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ABSTRACT

Marine seismic acquisition methods and systems are described. One system comprises a first vessel having a seismic streamer array disposed thereon, and one or more controllers programmed to cause the first vessel to travel along a first coil path during a multivessel coil shoot.

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MULTI-VESSEL COIL SHOOTING ACQUISITION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is divided from and claims the benefit of the filing and priority dates of application no. 2010249891 filed 17 May 2010, the content of which as filed is incorporated herein by reference in its entirety, which in turn is based on and claims the benefit of the priority established by United States Patent Application No. 61/180,154 filed 21 May 2009, United States Patent Application No. 61/218,346 filed 18 June 2009, and United States Provisional Patent Application Serial No. 12/650,268 filed 30 December 2009. These applications, each entitled “Multi-Vessel Coil Shooting Acquisition”, are hereby incorporated by reference for all purposes as if set forth *verbatim* herein.

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

[0002] The present invention relates to the field of marine survey data acquisition methods. More specifically, the invention relates to methods for acquiring high quality long-offset, full-azimuth survey data.

2. DESCRIPTION OF THE RELATED ART

[0003] The performance of a marine seismic acquisition survey typically involves one or more vessels towing at least one seismic streamer through a body of water believed to overlie one or more hydrocarbon-bearing formations. WesternGeco L.L.C. currently conducts high-resolution Q-Marine™ surveys, in some instances covering many square kilometres. In many areas of the world hydrocarbon reservoirs located in structurally complex areas may not be adequately illuminated even with advanced towed marine streamer acquisition methods.

[0004] For example, the shallow, structurally complex St. Joseph reservoir off Malaysia produces oil and gas in an area that poses many surveying and imaging challenges. Strong currents, numerous obstructions and infrastructure, combined with difficult near-surface conditions, may hinder conventional survey attempts to image faults, reservoir sands, salt domes, and other geologic features.

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[0005] A survey vessel known as a Q-Technology™ vessel may conduct seismic surveys towing multiple, 1000–10,0000-metre cables with a separation of 25–50 metres, using the WesternGeco proprietary calibrated Q-Marine™ source. “Q” is the WesternGeco proprietary suite of advanced seismic technologies for enhanced reservoir location, description, and management. For additional information on Q-Marine™, a fully calibrated, point-receiver marine seismic acquisition and processing system, as well as Q-Land™ and Q-Seabed™, *see* http://www.westerngeco.com/q-technology.

[0006] To achieve high density surveys in regions having a combination of imaging and logistical challenges, a high trace density and closely spaced streamers may be used. However, this presents the potential of entangling and damaging streamer cables and associated equipment, unless streamer steering devices are closely monitored and controlled. Wide-azimuth towed streamer survey data is typically acquired using multiple vessels, for example: one streamer vessel and two source vessels; two streamer vessels and two source vessels; or one streamer vessel and three source vessels. Many possible marine seismic spreads comprising streamers, streamer vessels, and source vessels may be envisioned for obtaining wide- or rich-azimuth survey data.

[0007] U.S. Application No. 11/335,365, filed 19 January 2006, discusses some of these. This document discusses shooting and acquiring marine seismic data during turns of linear marine surveys and during curvilinear paths. While an advance in the art, the art continues to seek improvements to marine seismic data acquisition techniques.

[0008] Cole, R.A. et al, “A circular seismic acquisition technique for marine three dimensional surveys”, Offshore Technology Conference, OTC 4864, 6 to 9 May 1985, Houston, Texas, described a concentric circle shooting scheme for obtaining three dimensional marine survey data around a sub-sea salt dome. While perhaps useful when the location of the feature is known, this technique would not be efficient or productive for finding new oil and gas deposits, or for monitoring changes in same if such information is desired.

[0009] A great leap in acquisition technology was described in U.S. Application No. 12/121,324, filed on 15 May 2008. This reference describes methods for efficiently acquiring wide-azimuth towed streamer seismic data, which is also known as the “coil shooting” technique.

[0010] While the Q suite of advanced technologies for marine seismic data acquisition and processing may provide detailed images desired for many reservoir management

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decisions, including the ability to acquire wide- and/or rich azimuth data, the ability to acquire higher quality marine seismic data with less cost, or to increase the fold while also increasing the diversity of azimuth and offset, are constant goals of the marine seismic industry and would be viewed as advances in the art.

SUMMARY OF THE INVENTION

[0011] In a first aspect of the present invention, there is provided a marine seismic acquisition system, comprising:

a streamer/source vessel having a source and a streamer array disposed behind the source;

a first source vessel having at least one source attached thereto, the first source vessel being configured to trail behind the streamer/source vessel, and both the streamer/source vessel and the first source vessel being configured to travel along a first curved path;

a second source vessel having at least one source attached thereto, the second source vessel being configured to travel along a second curved path inside a perimeter of the first curved path; and

a third source vessel having at least one source attached thereto, the third source vessel being configured to travel along a third curved path inside a perimeter of the second curved path.

[0012] The first curved path, the second curved path and the third curved path may form concentric circles during a revolution.

[0013] The radii of the first curved path, the second curved path and the third curved path may be different.

[0014] In a second aspect of the present invention, there is provided a method, comprising:

towing a source and a streamer array with a streamer/source vessel along a first curved path, the streamer array being disposed behind the source;

towing a first source with a first source vessel along the first curved path, wherein the first source vessel is trailing behind the streamer/source vessel;

towing a second source with a second source vessel along a second curved path inside a perimeter of the first curved path;

towing a third source with a third source vessel along a third curved path inside a perimeter of the second curved path; and

conducting a multivessel coil shoot using the streamer/source vessel, the first source vessel, the second source vessel and the third source vessel.

[0015] The first curved path, the second curved path and the third curved path may form concentric circles during a revolution.

[0016] The radii of the first curved path, the second curved path and the third curved path may be different.

[0017] The above presents a simplified summary of the invention in order to provide a basic understanding of some aspects of the invention. This summary is not an exhaustive overview of the invention. It is not intended to identify key or critical elements of the invention or to delineate the scope of the invention. Its sole purpose is to present some concepts in a simplified form as a prelude to the more detailed description that is discussed later.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The invention may be understood by reference to the following description taken in conjunction with the accompanying drawings, in which like reference numerals identify like elements, and in which:

FIG. 1 conceptually illustrates in a "bird's eye" view one particular embodiment of a multi-vessel towed array, marine seismic survey using a coil shoot implemented in accordance with one aspect of the present invention;

FIG. 2A – **FIG. 2B** depict selected spread elements of the spread first shown in **FIG. 1** of a streamer array first shown in **FIG. 1**, including a streamer survey vessel, a plurality of streamers, seismic sensors, and a seismic source in a plan, overhead view;

FIG. **3A** – **FIG. 3B** depict a streamer only survey vessel and a source only survey vessel, respectively, such as may be used in some aspects of various embodiments;

FIG. 4 illustrates selected portions of the survey first shown in **FIG. 1**;

FIG. 5 is the offset-azimuth distribution for data acquired in the embodiment of **FIG. 1**;

FIG. 6 conceptually illustrates in a "bird's eye" view a second embodiment of a multi-vessel towed array, marine seismic survey using a coil shoot implemented in accordance with one aspect of the present invention;

FIG. 7 is the offset-azimuth distribution for data acquired in the embodiment of **FIG. 6**;

FIG. 8 conceptually illustrates in a "bird's eye" view a second embodiment of a multi-vessel towed array, marine seismic survey using a coil shoot implemented in accordance with one aspect of the present invention;

FIG. 9 is the offset-azimuth distribution for data acquired in the embodiment of **FIG. 8**;

FIG. 10 is an exemplary from a simulation of the embodiment of **FIG. 1**;

FIG. **11A**-**FIG. 11C** illustrate design considerations for use in planning a multi-vessel coil shoot;

FIG. 12 illustrates a controlled sources electromagnetic survey, according to one particular embodiment; and

FIG. 13A – **FIG. 13B** compare the illumination of a steep-dip subsalt reservoir with a two streamer vessel, four source vessel (six sources) wide azimuth parallel geometry acquisition and with a two streamer vessel, four source vessel (six sources) coil shooting acquisition.

While the invention is susceptible to various modifications and alternative forms, the drawings illustrate specific embodiments herein described in detail by way of example. It should be understood, however, that the description herein of specific embodiments is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

[0019] One or more specific embodiments of the present invention will be described below. It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein, but include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business related constraints, which may vary from one implementation to another. Moreover, it

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should be appreciated that such a development effort might be complex and time consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those skilled in the art having the benefit of this disclosure.

[0020] In the following description, numerous details are set forth to provide an understanding of the present invention. However, it will be understood by those skilled in the art that the present invention may be practiced without these details and that numerous variations or modifications from the described embodiments may be possible. For example, in the discussion herein, aspects of the invention are developed within the general context of acquiring high quality marine seismic data in a more cost efficient manner, which may employ computer-executable instructions, such as program modules, being executed by one or more conventional computers. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types.

[0021] Moreover, those skilled in the art will appreciate that the invention may be practiced in whole or in part with other computer system configurations, including hand-held devices, personal digital assistants, multiprocessor systems, microprocessor-based or programmable electronics, network PCs, minicomputers, mainframe computers, and the like. In a distributed computer environment, program modules may be located in both local and remote memory storage devices. It is noted, however, that modification to the systems and methods described herein may well be made without deviating from the scope of the present invention. Moreover, those skilled in the art will appreciate, from the discussion to follow, that the principles of the invention may well be applied to other aspects of seismic data acquisition. Thus, the systems and method described below are but illustrative implementations of a broader inventive concept.

[0022] The present invention relates to methods for efficiently acquiring marine seismic data, wherein efficiency may be defined as more cost effective in that less seismic resources are used. It also provides improved seismic imaging using minimal marine seismic equipment (only one vessel is required, although an additional source vessel may be used, as explained more fully herein). Furthermore, a richer azimuth survey can be acquired than what is acquired with systems and methods employed to date that are based on parallel acquisition geometry concept.

[0023] The systems and methods of the invention may be particularly adept at acquiring wide- and/or rich azimuth marine seismic data, and acquiring such data while traversing generally curved advancing paths, which may be characterized as coil patterns or paths. When viewed in plan view, certain paths useful in the invention may resemble overlapping circles, as in a flattened coil. The time to shoot a survey may be longer with the inventive methods compared to traditional linear surveys. If the same survey can be acquired with a four vessel configuration sailing generally parallel the total time required may be shorter; however the total cost is higher for multiple vessel marine seismic data acquisition, and multiple vessels are not always available.

[0024] A distinct feature of the inventive methods is that the azimuth is changing from shot to shot. This excludes redundancy in the azimuths acquired, whereas conventional marine acquisition is based on parallel acquisition geometry and this implies azimuth redundancy. A wider azimuth range can be acquired with parallel geometry by adding extra vessels or by repeating the survey with different cross-line offsets, however both of these options add to the cost of the seismic survey.

[0025] Other possible benefits of methods of the present invention include:

- a line change is required only for data management reasons, otherwise the survey may be acquired continuously;
- high efficiency data acquisition: the line change is in the order of few minutes;
- the azimuths are different from shot to shot;
- rich azimuth-and offset distribution data is collected;
- very high fold is acquired;
- coil shooting methods of the invention are less sensitive to currents;
- no infill or a minimum amount of infill is required;
- the coil shooting methods are less sensitive to seismic interferences;
- the effect of perturbations due to the obstructions may be less than for multiple-vessel, linear wide-azimuth acquisition; and
- the methods offer improved reservoir illumination (including, but not limited to, sub-salt reservoir illumination) and more effective coherent noise attenuation due to the high variability of azimuths.

Note that not all embodiments will necessarily exhibit all of the benefits discussed herein. To the extent that various embodiment manifest some of the benefits, not all of them will exhibit them to the same degree.

[0026] A rich- or wide-azimuth towed streamer survey may be acquired in accordance with the present invention using a single streamer vessel comprising multiple streamers and a minimum of one source array. In certain embodiments the methods include positioning of streamers and/or sources employing positioning apparatus or systems (for example satellite-based systems), one or more streamer steering devices, one or more source array steering devices, and/or one or more noise attenuation apparatus or systems. One system, known as Q-Marine™ includes these features and may be useful in methods of the invention.

[0027] The coil shooting is generally described in more detail in U.S. Application No. 12/121,324, filed on 15 May 2008, which is incorporated herein by reference in its entirety. Note, however, that the embodiments disclosed therein are single vessel techniques. Single vessel coil shooting is a very economical and efficient way of acquiring full-azimuth survey data. But the offset among the data may be limited by the lengths of the streamers.

[0028] For acquisition of long offset data, improved efficiency and better distribution of shots, multi-vessel methods as described below may be used. Multi-vessel configuration can be used to acquire coil shooting data. Examples of multi-vessel configuration that can be used for coil shooting are:

- 2 receiver vessels and two source vessels or 2 × 4, depicted in **FIG. 1**;
- 1 receiver vessel and three source vessels or 1 × 4, shown in **FIG. 6**; and
- two receiver vessels (dual coil) or 2 × 2, depicted in **FIG. 8**.

Each of these embodiments will be discussed further below.

[0029] Turning now to the drawings, **FIG. 1** conceptually illustrates one particular embodiment of a multi-vessel, towed array, marine seismic survey spread 100 implemented in accordance with one aspect of the present invention. The spread 100 comprises four survey vessels 111–114, two streamer arrays 121-122, and a plurality of sources 131-134. The vessels 111, 114 are “receiver vessels” in that they each tow a respective one of the streamer arrays 121, 122, although they also tow a respective source 131, 134. Because they also tow the sources 131, 134, the receiver vessels 111, 114 are sometimes called “streamer/source” vessels or “receiver/source” vessels. In some embodiments, the receiver vessels may omit the sources 131, 134. In such embodiments, the receiver vessels are sometimes called “streamer only” vessels because they only tow streamers. The vessels 112-113 are “source vessels” in that they each tow a respective source or source array 131 - 135 but no streamer arrays, that is they two the seismic sources 132-133 to the exclusion of any streamer arrays. The vessels 112-113 are therefore sometimes called “source only” vessels.

[0030] Each streamer array 121, 122 comprises a plurality of streamers 140 (only one indicated). The present invention admits wide variation in the implementation of the streamers 140. As will be discussed further below, the streamers 140 are "multicomponent" streamers as will be discussed further below. Examples of suitable construction techniques may be found in U.S. Patent No. 6,477,711, U.S. Patent No. 6,671,223, U.S. Patent No. 6,684,160, U.S. Patent No. 6,932,017, U.S. Patent No. 7,080,607, U.S. Patent No. 7,293,520, and U.S. Application No. 11/114,773, incorporated by reference below. Any of these alternative multicomponent streamers may be used in conjunction with the presently disclosed technique. However, the invention is not limited to use with multicomponent streamers and may be used with conventional, pressure-only streamers used in 2D surveys.

[0031] To further an understanding of the present invention, one particular embodiment of the streamer arrays will now be disclosed with respect to **FIG. 2A** – **FIG. 2B**. **FIG. 2A** depicts one particular embodiment of the survey vessel 111, streamer array 121, and seismic source 131 in a plan, overhead view. On board the survey vessel 111 is a computing apparatus 200. The computing apparatus 200 controls the streamer array 121 and the source 131 in a manner well known and understood in the art. The towed array 121 comprises ten streamers 140 (only one indicated). The number of streamers 140 in the towed array 121 is not material to the practice of the invention. These aspects of the apparatus may be implemented in accordance with conventional practice.

[0032] At the front of each streamer 140 is a deflector 206 (only one indicated) and at the rear of every streamer 140 is a tail buoy 209 (only one indicated) used to help control the shape and position of the streamer 140. Located between the deflector 206 and the tail buoy 209 are a plurality of seismic cable positioning devices known as "birds" 212. In this particular embodiment, the birds 212 are used to control the depth at which the streamers 140 are towed, typically a few metres.

[0033] The streamers 140 also include a plurality of instrumented sondes 214 (only one indicated) distributed along their length. The instrumented sondes 214 house, in the illustrated embodiment, an acoustic sensor 220 (*e.g.*, a hydrophone) such as is known to the art, and a particle motion sensor 223, both conceptually shown in **FIG. 2B**. The particle motion sensors 223 measure not only the magnitude of passing wavefronts, but also their direction. The sensing elements of the particle motions sensors may be, for example, a velocity meter or an accelerometer.

[0034] The sensors of the instrumented sondes 214 then transmit data representative of the detected quantity over the electrical leads of the streamer 140 to the computing apparatus 200. The streamer 140 in this particular embodiment provides a number of lines (*i.e.*, a power lead 226, a command and control line 229, and a data line 232) over which signals may be transmitted. Furthermore, the streamer 140 will also typically include other structures, such as strengthening members (not shown), that are omitted for the sake of clarity.

[0035] The inline separation of the streamer components and the crossline separation of the streamers will be determined in accordance with techniques well known in the art in view of implementation specific requirements for the survey to be conducted.

[0036] Returning to **FIG. 1**, the sources 131–134 typically will be implemented in arrays of individual sources. The sources 131–134 may be implemented using any suitable technology known to the art, such as impulse sources like explosives, air guns, and vibratory sources. One suitable source is disclosed in U.S. Patent No. 4,657,482, incorporated by reference below. The embodiment illustrated in **FIG. 1** simultaneously shoots several of the sources 131–134. Accordingly, care should be taken so that the sources 131–137 can be separated during subsequent analysis. There are a variety of techniques known to the art for source separation and any such suitable technique may be employed. Source separation may be achieved by a source encoding technique in which one source is coherent and another source is incoherent in a certain collection domain, such as common depth point, common receiver or common offset. Another way source separation technique is disclosed in C. Beasley & R. E. Chambers, 1998, "A New Look at Simultaneous Sources", 60^{th} Conference and Exhibition, EAGE, Extended Abstracts, 02-38.

[0037] As was noted above, some receiver vessels (*e.g.*, "streamer only" vessels, or "receiver only" vessels) may omit the sources 131, 134 and the source vessels 112-113 tow only sources. **FIG. 3A** illustrates a receiver only vessel 300 and **FIG. 3B** illustrates a source only vessel 310 towing a seismic source 312.

[0038] The relative positions of the vessels 111–114 described above, as well as the shape and depth of the streamers 140, may be maintained while traversing the respective sail lines 171–174 using control techniques known to the art. Any suitable technique known to the art may be used. Suitable techniques includes those disclosed in U.S. Patent No. 6,671,223, U.S. Patent No. 6,932,017, U.S. Patent No. 7,080,607, U.S. Patent No. 7,293,520, and U.S. Application No. 11/114,773, incorporated by reference below.

[0039] The illustrated embodiment uses WesternGeco Q-Marine technology that provides features such as streamer steering, single-sensor recording, large steerable calibrated source arrays, and improved shot repeatability, as well as benefits such as better noise sampling and attenuation, and the capability to record during vessel turns, all contribute to the improved imaging. More particularly, each of the vessels 111–114 is a Q™ vessel owned and operated by WesternGeco. Each vessel 111-114 is provided with a GPS receiver coupled to an integrated computer-based seismic navigation (TRINAV™), source controller (TRISOR™), and recording (TRIACQ™) system (collectively, TRILOGY™), none of which are separately shown. The sources 131–134 are typically TRISOR™-controlled multiple air gun sources.

[0040] The above is but one exemplary embodiment. The spread 100 may be implemented using any technology suitable to the art. The one caveat is that the spread controllers in the spread must be capable of controlling the position of the spread elements during the acquisition described below. One advantage of using the Q-Marine technology is that it provides superior control relative to most other implementations in the art.

[0041] **FIG. 4** is a "snapshot" during the acquisition described above for the vessel 111 as it traverses its respective sail line 171. For the sake of clarity, and so as not to obscure this aspect of the invention, some detail is omitted. For example, only the receiver vessel 111, streamer array 121, and source 131 are shown because the operation of the other spread elements can readily be extrapolated therefrom. Some elements of the streamer 140, namely the positioning devices, are likewise omitted for the same reason.

[0042] **FIG. 4** also shows a subterranean geological formation 430. The geological formation 430 presents a seismic reflector 445. As those in the art having the benefit of this disclosure will appreciate, geological formations under survey can be much more complex. For instance, multiple reflectors presenting multiple dipping events may be present. FIG. 4 omits these additional layers of complexity for the sake of clarity and so as not to obscure the present invention.

[0043] Still referring to **FIG. 4**, the seismic source 131 generates a plurality of seismic survey signals 425 in accordance with conventional practice as the survey vessel 111 tows the streamers 140 across the area to be surveyed in predetermined coil pattern described above. The seismic survey signals 425 propagate and are reflected by the subterranean geological formation 430. The receivers 214 detect the reflected signals 435 from the geological formation 430 in a conventional manner. The receivers 214 then generate data representative of the reflections 435, and the seismic data is embedded in electromagnetic signals.

[0044] The signals generated by the receivers 214 are communicated to the data collection unit 200. The data collection unit 200 collects the seismic data for subsequent processing. The data collection unit 200 may process the seismic data itself, store the seismic data for processing at a later time, transmit the seismic data to a remote location for processing, or some combination of these things.

[0045] The survey of **FIG. 1** is a wide-azimuth survey. The offset-azimuth plot for this survey is illustrated in **FIG. 5.**

[0046] The invention admits variation in its implementation of not only the spread elements, but the spread itself and the design of the survey. **FIG. 6** depicts an alternative embodiment 600 employing a single receiver vessel 605 and three source vessels 610. Note that, in this embodiment, all the vessels 605, 610 tow a source 615 while only the receiver vessel 605 tows a streamer array 630. The offset-azimuth plot for the embodiment 600 is shown in **FIG. 7**. Note that the sail lines 621-623, shown in **FIG. 6**, form three concentric circles. This may be referred to as a 1×4 coil shoot because there is one streamer array and four sources.

[0047] **FIG. 8** depicts a third embodiment 800 using two receiver vessels 805, each towing a respective source 810 and a respective streamer array 830, on offset sail lines 821-822. This is a “dual coil” pattern, or a 2×2 coil shoot. The offset-azimuth plot for the embodiment 800 is shown in **FIG. 9**. Still other alternative embodiments may become apparent to those skilled in the art.

[0048] Multi-vessel coil shooting such as that described above provides collection of longer offsets and improved efficiency. From the offset-azimuth diagrams presented in **FIG. 5**, **FIG. 7**, and **FIG. 9**, one can see that offsets longer than 12 km and full azimuth can be acquired. Multi-vessel coil shooting also allows larger interval between circles than does single vessel coil shooting. For instance, if for single vessel coil shooting the interval between circles (circle roll) is 1200 m, for dual coil shooting acquisition the circle roll could be 1800m in *x* and *y* directions, and this will reduce the total number of days for the acquisition.

[0049] As will be apparent to those skilled in the art from the disclosure herein, the shot distribution from multi-vessel coil shooting is not along one single circle as in single vessel coil shooting, but along multiple circles. The maximum number of circles is equal to the number of vessels. The pattern of shot distribution is nearly random and this is a benefit for imaging and multiple attenuation. An example of shot distribution from simulation of a 2 × 2 coil shooting acquisition is presented in **FIG. 9**.

[0050] In each of **FIG. 1**, **FIG. 6**, and **FIG. 8**, only a single set of sail lines is shown. Those in the art will appreciate that the survey areas are typically rather larger, and that a single set of sail lines will be insufficient to cover an entire survey area. Accordingly, preparation for the survey will typically involve the planning of multiple, circular sail lines. This can be adapted from techniques used in single vessel coil shooting as disclosed in U.S. Application No. 11/335,365, filed 19 January 2006, and incorporated below.

[0051] Design parameters for multi-vessel coil shooting include: the number of streamers; the streamer separation; the streamer length; the circle radius, the circle roll in X and Y directions; the number of vessels; and the relative location of the vessels relative to a master vessel. These parameters are selected to optimize: data distribution in offset-azimuths bins or in offset-vector tiles; and cost efficiency. Those skilled in the art having the benefit of this disclosure will appreciate that these factors can be combined in a number of ways to achieve the stated goals depending upon the objective of and the constraints on the particular survey. Their application will therefore be implementation specific.

[0052] As noted above, one particular consideration in a multivessel coil shoot is how the vessels are positioned relative to a master vessel. The master vessel is one of the streamer vessels. One factor in this consideration is the position of the source vessel relative to the streamer vessel; in Figure 1, the source vessels were placed behind the streamer vessels; this arrangement will generate positive and negative offsets (or "split-spread" type data). Other factors include the circle radii of the source vessels and the position of the second streamer vessel vs. the master vessel. The offset and azimuth distribution for multivessels coil shooting is determined d by these factors.

[0053] To speed up the acquisition for a coil shoot, one may use two streamer vessels separated by certain distance. However, we do not have the benefit of a wider footprint and offset-azimuth distribution that is acquired with multivessel acquisition. Also, single vessel acquisition can use also an additional source vessel but this is mostly used to undershoot isolated obstructions

[0054] **FIG. 11A**-**FIG. 11B** show how the offset azimuth bins and offset-vector tiles are defined. The objective of survey design is to have a uniform data distribution that will allow applying the appropriate processing sequence in these domains. **FIG. 11C** shows an example of data distribution for an offset range of 400 m to 600 m and azimuth range 0–45° for a 2×4 coil shooting acquisition.

[0055] Multi-vessel coil shooting allows more flexibility in survey design than a single vessel coil shooting. Depending on the survey objectives, *i.e.*, if the survey is a reservoir development type or an exploration type survey the roll interval can vary. For an exploration type survey the roll interval is larger than the roll interval for a development type survey due to the fact that for multi-vessel coil shooting the shots are distributed on several circles and this generates a larger subsurface footprint , which allows to increase the roll interval. In this way the data density and the cost-efficiency could be balanced to accommodate the survey objectives.

[0056] Table-1 shows a comparison between a single coil shooting survey, a dual coil shooting survey and a 2×4 coil shooting survey in terms of roll interval in X and Y directions, data density and total number of days required to acquire a survey that covers an area of 30 km × 30 km. The number of days represents 100 % production time.

Table 1. Comparison Between Different Coil Shooting Design Options & 2×4 RAZ for an area of 30 km × 30 km

Configuration	Roll	No. of Circles	No. of Shots	No. of Days
Single Coil	1400 m	484	507,232 (5,600 tr/s)	103
Dual Coil	1800 m	256	268,288 (11,200 tr/s)	55
2×4 coil	2400 m	169	177,112 (112,200 tr/s)	37

[0057] Most towed marine streamers are used in seismic surveys. The towed marine streamers may also be used in other types of surveys, for example, Controlled Sources Electromagnetic surveys ("CSEM"). In a CSEM survey at least one "vertical" electromagnetic (EM) source is towed by a marine vessel. EM receivers are also towed by either the same marine vessel or by a different marine vessel. In this manner, the EM source is towed along with the EM receivers through a body of water to perform CSEM surveying.

[0058] **FIG. 12** shows an exemplary marine survey arrangement that includes a marine vessel 1200 that tows an assembly 1202 of a vertical EM source 1204 (made up of source electrodes 1234 and 1236), electric field receivers (made up of electrodes 1240, 1242, 1244, 1246, 1250, 1252, 1254, and 1256), and magnetometers 1208. The electric field receivers are used to measure electric fields. The magnetometers 1208 (either 1-2-3 components or total field magnetometers) are used to measure magnetic fields. The magnetometers 1208 can be used to measure the magnetic fields at various offsets. The electric field receivers and magnetometers collectively are considered EM receivers (for measuring both electrical and magnetic fields).

[0059] The electrical cable 1230 includes a first source electrode 1234, and the cable 1232 includes a second source electrode 1236, where the source electrodes 1234 and 1236 are spaced apart by the distance D. The source electrodes 1234 and 1236 are part of the vertical EM source 1204. The source electrodes 1234 and 1236 are aligned above and below each other such that when a current is passed between them (with the direction of current flow depicted with double arrows 1238), a vertical electric dipole is created.

[0060] In operation, as the marine vessel 1200 tows the assembly 1202 through the body of water 1214, the controller 1224 can send commands to the electronic module 1210 to cause activation of the vertical EM source 1204. Activation of the vertical EM source 1204 causes EM fields according to the TM mode to be generated and to be propagated into the subterranean structure 1220. EM signals that are affected by the subterranean structure 1220 are detected by the electric field receivers and the magnetometers 1208 of the assembly 1202. As noted above, the electric field receivers made up of the receiver electrodes 1240, 1242, 1244, 1246, 1250, 1252, 1254, and 1256 measure the electric fields, with receiver electrodes along each cable measuring horizontal electric fields, and two vertically spaced receiver electrodes on respective cables 1230 and 1232 measuring vertical electric fields. Also, the magnetometers 1208 measure magnetic fields.

[0061] The multi-vessel coil shoot survey disclosed herein can also be employed in a CSEM survey such as that described above. One example of a CSEM streamer is disclosed and claimed in U.S. Application No. 12/174,179, filed 15 July 2008, incorporated by reference below.

[0062] Typical benefits of multivessel coil shooting such as is disclosed herein include:

- improved subsurface illumination due to the long offsets (up to 14 km) and full-azimuth data acquired;
- near offsets and far offset are acquired from each shot;
- improved multiple attenuation due to larger offsets;
- improved cost efficiency due to a larger roll interval;

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- high density data can be acquired by using simultaneous sources; note: if 4 sources are available and all 4 shoot simultaneously the data density is increased 4× vs. sequential shooting;
- enables subsalt AVO analysis due to the fact that larger angles of incidence are acquired ; note: longer offsets increases the angle of incidence for the subsalt sediments; and
- easy to undershoot isolated obstructions.

Note that not all embodiments will manifest each of these benefits to the same degree. Indeed, some embodiments may not exhibit all of these benefits, omitting some of them in particular implementations. Conversely, those skilled in the art may appreciate benefits and advantages in addition to those set forth above.

[0063] For example, consider **FIG. 13A** – **FIG. 13B**. **FIG. 13A** – **FIG. 13B** compare the illumination of a steep-dip subsalt reservoir with a two streamer vessel, four source vessel (six sources) wide azimuth parallel geometry acquisition and with a two streamer vessel, four source vessel (six sources) coil shooting acquisition, respectively. That is, **FIG. 13B** can be acquired using the embodiment of **FIG. 1**. These drawings are "hit maps", wherein coloration/shading represent the number hits per bin, and were derived based on ray tracing. It could be seem that the illumination of the steep-dip subsalt reservoirs requires long offset and full azimuth data. In **FIG. 13A**, the maximum offset was 8600 m wherein the maximum offset in **FIG. 13B** was 1400 m.

[0064] Thus, in accordance with the present invention, methods are described for acquiring marine seismic data that may be more cost effective and provide improved seismic imaging compared to presently employed methods. Methods of the invention comprise acquiring wide- or rich-azimuth data using a single streamer vessel (in certain embodiments using a single Q-Technology™ streamer vessel) towing multiple streamer cables using one or more calibrated marine seismic sources (in certain embodiments Q-Marine™ sources), wherein the streamer vessel and the one or more source arrays traverse a generally curved advancing shooting pattern. In certain embodiments one or more source arrays may traverse a smaller or larger curved pattern than the streamer vessel.

[0065] As used herein the phrase "generally curved advancing path" means that the vessels and streamers travel generally in a curve, and there is an advancement in one or more of the X and Y directions, as explained further herein. The path may be expresses as a coil. The curve may be circular, oval, elliptical, figure 8, or other curved path. Generally, multiple vessels having sources are used in various configurations, for example:

- 1 × 3 (one vessel has streamers, three vessels have sources),
- 2 × 2 (two vessels total, each have streamers and sources),
- 2 × 4 (two vessels have streamers and four have sources).

Those in the art having the benefit of this disclosure will realize additional alternative embodiments by which the invention may be disclosed.

[0066] Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims. "Means for" clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures.

[0067] As use herein, the phrase "capable of" as used herein is a recognition of the fact that some functions described for the various parts of the disclosed apparatus are performed only when the apparatus is powered and/or in operation. Those in the art having the benefit of this disclosure will appreciate that the embodiments illustrated herein include a number of electronic or electro-mechanical parts that, to operate, require electrical power. Even when provided with power, some functions described herein only occur when in operation. Thus, at times, some embodiments of the apparatus of the invention are "capable of" performing the recited functions even when they are not actually performing them—*i.e.*, when there is no power or when they are powered but not in operation.

[0068] The following documents are hereby incorporated by reference for the noted teaching as if set forth herein verbatim:

- U.S. Patent No. 4,757,482, entitled, "Modular Airgun Array Method, Apparatus and System", and issued 12 July 1988, to Bolt Technology Corporation, as assignee of the inventor Augustus H. Fiske, Jr. for its teachings seismic source design and construction;

- U.S. Patent No. 6,477,711, entitled, "Method of Making a Marine Seismic Streamer", and issued 5 November 2002, to Schlumberger Technology Corporation, as assignee of the inventors Nils Lunde, *et al.*, for its teachings regarding streamer design and construction;

- U.S. Patent No. 6,671,223, entitled, "Control Devices for Controlling the Position of a Marine Seismic Streamer", and issued 30 December 2003, to WesternGeco, LLC, as assignee of the inventor Simon Hastings Bittleston, for its teachings regarding streamer design and construction as well as its teachings about spread control;

- U.S. Patent No. 6,684,160, entitled, "Marine Seismic Acquisition System and Method", and issued 27 January 2004, to WesternGeco, LLC, as assignee of the inventors Ali Osbek *et al.*, for its teachings regarding streamer design and construction;

- U.S. Patent No. 6,932,017, entitled, "Control System for Positioning of Marine Seismic Streamers", and issued 23 August 2005, to WesternGeco, LLC, as assignee of the inventors Øyvind Hillesund and Simon Bittleston for its teachings regarding streamer design and construction as well as its teachings about spread control;

- U.S. Patent No. 7,080,607, entitled, "Seismic Data Acquisition Equipment Control System", and issued 25 July 2006, to WesternGeco LLC, as assignee of the inventors Øyvind Hillesund and Simon Bittleston for its teachings regarding streamer design and construction as well as its teachings about spread control;

- U.S. Patent No. 7,293,520, entitled, "Control System for Positioning of Marine Seismic Streamers", and issued 13 November 2007, to WesternGeco LLC, as assignee of the inventors Øyvind Hillesund and Simon Bittleston for its teachings regarding streamer design and construction as well as its teachings about spread control;

- U.S. Application No. 11/114,773, entitled, "Seismic Streamer System and Method", and filed 26 April 2005, in the name of the inventors Rohitashva Singh *et al.* for its teachings regarding multicomponent streamer design, construction and operation;

- U.S. Application No. 11/335,365, entitled, "Methods and Systems for Efficiently Acquiring Towed Streamer Seismic Surveys", and filed 19 January 2006, in the name of the inventors Nicolae Moldoveanu and Steven Fealy for its teachings regarding the design of circular, coil shoot sail lines;

- U.S. Application No. 12/351,156, entitled, "Acquiring Azimuth Rich Seismic Data in the Marine Environment Using a Regular Sparse Pattern of Continuously Curved Sail Lines", and filed 9 January 2009, in the name of the inventors David Ian Hill *et al.* for its teachings regarding the design of circular, coil shoot sail lines;
- U.S. Application No. 12/121,324, entitled "Methods for Efficiently Acquiring Wide-Azimuth Towed Streamer Seismic Data", and filed on 15 May 2008, in the name of the inventors Nicolae Moldoveanu and Steven Fealy for its teachings regarding the design of circular, coil shoot sail lines; and
- U.S. Application No. 12/174,179, entitled "Surveying Using Vertical Electromagnetic Sources that are Towed Along with Survey Receivers", and filed on 15 July 2008, in the name of the inventors David L. Alumbaugh, *et al.* for its teachings regarding CSEM surveys; and
- United States Provisional Patent Application No. 61/180,154, entitled "Multi-Vessel Coil Shooting Acquisition", and filed 21 May 2009, in the name of the inventors Nicolae Moldoveanu and Steven Fealy, for all its teachings;
- United States Provisional Patent Application No. 61/218,346, entitled "Multi-Vessel Coil Shooting Acquisition", and filed 18 June 2009, in the name of the inventors Nicolae Moldoveanu and Steven Fealy, for all its teachings;
- Beasley, C, J & R.E., Chambers, 1998, "A New Look at Simultaneous Sources", 60th Conference and Exhibition, EAGE, Extended Abstracts, 02-38, for its teachings regarding source separation techniques.

[0069] This concludes the detailed description. The particular embodiments disclosed above are illustrative only, as the invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the invention. Accordingly, the protection sought herein is as set forth in the claims below.

[0070] In the claims that follow and in the preceding description of the invention, except where the context requires otherwise owing to express language or necessary implication,

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the word “comprise” or variations such as “comprises” or “comprising” is used in an inclusive sense, that is, to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

[0071] Further, any reference herein to prior art is not intended to imply that such prior art forms or formed a part of the common general knowledge in any country.

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THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A marine seismic acquisition system, comprising:

a streamer/source vessel having a source and a streamer array disposed behind the source;

a first source vessel having at least one source attached thereto, the first source vessel being configured to trail behind the streamer/source vessel, and both the streamer/source vessel and the first source vessel being configured to travel along a first curved path;

a second source vessel having at least one source attached thereto, the second source vessel being configured to travel along a second curved path inside a perimeter of the first curved path; and

a third source vessel having at least one source attached thereto, the third source vessel being configured to travel along a third curved path inside a perimeter of the second curved path.

2 The marine seismic acquisition system of claim 1, wherein the first curved path, the second curved path and the third curved path form concentric circles during a revolution.

3. The marine seismic acquisition system of claim 1 or claim 2, wherein the radii of the first curved path, the second curved path and the third curved path are different.

4. A method, comprising:

towing a source and a streamer array with a streamer/source vessel along a first curved path, the streamer array being disposed behind the source;

towing a first source with a first source vessel along the first curved path, wherein the first source vessel is trailing behind the streamer/source vessel;

towing a second source with a second source vessel along a second curved path inside a perimeter of the first curved path;

towing a third source with a third source vessel along a third curved path inside a perimeter of the second curved path; and

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conducting a multivessel coil shoot using the streamer/source vessel, the first source vessel, the second source vessel and the third source vessel.

5. The method of claim 4, wherein the first curved path, the second curved path and the third curved path form concentric circles during a revolution.

6. The method of claim 4 or claim 5, wherein the radii of the first curved path, the second curved path and the third curved path are different.

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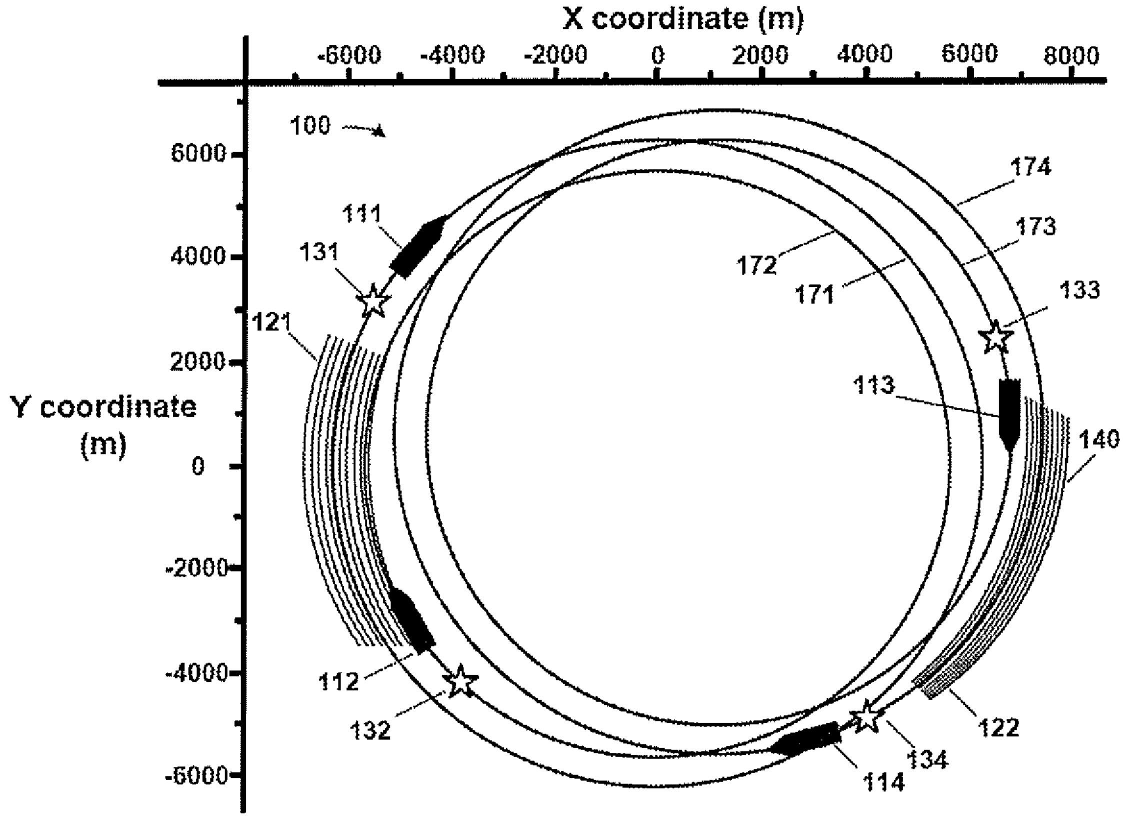

FIG. 1

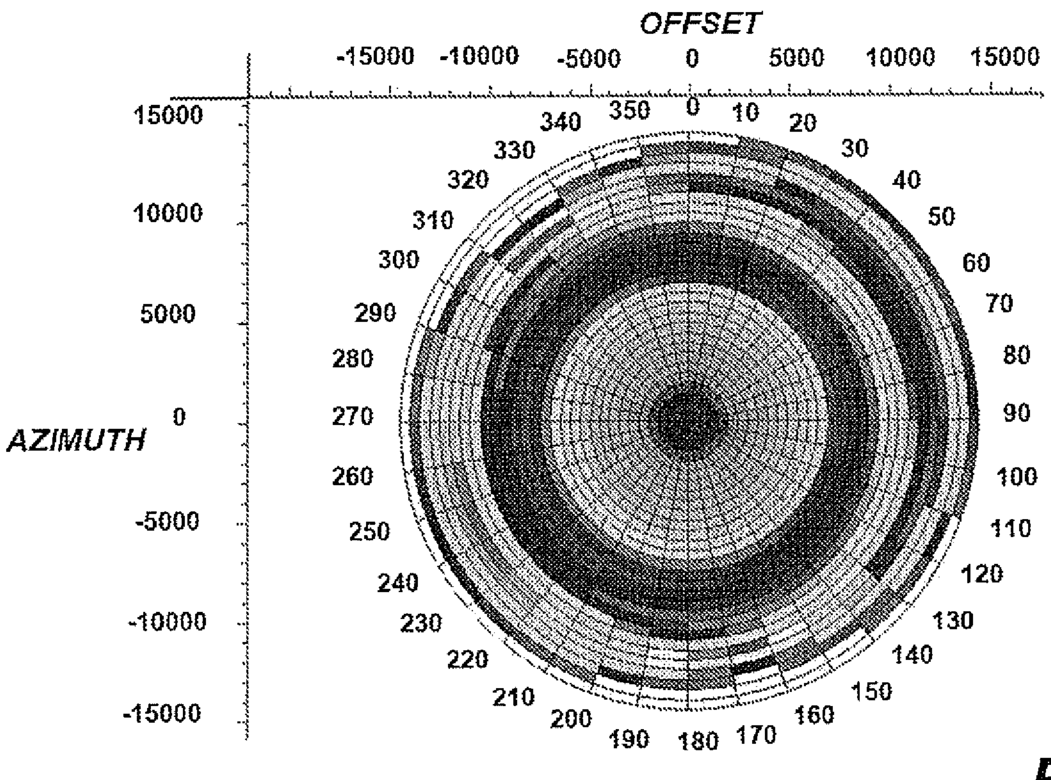

FIG. 5

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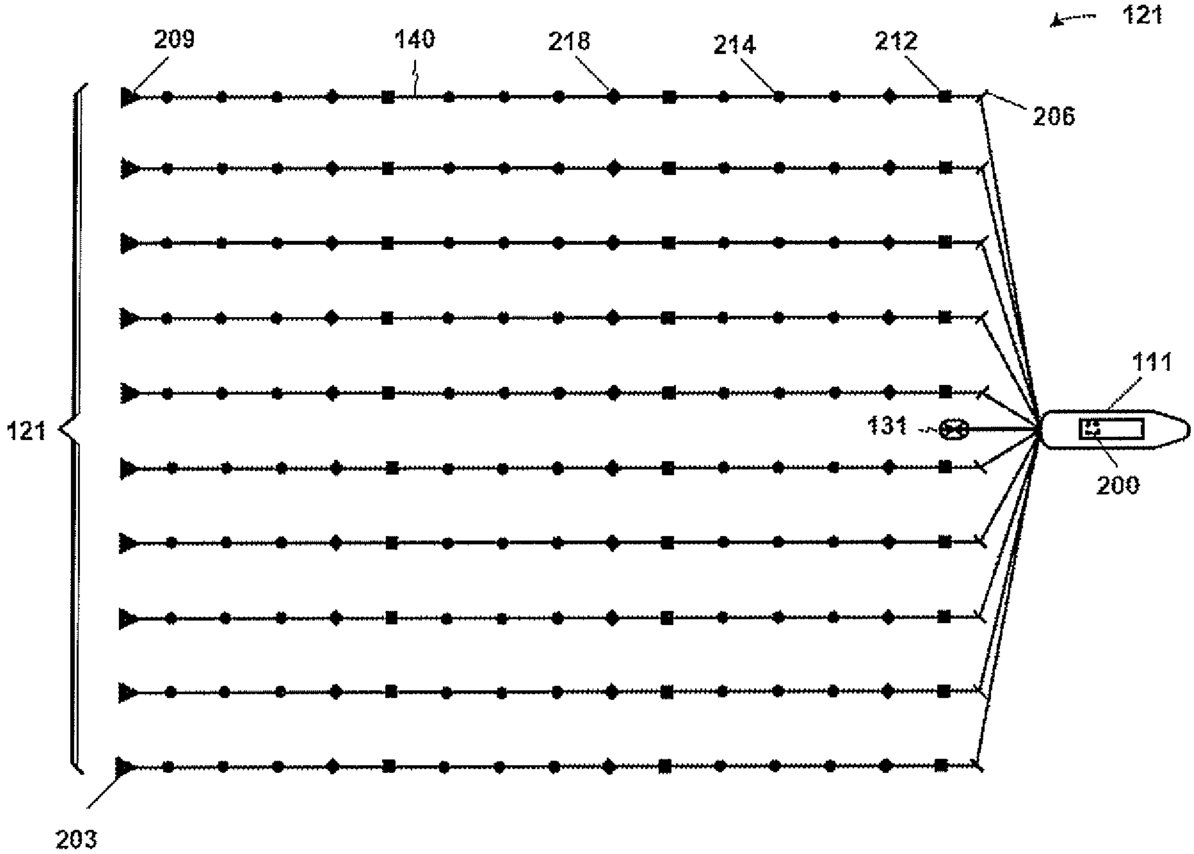
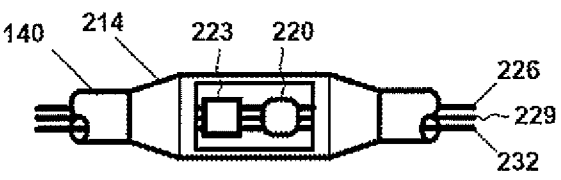


FIG. 2A

FIG. 2B



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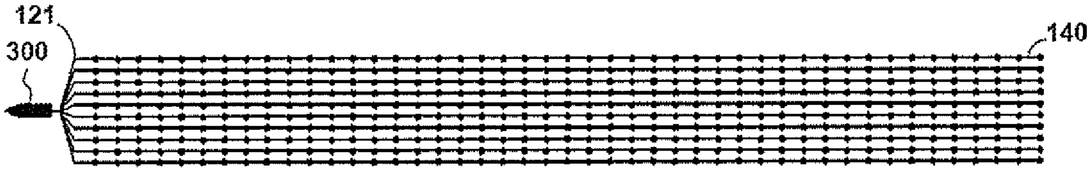
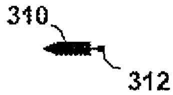


FIG. 3A

FIG. 3B



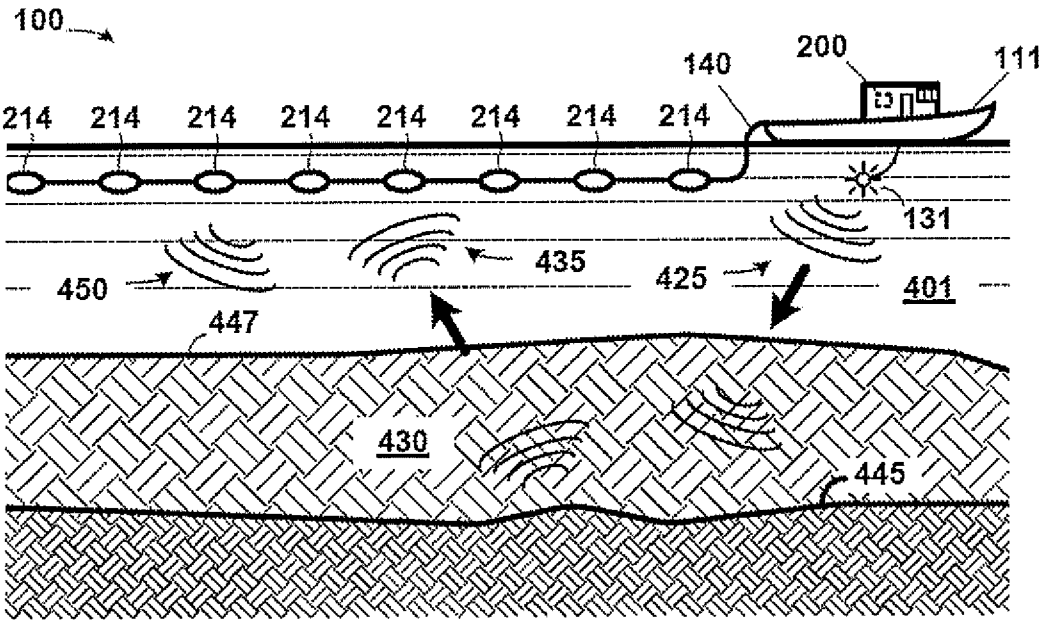


FIG. 4

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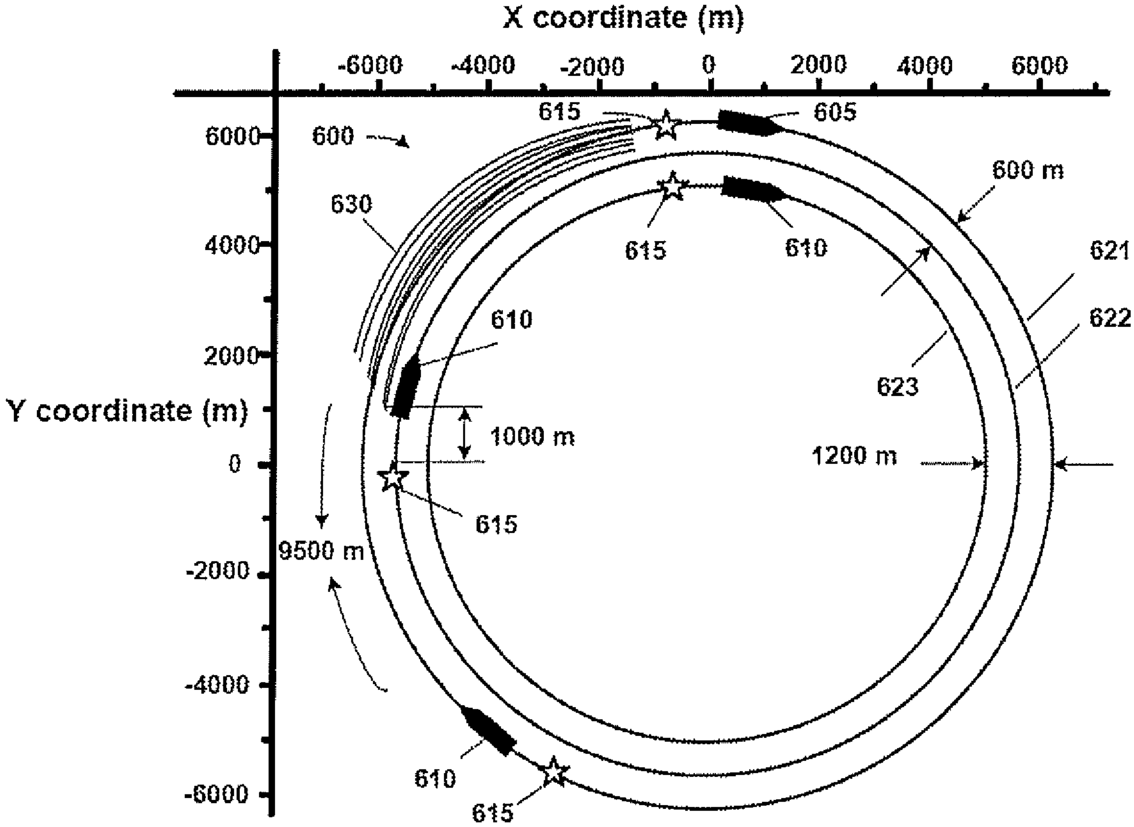


FIG. 6

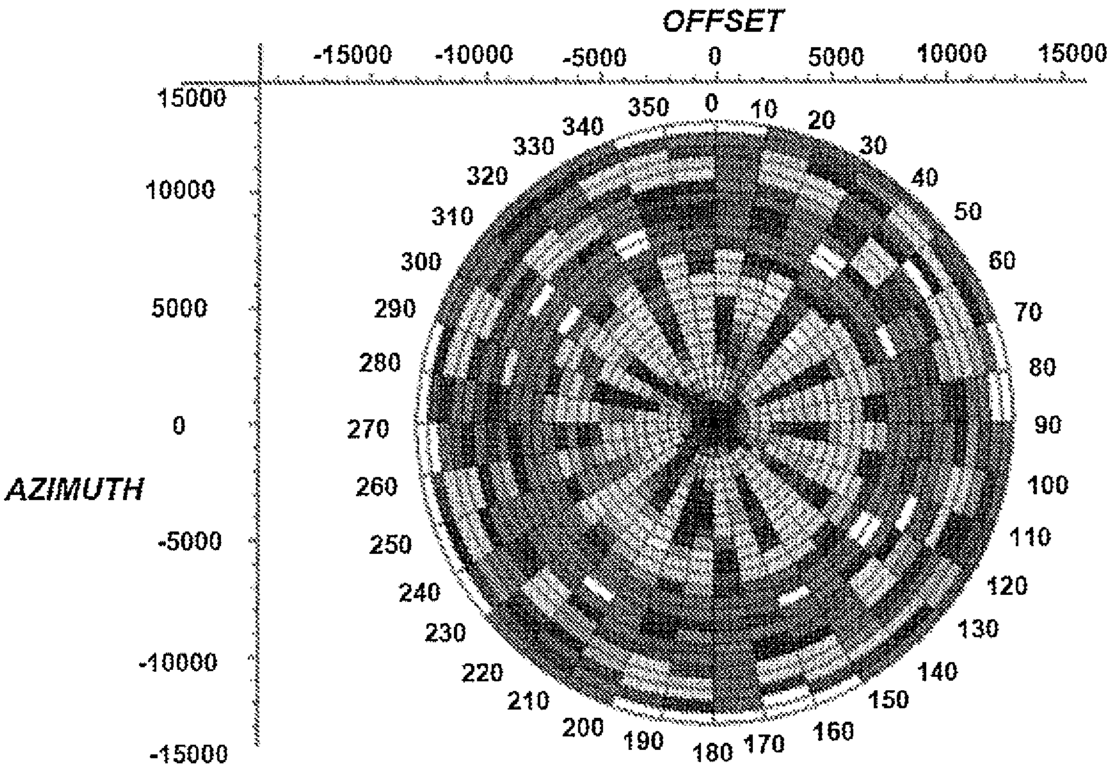
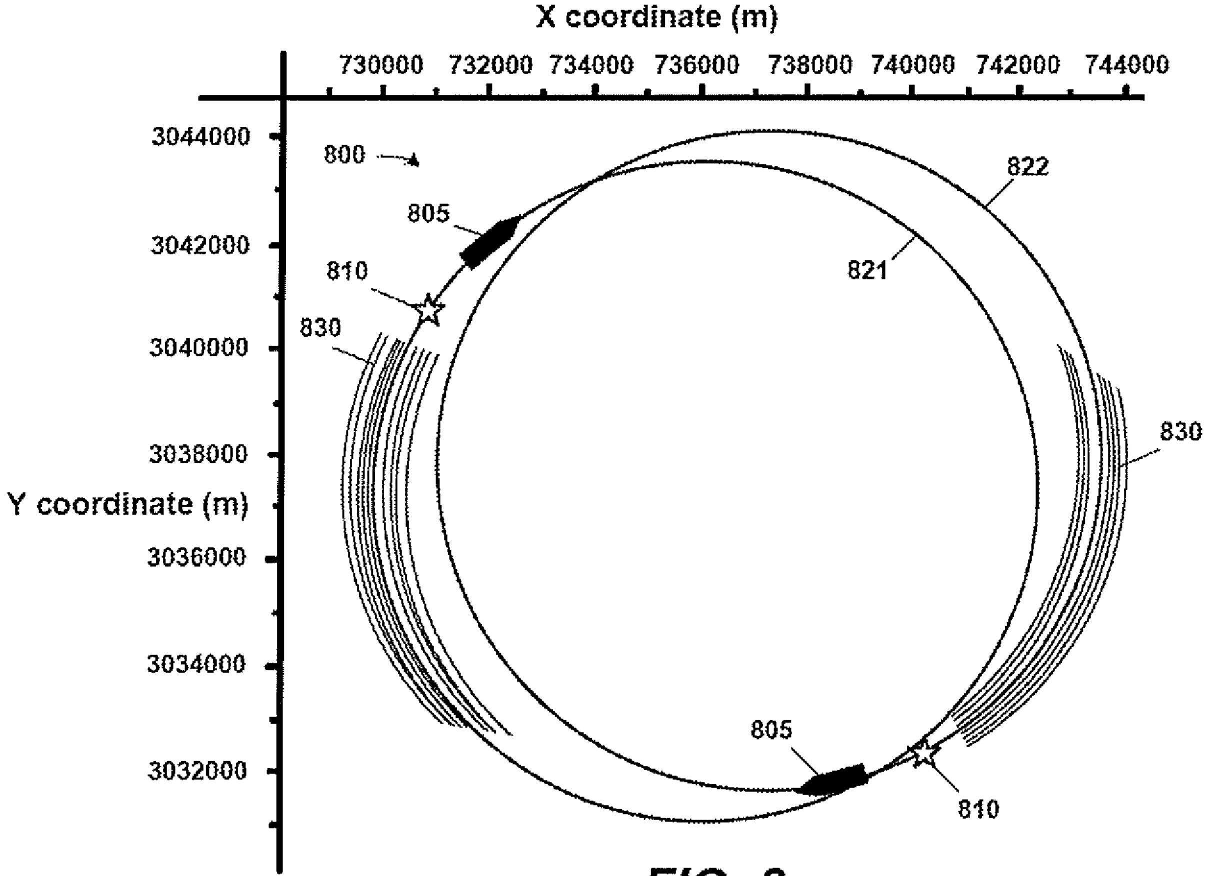


FIG. 7



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738000
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3042000
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3038000
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3034000
3032000
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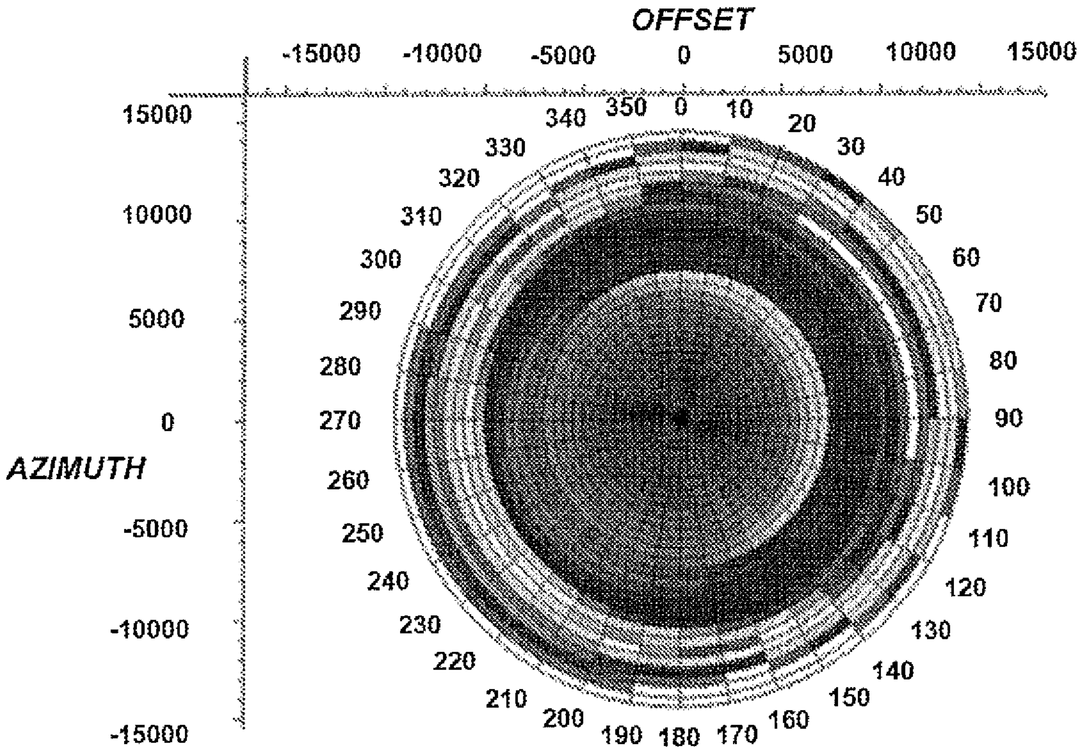
810
830
822
821
830
805
810

FIG. 8



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5000
10000
15000
15000
10000
5000
0
AZIMUTH
-5000
-10000
-15000
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0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
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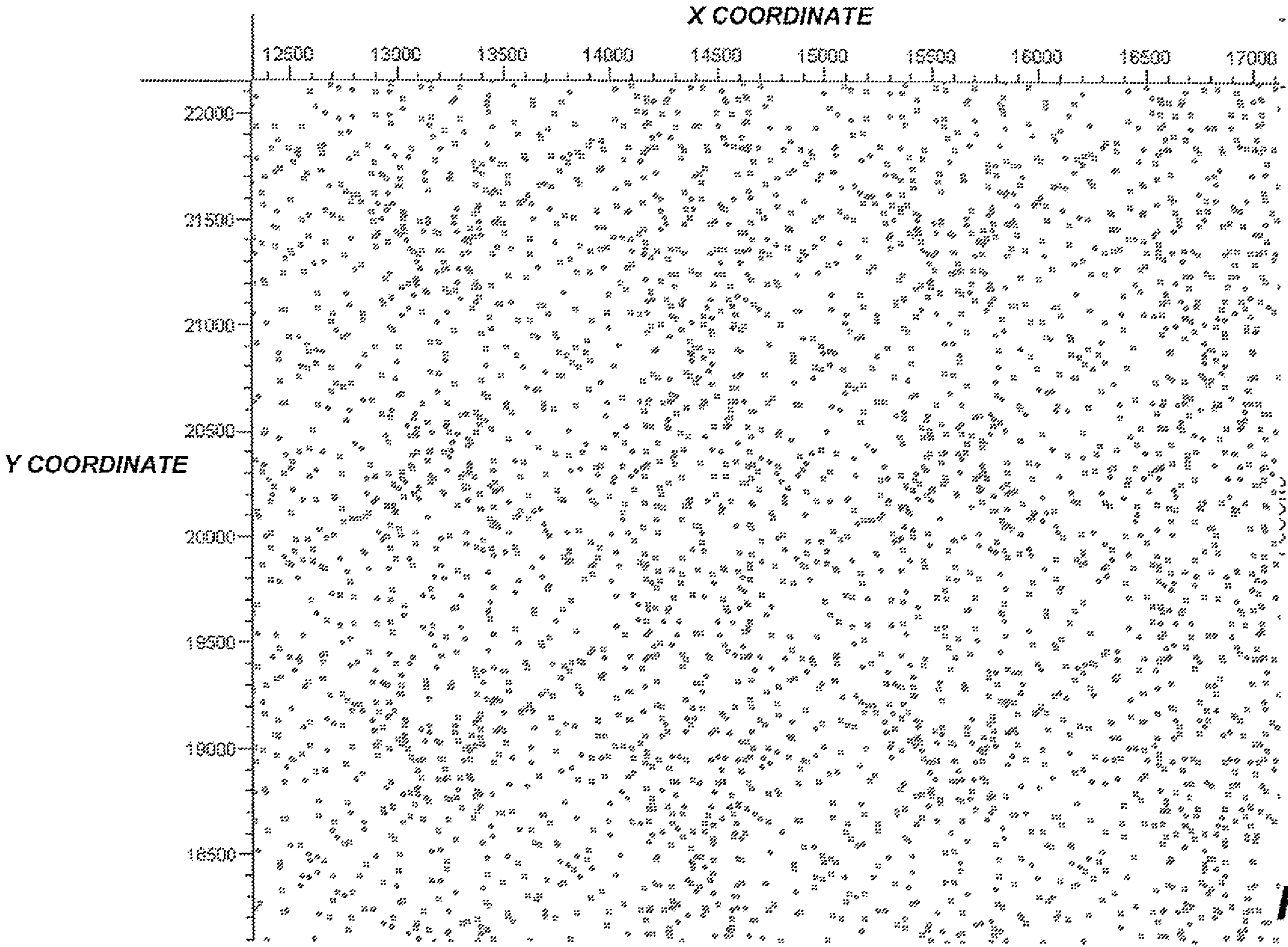
330
340

FIG. 9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16000
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FIG. 10

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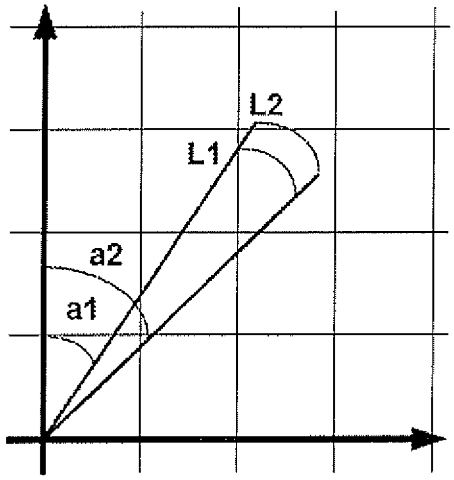


FIG. 11A

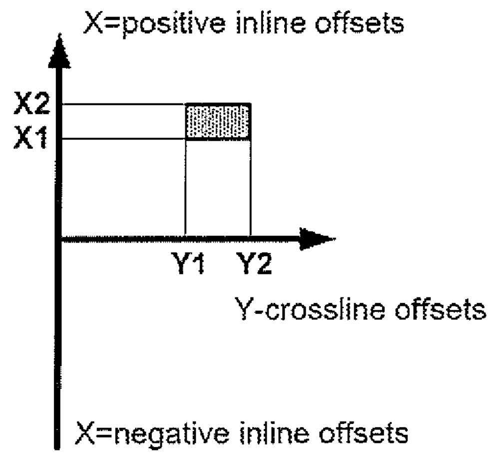


FIG. 11B

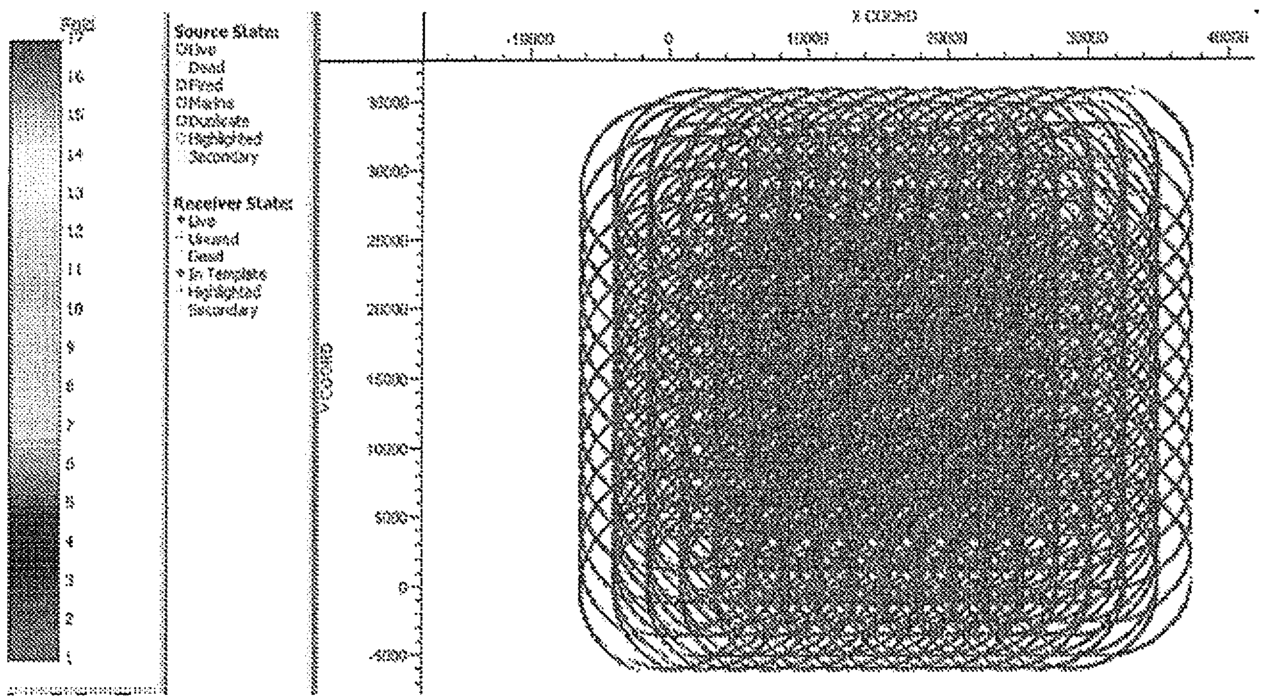
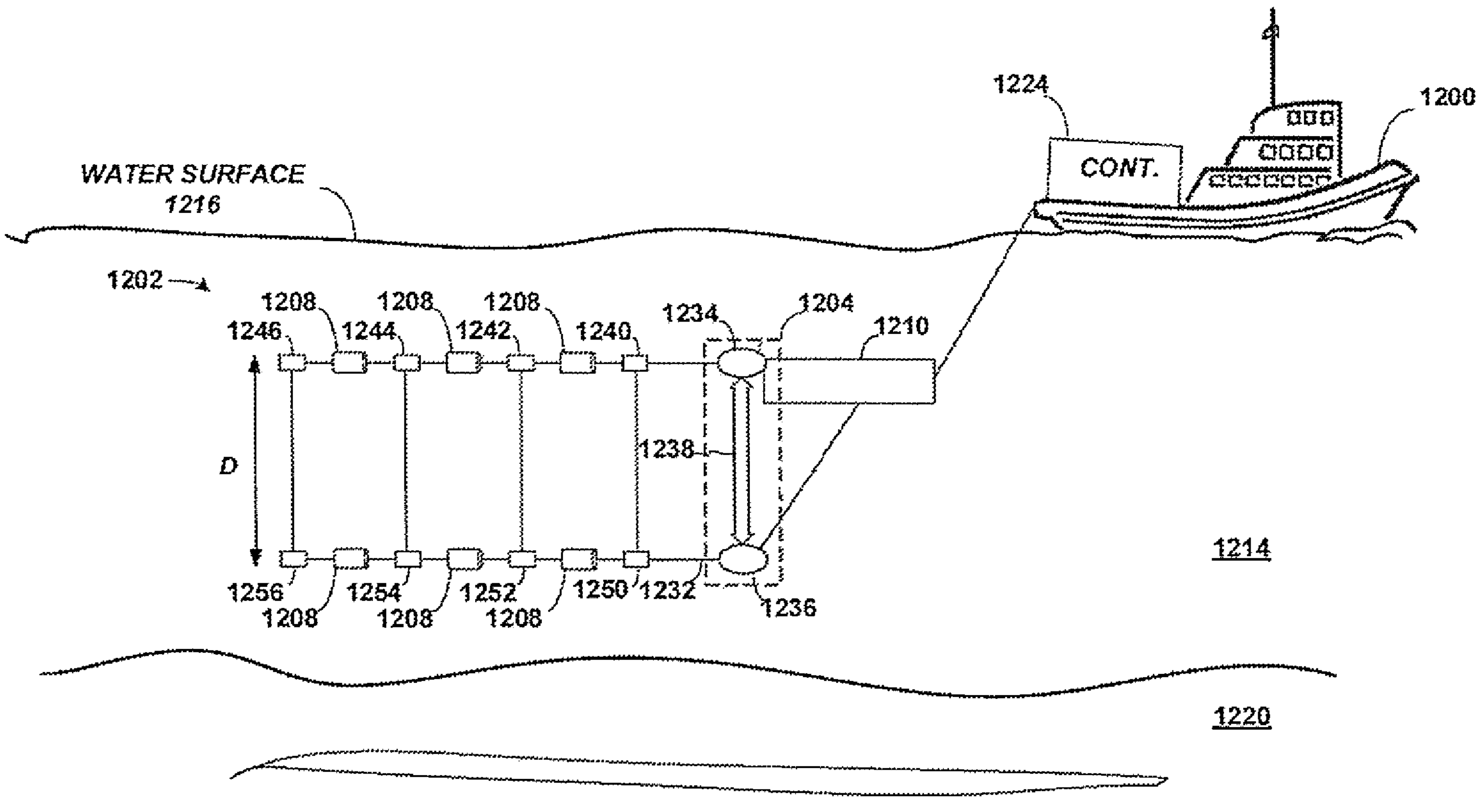


FIG. 11C



WATER SURFACE
1216
1202
1208
1246
1244
1242
1240
1234
1204
1210
1224
CONT.
1200
D
1238
1214
1256
1254
1252
1250
1232
1236
1220

FIG. 12

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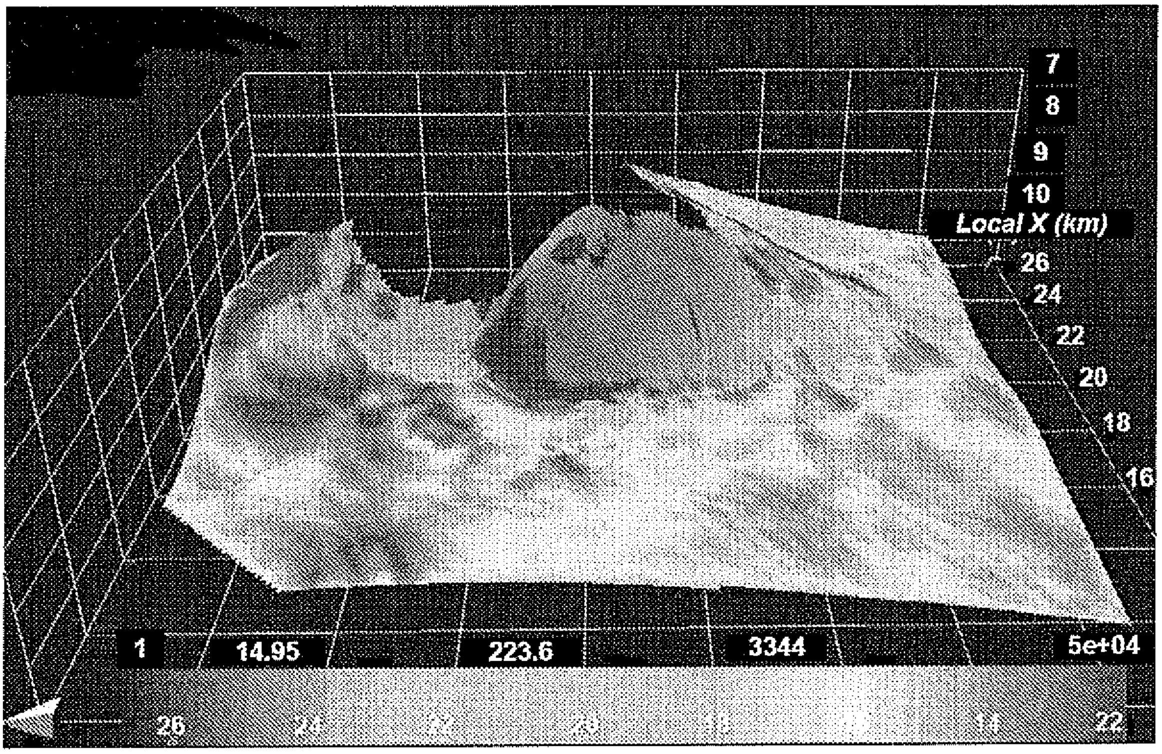

FIG. 13A

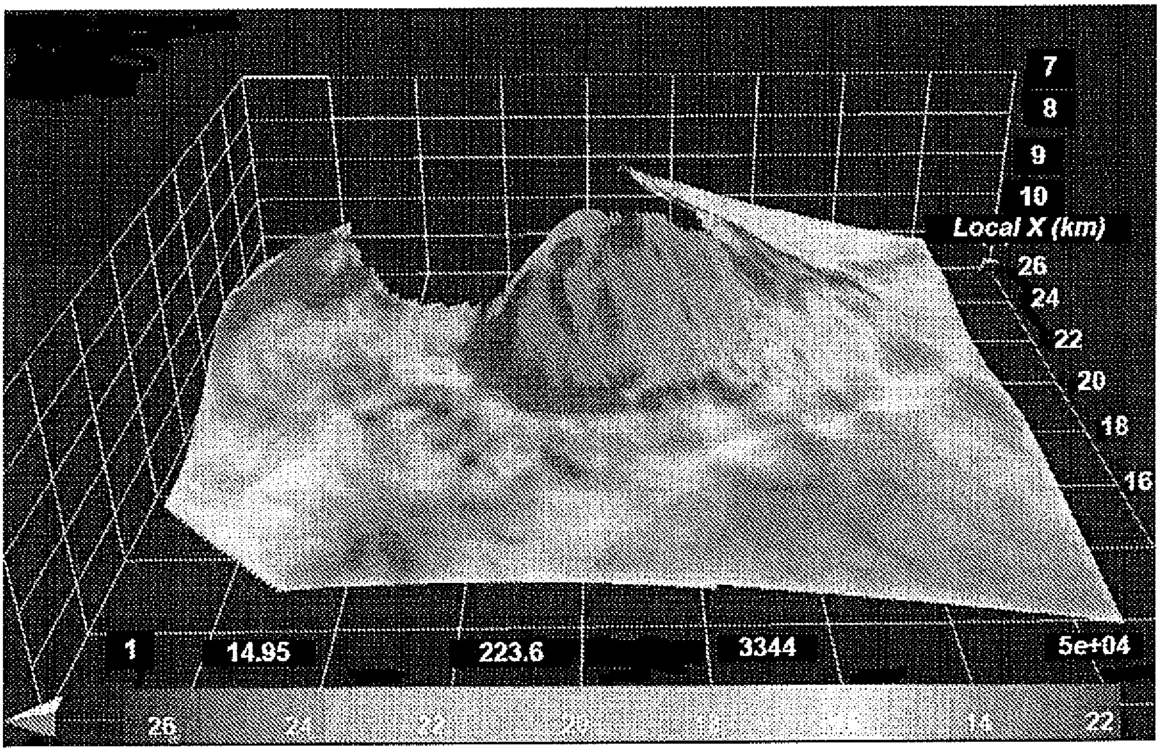

FIG. 13B