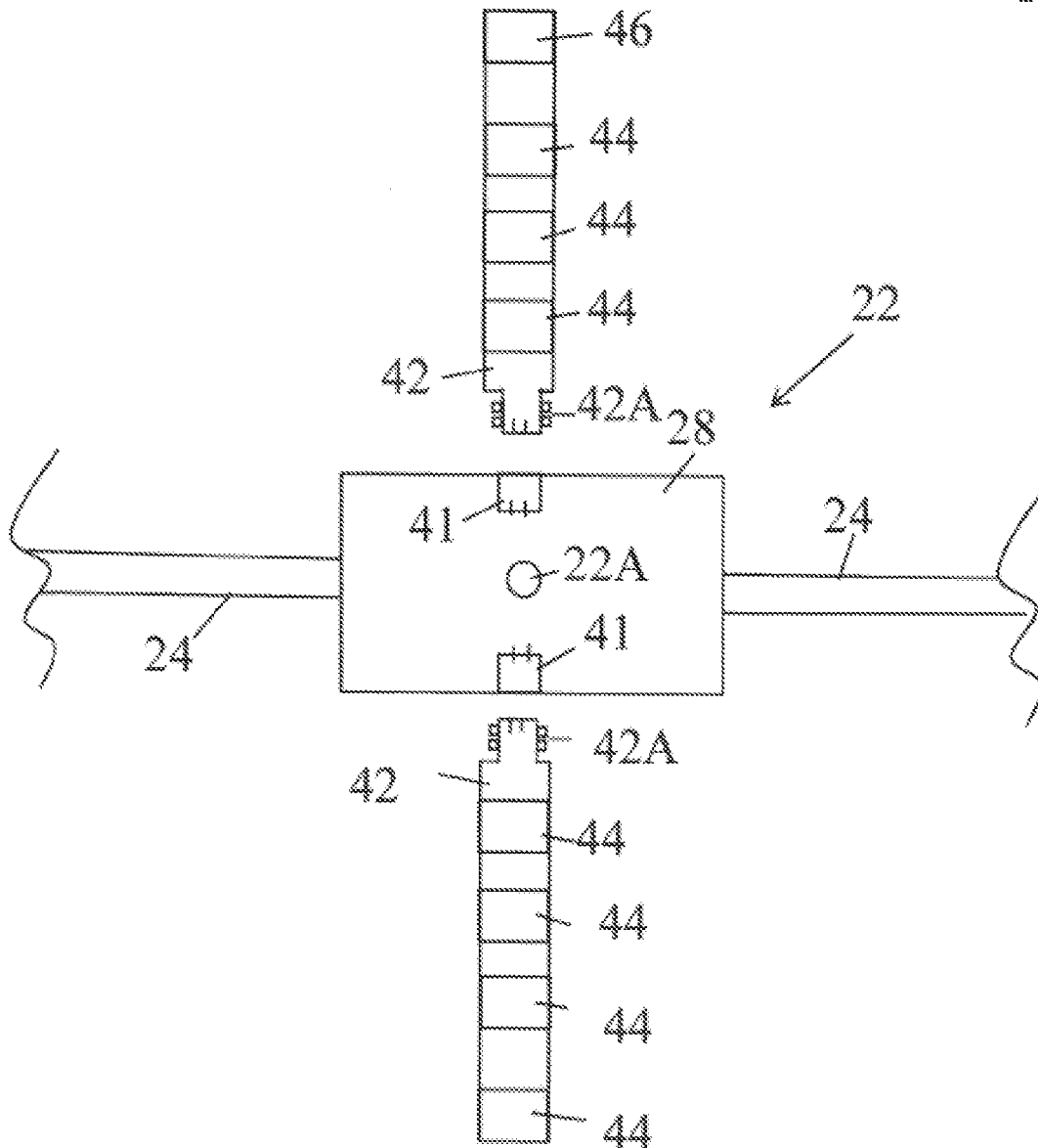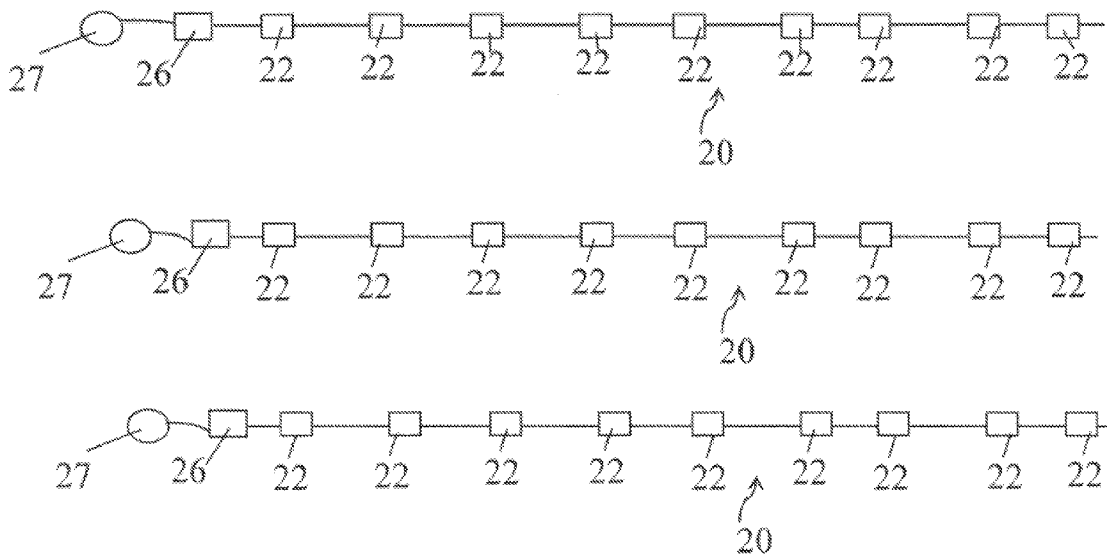
FIG. 3

46

44

44

44

42   42A 28

22

41

24

22A

24

41

24

42   42A

44

44

44

44

FIG. 4

FIG. 5

27D

| GPS AND DATA TX/RX | 52 | 54 | DATA STORAGE |

CPU

50

| POWER SUPPLY | 58 | 56 | TX / RX |

27C

To 26
(OBC)

FIG. 6

Data Recorded in Main Control Unit — 70

Data Recorded In n-th Control Unit — 72

• • • • • •

Data Recorded In (n+1)th Control Unit — 74

Improve using Quality Criteria from Ind. units — 82

Derive Quality Criteria — 76

Telemetry communication

Derive Quality Criteria — 78

Improve using Quality Criteria from Combined units — 84

Derive combined Quality Criteria — 80

FIG. 7

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┌──────────────┐            ┌──────────────┐
│    Data      │── 86       │  Ship borne  │── 88
│   Recorded   │            │ Command Center│
│   in  Main   │◄─────────► │              │
│ Control Unit │            │              │
└──────┬───────┘            └──────┬───────┘
       │                           │
       │                           ▼
       │                    ┌──────────────┐
       │                    │   Quality    │── 90
       │                    │   Control    │
       │                    │  processing  │
       │                    └──────┬───────┘
       │                           │
       ▼                           ▼
┌──────────────┐            ┌──────────────┐
│ Improve using│── 94       │    Change    │── 92
│Quality Criteria│◄────────│    Survey    │
│    from      │            │  Parameters  │
│  Ind. units  │            │              │
└──────────────┘            └──────────────┘
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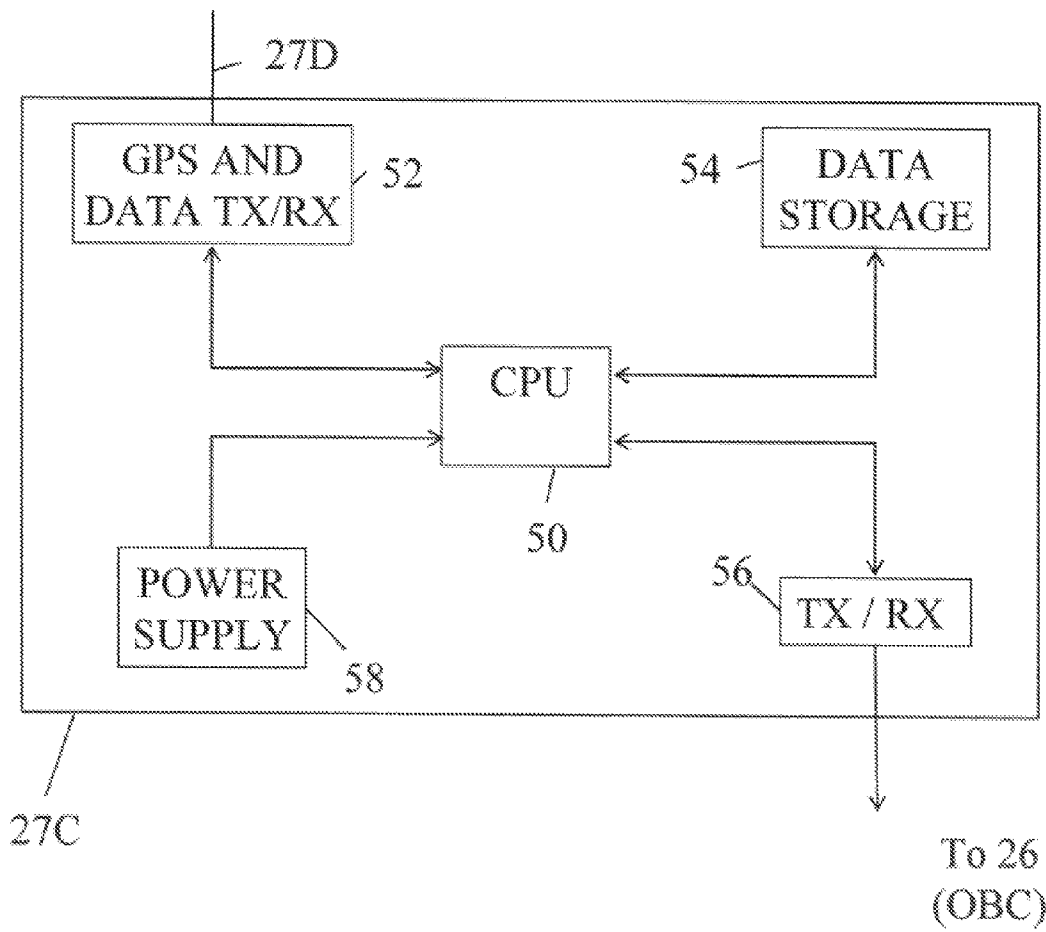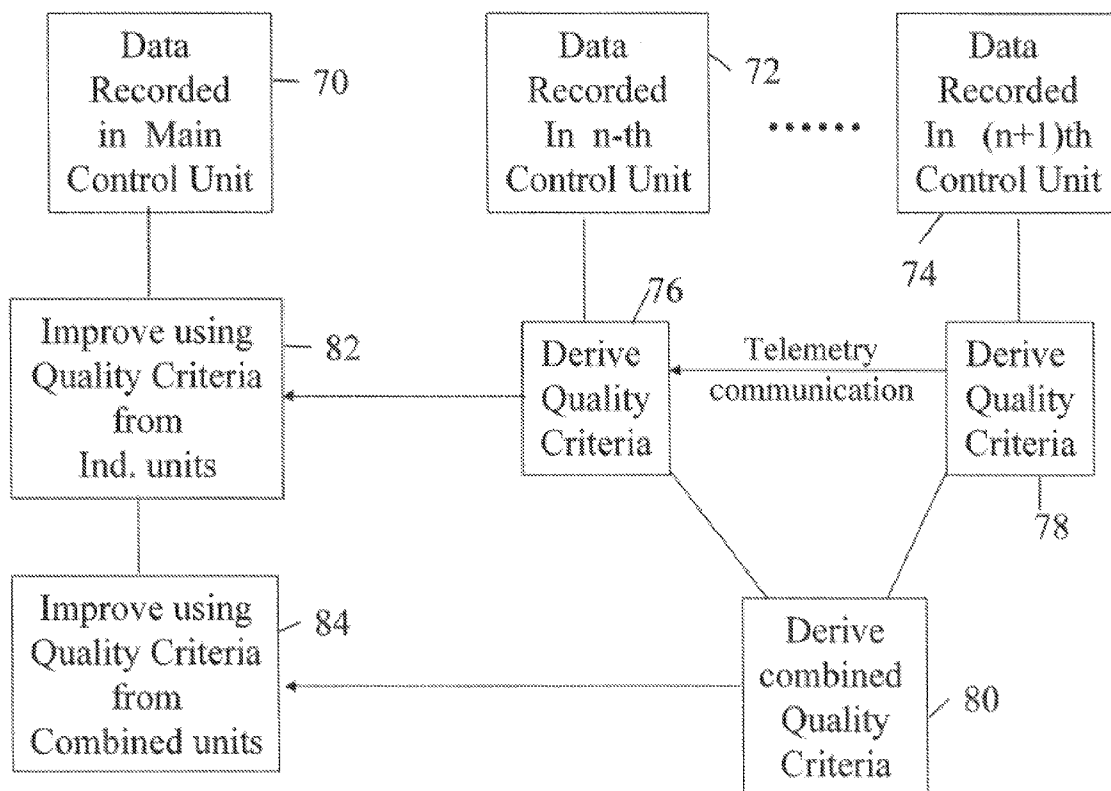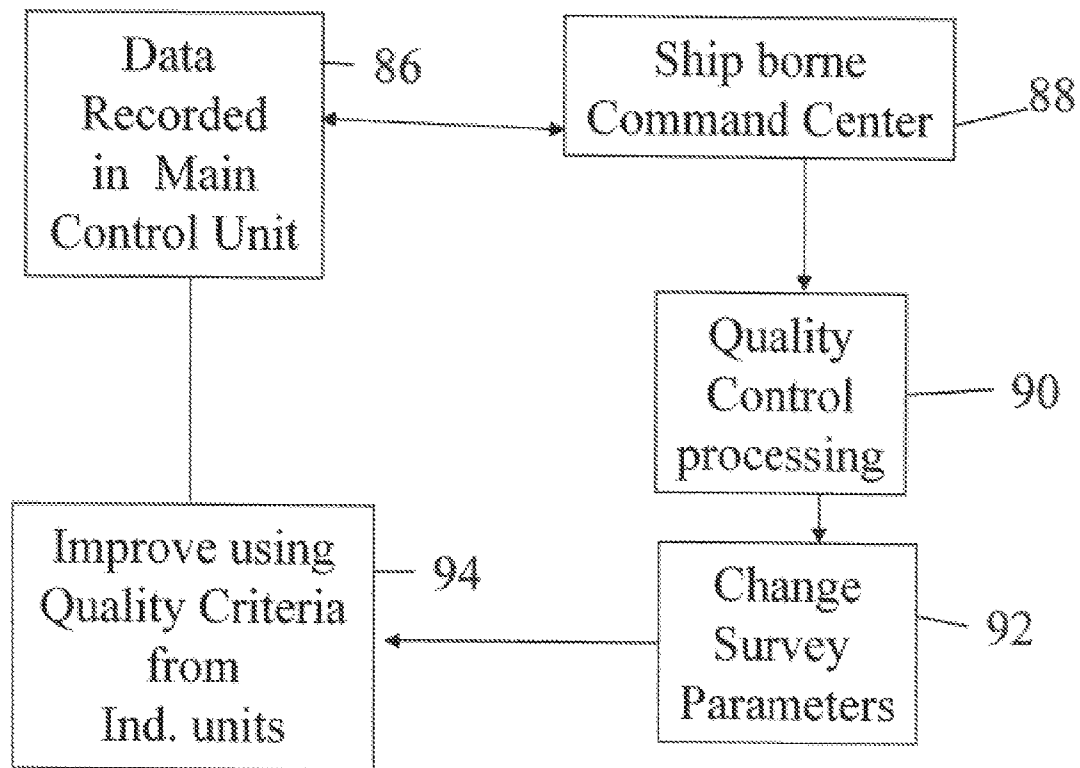
FIG. 8

BUOY-BASED MARINE ELECTROMAGNETIC SIGNAL ACQUISITION SYSTEM

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 marine electromagnetic geophysical surveying. More specifically, the invention relates to cables and related apparatus for acquiring, recording and transmitting electromagnetic signals produced for subsurface Earth surveying.

2. Background Art

Electromagnetic geophysical surveying includes "controlled source" and natural source electromagnetic surveying. Controlled source electromagnetic surveying includes imparting an electric field or a magnetic field into the Earth formations, those formations being below the sea floor in marine surveys, and measuring electric field amplitude and/or amplitude of magnetic fields by measuring voltage differences induced in electrodes, antennas and/or interrogating magnetometers disposed at the Earth's surface, or on or above the sea floor. The electric and/or magnetic fields are induced in response to the electric field and/or magnetic field imparted into the Earth's subsurface, and inferences about the spatial distribution of conductivity of the Earth's subsurface are made from recordings of the induced electric and/or magnetic fields.

Natural source electromagnetics includes multi-components ocean bottom receiver stations and by taking the ratio of perpendicular field components, one can eliminate the need to know the natural source. Hereto, natural source electromagnetics for marine applications has been restricted to autonomous recording stations.

Controlled source electromagnetic surveying known in the art includes imparting alternating electric current into formations below the sea floor. 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 geophys-

ics, 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.

Other publications of interest in the technical field of electromagnetic surveying include Edwards, N., 2005, *Marine controlled source electromagnetics: Principles, Methodologies, Future commercial applications:* Surveys in Geophysics, No. 26, 675-700; Constable, S., 2006, *Marine electromagnetic methods—A new tool for offshore Exploration:* The Leading Edge v. 25, No. 4, p. 438-444; Christensen, N. B. and Dodds, K., 2007, *1D inversion and resolution analysis of marine CSEM data,* Geophysics 72, WA27; Chen, J., Hoversten, G. M., Vasco, D., Rubin, Y., and Hou, Z., 2007, *A Bayesian model for gas saturation estimation using marine seismic AVA and CSEM data,* Geophysics 72, WA85; Constable, S. and Srnka, L. J., 2007, *An introduction to marine controlled-source electromagnetic methods for hydrocarbon exploration,* Geophysics 72, WA3; Evans, R. L., 2007, *Using CSEM techniques to map the shallow section of seafloor: From the coastline to the edges of the continental slope,* Geophysics 72, WA105; Darnet, M., Choo, M. C. K., Plessix, R. D., Rosenquist, M. L., Yip-Cheong, K., Sims, E., and Voon, J. W. K., 2007, *Detecting hydrocarbon reservoirs from CSEM data in complex settings: Application to deepwater Sabah, Malaysia,* Geophysics 72, WA97; Gribenko, A. and Zhdanov, M., 2007, *Rigorous 3D inversion of marine CSEM data based on the integral equation method,* Geophysics 72, WA73; Li, Y. and Key, K. 2007, *2D marine controlled-source electromagnetic modeling: Part 1—An adaptive finite-element algorithm,* Geophysics 72, WA51; Li, Y. and Constable, S., 2007, *2D marine controlled-source electromagnetic modeling: Part 2—The effect of bathymetry,* Geophysics 72, WA63; Scholl, C. and Edwards, R. N., 2007, *Marine downhole to seafloor dipole-dipole electromagnetic methods and the resolution of resistive targets,* Geophysics 72, WA39; Tompkins, M. J. and Srnka, L. J., 2007, *Marine controlled-source electromagnetic methods—Introduction,* Geophysics 72, WA1; Um, E. S. and Alumbaugh, D. L., 2007, *On the physics of the marine controlled-source electromagnetic method,* Geophysics 72, WA13; Dell'Aversana, P., 2007, *Improving interpretation of CSEM in shallow water,* The Leading Edge 26, 332; Hokstad, K., and Rosten, T., 2007, *On the relationships between depth migration of controlled-source electromagnetic and seismic data,* The Leading Edge 26, 342; Johansen, S. E., Wicklund, T. A. and Amundssen, H. E. F., 2007, *Interpretation example of marine CSEM data,* The Leading Edge 26, 348; and MacGregor, L., Barker, N., Overton, A., Moody, S., and Bodecott, D., 2007, *Derisking exploration prospects using integrated seismic and electromagnetic data—a Falkland Islands case study,* The Leading Edge 26, 356.

Following are described several patent publications which describe various aspects of electromagnetic subsurface Earth surveying. 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 detach-

ment 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. There is no active source in such MT methods, which rely upon naturally occurring EM fields.

U.S. Pat. No. 6,603,313 B1 issued to Srnka discloses a method for surface estimation of reservoir properties, in which average earth resistivities above, below, and horizontally adjacent to specifically located subsurface geologic formations are first determined or estimated 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 the sea floor, 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 (fractional volume in the formation of clay-bearing rocks called "shale") properties.

U.S. Pat. No. 6,628,119 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 issued to Strack discloses 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 are 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.

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 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 so as to 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 subsurface formations.

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 and U.S. Pat. No. 6,914,433 *Detection of subsurface resistivity contrasts with application to location of Fluids* (Wright, et al) relate 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 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. 5,563,513 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.

Other U.S. Patent documents that provide background information concerning the present invention include the following:

U.S. Pat. No. 4,535,292 Transmitter for an electromagnetic survey system with improved power supply switching system (Ensing).

U.S. Pat. No. 5,130,655 Multiple-coil magnetic field sensor with series-connected main coils and parallel-connected feedback coils (Conti).

U.S. Pat. No. 5,877,995 Geophysical prospecting (Thompson et al.).

U.S. Pat. No. 5,955,884 Method and apparatus for measuring transient electromagnetic and electrical energy components propagated in an earth formation (Payton et al.).

U.S. Pat. No. 6,188,221 Method and apparatus for transmitting electromagnetic waves and analyzing returns to locate underground fluid deposits (Van de Kop et al.).

U.S. Pat. No. 6,225,806 Electroseismic technique for measuring the properties of rocks surrounding a borehole (Millar et al.).

U.S. Pat. No. 6,339,333 Dynamic electromagnetic methods for direct prospecting for oil (Kuo).

U.S. Pat. No. 6,628,119 Method and apparatus for determining the content of subterranean reservoirs (Eidesmo, et al).

U.S. Pat. No. 6,664,788 Nonlinear electroseismic exploration (Scott C. Hornbostel, et al).

U.S. Pat. No. 6,696,839 Electromagnetic methods and apparatus for determining the content of subterranean reservoirs (Svein Ellingsrud et al).

U.S. Pat. No. 6,717,411 Electromagnetic method and apparatus for determining the nature of subterranean reservoirs using refracted electromagnetic waves (Ellingsrud, et al).

U.S. Pat. No. 6,859,038 Method and apparatus for determining the nature of subterranean reservoirs using refracted electromagnetic waves (Svein Ellingsrud, et al).

U.S. Pat. No. 6,864,684 Electromagnetic methods and apparatus for determining the content of subterranean reservoirs (Ellingsrud, et al).

U.S. Pat. No. 7,023,213 Subsurface conductivity imaging systems and methods (Edward Nichols).

U.S. Pat. No. 7,038,456 Method and apparatus for determining the nature of subterranean reservoirs (Ellingsrud, et al).

U.S. Pat. No. 7,042,801 System for geophysical prospecting using induce electrokinetic effect (Andrey Berg).

U.S. Pat. No. 7,126,338 Electromagnetic surveying for hydrocarbon reservoirs (MacGregor, Lucy et al.).

U.S. Pat. No. 7,141,968 Integrated sensor system for measuring electric and/or magnetic field vector components (Hibbs, et al).

U.S. Pat. No. 7,141,987 Sensor system for measurement of one or more vector components of an electric field (Hibbs, et al).

U.S. Pat. No. 7,145,341 Method and apparatus for recovering hydrocarbons from subterranean reservoirs (Ellingsrud, et al).

U.S. Pat. No. 7,191,063 Electromagnetic surveying for hydrocarbon reservoirs (Tompkins).

U.S. Pat. Appl. Pub. No. 2006/0091889 Method and apparatus for determining the nature of subterranean reservoirs (Ellingsrud, Svein et al) application Ser. No. 11/301,010 filed on Dec. 12, 2005, granted as U.S. Pat. No. 7,202,669 on Apr. 10, 2007.

U.S. Pat. Appl. Pub. No. 2006/0129322 Electromagnetic surveying for hydrocarbon reservoirs (MacGregor, Lucy et al)

U.S. Pat. Appl. Pub. No. 2006/0132137 Electromagnetic surveying for hydrocarbon reservoirs (MacGregor, Lucy et al).

U.S. Pat. Appl. Pub. No. 2006/0197532 Method and apparatus for determining the nature of submarine reservoirs (Eidesmo, Terje et al).

U.S. Pat. Appl. Pub. No. 2007/0021916 Electromagnetic surveying for hydrocarbon reservoirs (MacGregor, Lucy et al).

U.S. Pat. Appl. Pub. No. 2007/0075708, ELECTROMAGNETIC SURVEY SYSTEM WITH MULTIPLE SOURCES (Reddig, Ransom et al).

A typical f-CSEM marine survey can be described as follows. A recording vessel includes cables which connect to electrodes disposed near the sea floor. An electric power source on the vessel charges the electrodes such that a selected magnitude of alternating current, of selected frequency or frequencies, 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 (or sea floor), in a manner similar to f-CSEM. The electric current may be direct current (DC). At a selected time, the electric current is switched off, switched on, or has its polarity changed, and induced voltages and/or magnetic fields are measured, typically with respect to time over a selected time interval, at the Earth's surface or water surface. Alternative switching strategies are possible; as will be explained in more detail below. 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).

SUMMARY OF THE INVENTION

A sensor cable system for measuring electromagnetic response of the Earth's subsurface according to one aspect of

the invention includes a sensor cable deployable on the bottom of a body of water. The sensor cable has a plurality of electromagnetic sensing devices thereon at spaced apart locations. A system control unit is in signal communication with the sensing elements. The system control unit includes a transceiver for communicating signals to and from a corresponding sensor cable system. The system control unit includes a global positioning system signal receiver. The system control unit includes a processor configurable to receive signals detected by sensing elements in the corresponding sensor cable system. The processor is configurable to compute stacked signals from the sensing elements in the sensor cable and from sensing elements in the corresponding system. The processor is configurable to calculate a statistical measure of the stacked signals. The system control unit is disposed in a flotation device.

A method for acquiring a marine electromagnetic survey according to another aspect of the invention includes actuating an electromagnetic source deployed in a body of water at selected times. Signals related to at least one of an electric field and a magnetic field are detected at spaced apart locations along a first cable disposed proximate the bottom of the body of water. Signals related to at least one of an electric field and a magnetic field are detected at spaced apart locations along at least a second cable disposed proximate the bottom of the body of water. At least one of the detected signals and digital representations thereof are conducted from at least one of the first cable and the at least a second cable to a respective signal processing device for each of the first and at least a second cables disposed proximate the water surface. The detected signals are communicated from at least one of the signal processing devices to another one of the signal processing devices. The communicated signals and the conducted signals are processed in the other one of the signal processing devices.

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

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a marine EM acquisition system that may include acquisition sensor cables according to various aspects of the invention.

FIG. 2 shows one example of an acquisition module that may be used with the cable system shown in FIG. 1.

FIG. 3 shows another example of an acquisition module.

FIG. 4 shows an example of arrangement of an acquisition system.

FIG. 5 shows inducing magnetic fields in the Earth's subsurface.

FIG. 6 shows a system control unit according to one aspect of the invention.

FIG. 7 is a flow chart of signal processing made possible by communication between sensor cable control units.

FIG. 8 is a flow chart of signal processing including changing acquisition parameters by communication from a recording unit to a survey vessel.

DETAILED DESCRIPTION

One example of a marine electromagnetic (EM) survey acquisition system is shown schematically in FIG. 1. The system may include a survey vessel 10 that moves along the surface of a body of water 11 such as a lake or the ocean. The survey vessel 10 includes thereon certain equipment, shown generally at 12 and referred to for convenience as a "recording

system." The recording system 12 may include (none of the following shown separately for clarity of the illustration) navigation devices, source actuation and control equipment, and devices for recording and processing measurements made by various sensors in the acquisition system. The vessel 10 may tow a seismic energy source 14 such as an air gun or an array of such air guns, a vertical electric dipole "source" antenna 19 including vertically spaced apart electrodes 16C, 16D and a horizontal electric dipole "source" antenna 17, which may include horizontally spaced apart electrodes 16A, 16B. The vertical electrodes 16C, 16D are typically energized by current flowing through one of the lines going from either electrode 16C or 16D to the survey vessel 10. The other line may be electrically inactive and only used to keep the vertical dipole antenna in is preferred shape. The electrodes on the source antennas 17, 19 may be referred to as "source electrodes" for convenience. The recording system 12 may include a controllable power supply (not shown separately) to energize the source electrodes for the purpose of inducing electromagnetic fields in the subsurface below the water bottom 13.

In the present example the source electrodes 16A, 16B and 16C, 16D, respectively on each antenna 17, 19, can be spaced apart about 50 meters, and can be energized by the power supply (not shown) such that about 1000 Amperes of current flows through the electrodes. 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 source moment used in any particular implementation is not intended to limit the scope of this invention. An alternative arrangement of electromagnetic source will be explained below with reference to FIG. 5.

If the acquisition system is configured to record transient EM signals, the electric current used to energize the source electrodes can be direct current (DC) switched off at a particular time or at particular times. Such switching time may be conveniently correlated to a signal recording time index equal to zero. It should be understood, however, that switching DC off is only one implementation of electric current switching that is operable to induce transient electromagnetic effects in the Earth's subsurface. In other examples, the electric current (DC) may be switched on, may be switched from one polarity to the other (bipolar switching), or may be switched in a pseudo-random binary sequence (PRBS) or any hybrid derivative of such switching sequences. See, for example, Duncan, P. M., Hwang, A., Edwards, R. N., Bailey, R. C., and Garland, G. D., 1980, *The development and applications of a wide band electromagnetic sounding system using pseudo-noise source*, Geophysics, 45, 1276-1296 for a description of PBRS switching. The system may also be configured to record "frequency domain" signals in conjunction with or alternatively to recording transient signals. The power supply (not shown) may in such instances generate a continuous alternating current having one or more selected component frequencies to perform such frequency domain electromagnetic surveying.

The recording system 12 may include equipment (the source controller) that may actuate the seismic source 14 at selected times and may include devices that record, or accept recordings for processing, from seismic sensors (explained below with reference to FIG. 2) that may be disposed in a sensor cable 24 or elsewhere in the acquisition system.

In the present example, a plurality of ocean bottom cable systems 20, one of which is shown in FIG. 1, may include the sensor cable 24, an acquisition control unit 26 at the head end

of the sensor cable **24**, and a cable buoy **27** at the surface. The cable buoy **27**, which will be further explained below with reference to FIG. **6**, includes a support tower **27B** coupled to a floatation structure **27A**. The support tower **27B** may house a system control unit **27C** that includes, among other components, a global positioning system receiver (FIG. **6**) and a transceiver antenna **27D**. Only one ocean bottom cable system **20** is shown in FIG. **1** for clarity of the illustration. Typically, and as will be explained in more detail with reference to FIG. **4**, a plurality of cable systems is deployed in a selected pattern on the water bottom **13** to conduct an electromagnetic survey.

In the present example, the sensor cable **24** is shown disposed on the water bottom **13** for making measurements corresponding to Earth formations below the water bottom **13**. The sensor cable **24** may include thereon a plurality of longitudinally spaced apart sensor modules **22**. Examples of components in each sensor module **22** will be further explained below with reference to FIGS. **2** and **3**. Each sensor module **22** may have inserted into an upper side thereof a substantially vertically extending sensor arm **22A**. Details of one example of the vertically extending sensor arm **22A** will be explained below with reference to FIG. **3**. Preferably the vertically extending sensor arm **22A** includes therein or thereon some type of buoyancy device or structure (not shown separately) to assist in keeping the sensor arm **22A** in a substantially vertical orientation with respect to gravity. Each sensor module **22** may include extending from its lower side a spike **22C** as described, for example, in Scholl, C. and Edwards, N., 2007, *Marine downhole to seafloor dipole-dipole electromagnetic methods and the resolution of resistive targets* Geophysics, 72, WA39, for penetrating the sediments that exist on the, water bottom **13** to a selected depth therein. Disposed about the exterior of portions of the sensor cable **24** adjacent each longitudinal end of each sensor module **22** may be galvanic electrodes **23** which are used to measure voltages related to certain components of electric field response to induced electromagnetic fields in the subsurface. In the present example, laterally extending sensing arms **22B** may be disposed from one or both the sides of each sensor module **22**. Such sensing arms **22B** will be explained in more detail with reference to FIG. **3**.

Signals acquired by various sensing devices associated with each module **22** and the cable **24** may be transmitted to the acquisition control unit **26** for telemetry to the system control unit **27C** in the buoy **27**. Such transmission may be made by including in the cable **24** one or more electrical and/or optical conductors (not shown) to carry electrical power and/or data signals. The acquisition control unit **26** may be disposed on the water bottom **13** as shown on disposed in the buoy **27** at the discretion of the system designer. The acquisition control unit **26** may include any form of data storage device, for example a terabyte-sized hard drive or solid state memory. The manner of data storage and transfer with respect to the acquisition control unit **26** may be according to well known art and are not intended to limit the scope of this invention.

One example of the sensor module **22** is shown in cut away view in FIG. **2**. The sensor module **22** may include a sealed, pressure resistant housing **28** affixed to the cable **24** at a selected position along the cable **24**. The housing **28** may be affixed to the cable **24** by splicing within the cable, by molding the housing **28** thereon or by using water tight, pressure resistant electrical and mechanical connectors on each of the cable **24** and housing **28**, such as a connector shown in U.S. Pat. No. 7,113,448 issued to Scott.

The interior of the housing **28** may define a pressure sealed compartment that may include some or all of the components described below. Sensing elements in the module **22** may include a three-axis magnetometer M that includes horizontal Mx, My and vertical Mz component magnetic field sensors. A three component seismic particle motion sensor G may also be disposed in the housing **28**. The seismic particle motion sensor G may include three mutually orthogonal motion sensors Gx, Gy, Gz such as geophones or accelerometers. The seismic sensor G detects particle motion components of a seismic wavefield induced by the seismic source (**14** in FIG. **1**). The sensor module **22** may also include a hydrophone **30** in pressure communication with the water (**11** in FIG. **1**) for detecting the pressure component of the seismic wavefield induced by the seismic source (**14** in FIG. **1**). The sensor module **22** may also include a gravity sensor GR within the housing **28**. The sensor module **22** may include voltage measuring circuits **39**, **40** to measure voltages impressed across pairs of galvanic electrodes (**23** in FIG. **1**) disposed on opposed sides of the module **22** along the cable **24**. In the present example, the electrode pairs may also include an electrode disposed along or at the end of each of the vertical sensing arm **22A** (the electrode shown at **23B**) and the spike **22C** (the electrode shown at **23A**). The vertical sensing arm **22A** may be coupled to the housing **28** in a manner as will be explained below with reference to FIG. **3**.

Signals generated by each of the sensing devices described above may enter a multiplexer **32**. Output of the multiplexer **32** may be conducted through a preamplifier **34**. The preamplifier may be coupled to the input of an analog to digital converter (ADC) **36**, which converts the analog voltages from the preamplifier **34** into digital words for storing and processing by a central processor **38**, which may be any microprocessor based controller and associated data buffering and/or storage device known in the art. Data represented by digital words may be formatted for signal telemetry along the cable **24** to the recording node (**26** in FIG. **1**) for later retrieval and processing, such as by or in the recording system (**12** in FIG. **1**). The sensor module **22** may also include one or more high frequency magnetometers M_H in signal communication with the multiplexer **32** and the components coupled to the output thereof.

The example sensor module **22** of FIG. **2** is shown in plan view in FIG. **3**. The horizontal sensing arms **42** (also shown as **22B** in FIG. **1**) may be coupled to the housing **28** using pressure-sealed electrical connectors **42A** that mate with corresponding connectors **41** in the housing **28**. The sensing arms **42** may alternatively be permanently attached to the sensor module **22** and foldable as well. The connectors **42A**, **41** include one or more insulated electrical contacts to communicate power and/or signals to various sensing elements in the horizontal sensor arms **42**. The sensing elements may include a plurality of spaced apart single or multi-axis magnetic field sensors **44**, and a galvanic electrode **46**. The vertical sensing arm **22A** may be similarly configured to have an electrode and multiple magnetic field sensors. The spike (**22C** in FIG. **2**) may be similarly instrumented with such sensing devices. The various sensor arms and the spike may be configured such that they may be lockingly and quickly installed into the housing as shown as the cable **24** is extended into the water (**11** in FIG. **1**) from the survey vessel (**10** in FIG. **1**).

Configured as explained with reference to FIGS. **2** and **3**, the sensor module **22** includes sensing devices to measure electric field in three dimensions, magnetic field in three dimensions and magnetic field gradient in at least two directions. Magnetic field gradient may be measured along the direction of the cable **24** (the third direction) by measuring

difference between magnetic field measurements made in adjacent modules 22, or between successively more spaced apart modules 22 along the cable 24. By measuring spatial components of magnetic field gradient, it may be possible to determine components of electric field in a direction transverse to the magnetic field gradient measurements. Ampere's law states that the spatial gradient of the magnetic field is equivalent to the derivative in time of the dielectric displacement field plus the free current density, as shown in equation (1) below:

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{1}$$

Because the dielectric displacement field is coupled by the electrical permittivity ϵ to the electric field E, the change with respect to time of the y-component of the electric field, Ey, field can be calculated if the spatial changes of the z-component of the magnetic field, Hz, with respect to position along the cable, x, and cable direction spatial change in magnetic field, Hx, with respect to vertical, z, are known. Thus, by measuring magnetic field gradient along selected directions using a cable system as shown herein, it is possible to determine a transverse component of the electric field.

One example of deployment of the ocean bottom cable systems 20 is shown in FIG. 4. The systems 20 are arranged such that the sensor cables 24 form a selected pattern on the water bottom, such as parallel lines. The selected pattern of parallel lines shown in FIG. 4 is not intended to limit the scope of the invention. Each sensor cable 24 includes an associated acquisition control unit 26 and system control unit (FIG. 6) disposed in an associated buoy 27.

The systems shown in FIG. 1 and FIG. 4 include horizontal and/or vertical electric dipole antennas for inducing an electric field in the Earth's subsurface, wherein electric and magnetic responses of the Earth are measured. It should be understood that the invention is equally applicable where time varying magnetic fields are induced in the subsurface. Referring to FIG. 5, the survey vessel 10 may tow loop antennas 21A 21B at the end of a cable 21. The recording system 12 may pass electrical current through horizontal loop antenna 21A to induce a vertical magnetic field m_A in the subsurface, and through vertical loop antenna 21B to induce a horizontal magnetic field m_B in the subsurface. Measurements made by the various sensing devices in the system (see FIGS. 2 through 4) may be made in response to such magnetic fields. Magnetic fields may be induced in addition to as well as an alternative to electric fields for any particular electromagnetic survey.

The sensor cable systems (20 in FIG. 4) may also be used with magnetotelluric measurement methods and is not limited to use with controlled source electromagnetic measurement methods. In one example of a method according to the invention, a plurality of transient controlled source electromagnetic measurements (t-CSEM), including one or more of electric field and magnetic field are made along one or more selected directions using a cable as shown in FIG. 4. Preferably, such measurements of electric and magnetic field are made along three orthogonal directions. For such plurality of measurements, preferably the source antenna (FIG. 1) is in a substantially fixed position. The electric and magnetic field measurements are summed or stacked. The result of the stacking is a high quality t-CSEM signal response. The stacked t-CESM signal response may then be subtracted from the signals recorded over a substantial period of time. The result

will be the magnetotelluric (MT) response measured by all the various sensing elements on the cable. The MT response may be processed according to techniques known in the art. See, for example, U.S. Pat. No. 6,950,747 issued to Byerly.

When MT response is determined as explained above, and processed according to one or more techniques known in the art, it then becomes possible to perform a joint inversion of the t-CSEM and MT responses. If frequency domain electromagnetic response is measured, such response may also be jointly inverted. Joint inversion is described, for example, in U.S. Pat. No. 5,870,690 issued to Frenkel et al. A particular benefit that may be provided by making both CSEM and MT measurements from the same sets of sensing devices, and processed through the same electronic circuitry, for the purposes of join inversion is that the degree of scaling or other response matching that would be required if the MT and CSEM responses were measured using separate systems, is substantially reduced.

Using a sensor cable system 20 as shown herein, it is also possible to perform electric field mapping in order to correct the MT response measurements for static shifts. See, for example, Sternberg, B. K., Washburne, J. C. and Pellerin, L., 1988, *Correction for the static shift in magnetotellurics using transient electromagnetic soundings*, Geophysics, Volume 53, Issue 11, pp. 1459-1468. Prior to having a cable as explained herein, the technique disclosed in the foregoing publication was only applicable for land-based surveys. Using a cable and method according to the invention, however, it is possible to correct the MT response for statics using the t-CSEM response measured by the same sensing elements in the sensor cable disposed on the sea floor. See also, Torres-Verdin, C, 1991, *Continuous profiling of magnetotelluric fields*, Ph.D. Thesis, University of California, and Torres-Verdin, C. and Bostick Jr, F. X., 1992, *Principles of spatial surface electric field filtering in magnetotellurics: Electromagnetic array profiling (EMAP)*, Geophysics, Volume 57, Issue 4, pp. 603-622. As explained in one or more of the foregoing publications, the MT response may be subject to vertical shifting in the log domain. Such shifting is caused by relatively conductive or resistive "patches" of formation close to the water bottom. The t-CSEM response is substantially unaffected by such patches, however, and may be used to calibrate the MT response for the effects of such patches.

One example of a system control unit 27C is shown schematically in FIG. 6. By including the system control unit in a flotation device such as the buoy (27 in FIG. 1) or other device that provides above-water support for a communications antenna, it is possible for the system control unit 27C to communicate wirelessly with the recording system (12 in FIG. 1) and with the system control unit associated with each of the other sensor cable systems 20 in a multiple cable system deployment such as shown in FIG. 4. The purpose for such communication will be further explained below.

The system control unit 27C may include a central processor unit ("CPU") 50 which may be a microprocessor based controller of any type known in the art for autonomous or semi-autonomous control of a data acquisition and recording system. The CPU 50 may be in signal communication with a data storage device 54 such as a hard drive. The data storage device 54 may accept data signals through the CPU 50 from the sensor cable (24 in FIG. 1) associated with the particular cable system (20 in FIG. 1) either in unprocessed form, and/or, preferably, processed by the CPU 50 as explained below. A global positioning system ("GPS") receiver may be associated with a data and command signal transceiver 52 for detecting time and position signals from a GPS satellite (not shown). The GPS/data transceiver 52 may be in signal com-

munication with the CPU **50** and may include one or more forms of antenna **27D** for detecting GPS or similar positioning signals, and for communicating signals to and from the other system control units deployed (FIG. **4**) to conduct the EM survey. Time signals detected by the GPS/data transceiver **52** from the GPS satellite(s) may be used to time-stamp the data communicated from the sensor cable (**24** in FIG. **1**). A signal transceiver **56** may be in signal communication with the acquisition control unit (**26** in FIG. **1**) and communicates signals detected by the various sensors in the sensor cable (**24** in FIG. **1**) from the acquisition control unit **26** to the CPU **50** for processing and storage. Alternatively, the signals from the various sensing elements in the sensor cable (**24** in FIG. **1**) that are ultimately placed in telemetry for communication to a storage device (such as storage device **54**) may be communicated directly to the transceiver **56** from the CPUs (**38** in FIG. **2**) in the various sensor modules (**22** in FIG. **1**).

In one example, the CPU **50** may be programmed to perform one or more of the following data processing procedures. EM signals from the various sensors in the sensor cable (**24** in FIG. **1**) may be conducted to the CPU **50**, and then to the GPS/data transceiver **52** where they are transmitted to a particular one of the system control units **27C** that is configured as a "master" system control unit. The particular one of the system control units **27C** in any arrangement such as shown in FIG. **4** that may be configured to be the master system control unit is a matter of discretion for the system operator and is not intended to limit the scope of the invention. The configured master system control unit may receive data signals corresponding to the same actuations of the EM source (FIG. **1**) transmitted from each of the other system control units (transmitted from each of the respectively associated sensor cables). The master system control unit is also configured to receive signals from its own associated sensor cable (**24** in FIG. **1**). The signals transmitted from each system control unit to the master system control unit, as well as the signals transmitted from the sensor cable associated with the configured master system control unit, may be summed or stacked by the CPU **50** in the configured master system control unit. Such stacked signals may be stored in the data storage device **54** of the configured master system control unit for further processing and/or communication to the recording system (**12** in FIG. **1**). Such signal transmission from the "slave" system control units (all those system control units not configured as the master system control unit) to the master system control unit, and subsequent stacking, may be performed for any or all actuations of the electromagnetic source (FIG. **1**).

The particular system control unit configured to perform as the master system control unit may be changed during operation of a multiple cable system (e.g., deployed as shown in FIG. **4**) by transmission of suitable reconfiguration programming signals to the respective system control units by the recording system (**12** in FIG. **1**).

Other types of recorded signal pre-processing may be applied to the signals from each of the sensor cables. Some of these pre-processing techniques may use the signals stored in the slave control units to derive measures of coherent or non-coherent noise and then use processing techniques that reduce the noise in the data from the attached sensor cable. One example is to use signals from one of the control units located associated with the sensor cable that is deployed in a single position for the longest period of time to yield a better average or stacked signal. The average signal from such sensor cable is transmitted to the master control unit and used to derive a time based noise estimate which is then removed from each of the recorded signals from each sensor cable

before the signals are averaged (stacked). See, for example, Stephan, A., Strack, K.-M. 1991, *A simple approach to improve the signal to noise ratio for TEM' data using multiple receivers*, Geophysics 56, 863-869.). Other methods can be used to estimate coherent noise from the signal recordings and thus remove such noise from the recordings.

The stacked signals may be further evaluated to determine noise with respect to time for the entire survey system (FIG. **4**). For example, a total amount of noise in each stacked signal (calculated as explained above) may be calculated for each actuation of the EM source (FIG. **1**), and the noise amounts tracked over time. In the event the total amount of noise in any stacked signal exceeds a selected threshold, a warning signal may be generated in the master system control unit and such warning signal may be transmitted to the recording system to alert the system operator.

The stacked signals and a representative statistical measure of the stacked signals, such as the standard deviation, may also be communicated to the recording system (**12** in FIG. **1**) using the GPS/data transceiver **52**. Based on the stacked signals and their standard deviation, it may be determined whether to change certain signal acquisition parameters, for example, the direction along which the source is towed (tow line), the amount of electric current used to energize the source (FIG. **1**), and/or the waveform of the electric current used to energize the source.

The CPU **50** in the configured master system control unit may also be programmed to cross correlate signals from selected sensors in each of the sensor cables (**24** in FIG. **1**) to further reject noise in the acquired EM signals. Using the stacked trace and/or cross correlated traces it may be possible to optimize the arrangement of cable systems (**20** in FIG. **1** and see FIG. **4**) so that the highest possible quality data are acquired. Such optimization may require moving one or more of the cable systems during a survey depending on the stacked trace and cross correlated traces.

In one example, the designated master system control unit may be configured by transmission of appropriate command and programming signals to each system control unit **27C**.

On example of signal processing by communication of recorded and/or processed signals between control units is shown in a flow chart in FIG. **7**. Signals (data) representing measurements made by the sensors in each sensor cable are recorded in the master control unit at **70**, and in each of the slave control units, at **72** and **74**. Quality control criteria, such as stacked signals and statistical measures thereof (e.g., standard deviation) are shown for the slave units, respectively, at **76** and **78**. At **80**, signal acquisition parameters may be adjusted in response to the quality control criteria measured at each of the slave units. Such quality control criteria may be communicated by wireless telemetry to the master unit at **84**. At **82**, the quality control criteria from the slave units may be combined with quality control criteria from the master control unit to derive global quality control criteria.

In FIG. **8**, signals recorded by the master control unit, at **86**, may be communicated to the recording system (**12** in FIG. **1**). The recording system (**12** in FIG. **1**) may generate a command signal at **88** to reconfigure the quality control processing that takes place in the master control unit. The master control unit may then broadcast a command to the slave units at **90** to correspondingly reconfigure the quality control processing taking place therein. Additionally, or alternatively, the acquisition parameters may be changed in any or all of the master control unit and the slave units at **92** be broadcast command from the recording system (**12** in FIG. **1**). The changed survey

parameters may then be used to acquire signals, and such signals are recorded and transmitted to the master control unit for processing at **94**.

A sensor cable and EM measurement system and methods according to the various aspects of the invention may provide more electromagnetic measurement components with data quality checking capabilities, and may be easier to deploy than other EM cable systems and separate EM/seismic/gravity/magnetic cable sensing systems.

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 sensor cable system for measuring electromagnetic response of the Earth's subsurface, comprising:
    a sensor cable deployable on a bottom of a body of water, the sensor cable having a plurality of electromagnetic sensing elements thereon at spaced apart locations; and
    a system control unit in signal communication with the sensing elements, the system control unit including a transceiver for communicating signals to and from a corresponding sensor cable system, the system control unit including a global positioning system signal receiver, the system control unit including a processor configurable to receive signals detected by sensing elements in the corresponding sensor cable system, the processor configurable to compute at least one of preprocessed and stacked signals from the sensing elements in the sensor cable and from the sensing elements in the corresponding cable system, the processor configurable to calculate a statistical measure of the stacked signals, wherein the system control unit is disposed in a flotation device.

2. The system of claim **1** wherein the processor is configurable by detecting command signals from a recording unit disposed on a survey vessel.

3. The system of claim **1** wherein the sensor cable comprises:
    a plurality of sensor modules disposed at spaced apart locations along a cable, each module including at least one pair of electrodes associated therewith, the electrodes arranged to measure electric field substantially in a direction along the direction of the cable.

4. The system of claim **3** wherein each module further comprises at least one magnetic field sensor.

5. The system of claim **4** wherein the at least one magnetic field sensor is a triaxial magnetic field sensor.

6. The system of claim **3** wherein each module further comprises at least one laterally extending sensor arm affixed to the module, the at least one sensor arm including at least one electrode thereon.

7. The system of claim **6** wherein the at least one sensor arm comprises at least one magnetic field sensor.

8. The system of claim **6** wherein the at least one sensor arm comprises a plurality of spaced apart magnetic field sensors.

9. The system of claim **3** wherein each module further comprises a vertically extending sensor arm affixed to the module, the at least one sensor arm including at least one electrode thereon.

10. The system of claim **9** wherein the vertically extending sensor arm comprises at least one magnetic field sensor.

11. The system of claim **10** wherein the vertically extending sensor arm comprises a plurality of spaced apart magnetic field sensors.

12. The system of claim **3** wherein each module comprises at least one seismic sensor.

13. The system of claim **3** wherein the seismic sensor comprises a triaxial geophone.

14. The system of claim **3** wherein each module comprises electrical circuitry for digitizing and communicating signals detected by the at least one pair of electrodes and the at least one magnetic field sensor.

15. The system of claim **3** wherein each module comprises at least one magnetic field sensor.

16. The system of claim **3** wherein each module comprises a gravity sensor.

17. The system of claim **1** wherein the processor is configurable to transmit signals detected by the sensing elements in the cable to the corresponding system control unit, and wherein the corresponding system control unit is configurable to compute stacked signals from the sensing elements in the sensor cable and from the sensing elements in the corresponding cable system, the corresponding system control unit configurable to calculate a statistical measure of the stacked signals.

18. A method for acquiring a marine electromagnetic survey, comprising:
    actuating an electromagnetic source deployed in a body of water at selected times;
    detecting signals related to at least one of an electric field and a magnetic field at spaced apart locations along a first cable disposed proximate the bottom of the body of water;
    detecting signals related to at least one of an electric field and a magnetic field at spaced apart locations along at least a second cable disposed proximate the bottom of the body of water;
    conducting at least one of the detected signals and digital representations thereof from at least one of the first cable and the at least a second cable to a respective signal processing device for each of the first and at least a second cables disposed proximate the water surface;
    communicating the detected signals from at least one of the signal processing devices to another one of the signal processing devices; and
    processing the communicated signals and the conducted signals in the other one of the signal processing devices, the processing comprising generating stacked signals and calculating in the other one of the signal processing devices at least one statistical measure of the stacked signals.

19. The method of claim **18** further comprising receiving signals from a global positioning system satellite at the other one of the signal processing devices and time stamping the processed signals.

20. The method of claim **18** wherein processing further comprises determining a noise component of the stacked signals.

21. The method of claim **20** further comprising determining a change in the noise component between each of a plurality of actuations of the electromagnetic source.

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