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[Continued on next page]

(54) **Title:** DECLINATION COMPENSATION FOR SEISMIC SURVEYS
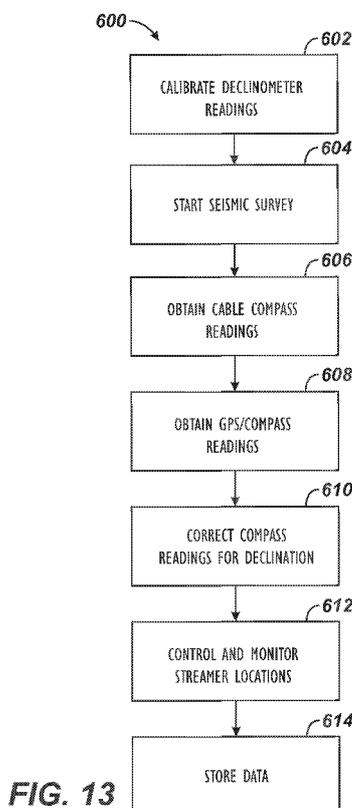
FIG. 13

(57) **Abstract:** In seismic survey for icy waters, streamers are towed behind a vessel under the water's surface to avoid ice. GPS readings may not be consistently obtained because the ice prevents a tail buoy with a GPS receiver from trailing from streamer at the surface. Instead, a device tows on the streamer under the water's surface. The streamer's absolute position is tracked by intermittently bringing the towed device to-ward the surface so GPS readings can be obtained. The streamer's absolute position can then be used in conjunction with compass readings and can correlate various seis-mic sensor signals obtained along the streamer during the survey. The compass read-ings can be corrected for declination using declinometer readings, which can be com-pensated for iron effects from the vessel or other device carrying the declinometer.

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DECLINATION COMPENSATION FOR SEISMIC SURVEYS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   This is a continuation-in-part of U.S. Pat. Appl. Ser. No. 12/719,783, filed 08-MAR-2010, which is incorporated herein by reference, to which priority is claimed, and which claims priority to U.S. Prov. Appl. Nos. 61/158,698, filed 09-MAR-2009; 61/246,367, filed 28-SEP-2009; and 61/261,329, filed 14-NOV-2009.

BACKGROUND

[0002]   Conventional marine seismic surveying uses a seismic source and a number of streamers towed behind a seismic survey vessel. These streamers have sensors that detect seismic energy for imaging formations under the seafloor. Deploying the streamers and sources and towing them during the survey can be relatively straightforward when operating in open waters with moderate swells or the like.

[0003]   However, marine locations covered by ice, debris, large swells, or other obstacles can make surveying more difficult, expensive, or even impossible. In icy waters, for example, the seismic survey vessel must break through ice and traverse waters filled with ice floes. The noise generated by ice impacts can also complicate the seismic record produced.

[0004]   Additionally, the ice floes on the water's surface make towing the source and streamers more difficult and prone to damage. Any components of the system at the water's surface can encounter ice, become bogged down, and lost. In addition, any cables or towlines coming off the vessel even from slipways can collect ice at the surface, potentially damaging the cables or towline. Likewise, ice pulled under the hull and rising behind the vessel can shear away these cables and lines. Some approaches for performing seismic surveys in icy regions known in the art are disclosed in U.S. Pat. Nos. 5,113,376 and 5,157,636 to Bjerkoy. To date, however, the problems associated with marine seismic surveying in icy or obstructed waters have not been significantly addressed.

[0005]   In addition to some of the physical challenges involved in surveying in arctic or icy regions, for example, variations in the earth's magnetic field in any

give region of the earth can cause problems in land-based and marine-based seismic surveying. As is known, the earth's magnetic field can be described by seven parameters, including declination (D), inclination (I), horizontal intensity (H), the north (X) and east (Y) components of the horizontal intensity, vertical intensity (Z), and total intensity (F) measured in nanoTeslas. Most of the geomagnetic field (*i.e.,* the main field) comes from the earth's outer core. Various mathematical models, such as the International Geomagnetic Reference Field (IGRF) and World Magnetic Model (WMM), can describe this main field and how it changes slowly over time. Although the changes of the field may be somewhat predictable, the geomagnetic field also varies due to currents inside the magnetosphere and the ionosphere and due to other variations that are less predictable.

[0006] The variations and changes in the geomagnetic field can affect seismic surveying in arctic regions as well as other locations. For example, compass readings from seismic survey equipment can be affected by differences in declination at arctic latitudes. As is known, magnetic declination represents an angle between magnetic north and true geographic north. The variation in declination depends on latitude and longitude and changes over time, and the variability in azimuth increases at arctic latitudes.

[0007] As will be appreciated, a compass reading can be corrected based on the magnetic declination (the angle between true north and the horizontal trace of the magnetic field) for the compass' location. To correct the compass' bearing, a true bearing is computed by adding the magnetic declination to the compass' magnetic bearing. Unfortunately, areas around the north and south magnetic poles can produce erratic or unusable compass readings, and some zones on the earth can have wide discrepancies in declination.

[0008] The published magnetic models of the earth invariably have errors or are not entirely accurate to a level of detail sometimes needed. Conventional marine-based seismic surveying can avoid problems by using a closed traverse in which GPS readings are consistently obtained by tail buoys on the streamers. In arctic exploration, however, the system cannot typically use a tail buoy due to ice floes so that the system cannot obtain GPS readings on a reliable basis. This makes

tracking and locating seismic survey equipment and data more problematic for icy or obstructed waters.

[0009]   The subject matter of the present disclosure is directed to overcoming, or at least reducing the effects of, one or more of the problems set forth above.

SUMMARY

[0010]   A seismic survey system operates in regions or at times in which variations in declination can create errors in geomagnetic field measurements taken during the survey. For example, arctic regions of the earth can have variations in declination that change in a seismic survey area, and errors in compass readings can be problematic in marine seismic surveys in such regions. The problems can be further exacerbated when the region has icy waters that limit the use of tail buoys to obtain GPS readings.

[0011]   In a marine-based system, for example, a vessel tows streamers during the survey. Compasses gather information for calculating the locations of the streamers during the marine seismic survey. As is known, the compasses give a magnetic azimuth, and their location has to be calculated in a geographical reference system. Because the compasses are sensitive to the declination of the local magnetic field, any local discrepancies can reduce the accuracy of reconstructing the streamer's locations from the compass readings. For this reason, the survey system measures the magnetic declination in real-time as the survey proceeds and corrects the geomagnetic field measurements (e.g., compass readings) in real time or later in processing.

[0012]   Correcting for declination can be useful in any form of marine seismic surveying and even in land-based seismic surveys. When performing marine surveys in arctic regions in particular, correcting for magnetic declination can be particularly useful because the system cannot always use GPS readings from a tail buoy or the like on the streamers to determine the locations of the sensors. Instead, the streamers have a number of cable compasses or other magnetic heading devices used for monitoring the location of the streamers during the survey. Without consistent GPS readings from a tail buoy, the survey system has to determine deformation of the current magnetic declination caused by variations

in the earth's crust, atmosphere, and the like so the compass readings can be corrected.

[0013]   As noted above, the survey system in arctic regions cannot typically use tail buoys to obtain absolute positions (*e.g.,* GPS readings) for the seismic streamers due to ice floes or other obstructions. Thus, the survey must use an open traverse. For this reason, the system needs to handle errors rigorously in the various compass readings along the streamers. As one solution, controllable vehicles on the streamers can be intermittently brought to the surface when clear of ice floes or other obstructions so that absolute positions (*e.g.,* GPS readings) can be obtained and communicated to the survey system. Such a controllable vehicle can be located at the tail end of the streamers or elsewhere.

[0014]   After obtaining the intermittent GPS readings, the controllable vehicles can then float back under the surface to avoid encountering ice and to keep the streamer protected under the water's surface. All the while, an Inertial Navigation System (INS) device, integrated navigation system, or other like system can supplement the intermittent GPS readings with relative position information so the location of the streamers can be determined even when significant ice floes at the surface prevent the controllable vehicles from obtaining new GPS readings. This relative position information includes inertial measurements of the streamer while towed under the surface of the water.

[0015]   At the same time, the survey system can obtain declination measurements and correct the various cable compass or other sensor readings on the streamers accordingly. To do this, a declinometer having a magnetometer can be deployed behind the vessel for obtaining the declination measurements. For example, the declinometer can be towed on the end of a streamer cable or towed off the stern of the vessel. Typically, such a declinometer is towed two or more lengths of the vessel behind the tow vessel.

[0016]   For some declinometers, issues with motion encountered by the declinometer when towed may over-complicate handling of the measurements the declinometer obtains. For example, the magnetometer reading may need to be corrected on a continual basis relative to the magnetometers spatial orientation while being towed. This can increase computational complexities. To avoid such

complications, the components for the declinometer can be used directly on the tow vessel even though the vessel produces some magnetic influence on the declination readings. Use on the vessel is possible when various calibration steps are performed to compensate for soft and hard iron effects caused by the vessel on the declinometer.

[0017]   The declinometer for use on the vessel obtains three-axis geomagnetic field readings using a magnetometer, such as an aeronautical 24-bit Honeywell strapdown magnetometer. The declinometer also uses a three-compass inertial measurement unit (IMU) device along with computing and motion compensation calculations associated with such a device. In the end, the system combines GPS readings and inertial measurements (*i.e.,* absolute position and inertial position) from the IMU device together and then compares the measurements to the three-axis geomagnetic field reading from the magnetometer to calculate declination corrections. In turn, the various cable compass or other sensor readings along the streamers can be corrected with this calculated declination.

[0018]   Correcting for declination determined at a tow vessel can apply to marine seismic surveys in icy or obstructed waters as well as other applications. In general, the techniques disclosed herein can be used in marine surveys where no tail buoy can be used to obtain GPS readings or such readings can only be sporadically obtained. For example, any form of marine seismic survey that uses streamers towed at a deep depth under the surface or at a slant from the tow vessel so that obtaining GPS readings for the streamers cannot be done may benefit from these techniques.

[0019]   As noted above, using declination measurements from the tow vessel to correct cable compass readings on the streamers requires calibration steps to be preformed to account for the vessel's influence on the declinometer. Briefly, the tow vessel traverses a circular pattern during calibration and obtains readings from the declinometer and IMU device. Readings from the IMU device are then used to correct for pitch and roll of the tow vessel. The survey system then corrects for hard iron effects from the tow vessel and for soft iron effects from ambient differences in the earth's geomagnetic field on the vessel. Software algorithms perform these corrections and determine compensation factors or parameters. A

deviation curve can also be used to monitor magnetic field, and magnetic observatory data in the region of interest may be used to enhance the calibration of the declinometer.

[0020]   Once obtained, the declination corrections can be applied to readings from any of the various devices used during a seismic survey, such as cable compasses, streamers, etc. The various readings can be adjusted in real-time, and raw data for both declination correction and compass readings can be stored for later use and processing. Moreover, the compass readings and the like can be corrected in real time so that the survey system can better monitor and control the streamers during the survey.

[0021]   It is believed that corrections at latitudes in arctic regions may be as much as 1 to 2degrees of difference. When multiple streamers are involved and have considerable length, variations along the length of the streamers can be compounded during a survey. Therefore, being able to correct the error in declination can be useful in monitoring and recording the locations of the streamers for seismic exploration. In the end, the correction may achieve accuracy as close as 0.1%.

[0022]   Other than marine applications, declination variations can be problematic in land-based applications where magnetic heading is used. Declination varies spatially and temporally, and the variances may be exacerbated at arctic latitudes, during solar storms, etc. Therefore, even land-based surveys can benefit from the disclosed techniques.

[0023]   The foregoing summary is not intended to summarize each potential embodiment or every aspect of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024]   Fig. 1 shows a process of correcting seismic survey signals for declination.

[0025]   Figs. 2A-2B show side and plan views of a marine seismic survey system according to certain teachings of the present disclosure for use in icy regions.

[0026]   Figs. 2C-2D illustrate side views of marine seismic survey systems having a flotation device and different types of controllable devices.

[0027]   Figs. 3A-3B illustrate one type of controllable device in two operating conditions.

[0028]   Fig. 4 illustrates an embodiment of a controllable device according to the present disclosure.

[0029]   Fig. 5 illustrate inner details and components of a controllable device.

[0030]   Fig. 6A illustrates a side view of a marine seismic survey system having a Remotely Operated Towed Vehicle (ROTV) as the controllable device at the tail end of the streamers.

[0031]   Fig. 6B illustrates a plan view of another marine seismic survey system having ROTVs at multiple locations on the streamers.

[0032]   Figs. 7A-7B shows a Remotely Operated Towed Vehicle (ROTV) in more detail.

[0033]   Fig. 8 schematically illustrates a control system for controlling the ROTVs and dead reckoning its location while being towed.

[0034]   Fig. 9 shows a control loop for dead reckoning and correcting drift in an Inertial Navigation System for a towed vehicle.

[0035]   Fig. 10 shows a steamer with sensors positioned thereon for determining the shape of the streamer using a GPS reading for a vessel, known sensor locations, a known controllable vehicle location, and various compass headings.

[0036]   Fig. 11 shows different arrangements of acoustic systems for performing acoustic cross-bracing to determine streamer positions.

[0037]   Figs. 12A-12B schematically illustrates elements of a control system on a towing vessel having declinometer components.

[0038]   Fig. 12C schematically shows a geomagnetic coordinate system.

[0039]   Fig. 12D schematically shows a vessel's coordinate system with attitude angles measured relative to geographical north and a horizontal plane.

[0040]   Fig. 13 illustrates a general flow diagram of a seismic survey using declination determined at a vessel.

[0041]   Fig. 14 shows a calibration process in flow chart form for determining declination at a tow vessel.

[0042]   Figs. 15A-15B shows two calibration patterns for a vessel.

[0043]   Figs. 16A-16B shows the calibration process in more detail.

[0044]   Fig. 16C schematically shows interpolation of the declination for a survey area based on declination from base stations.

[0045]   Fig. 17 graphically illustrates the steps to solve for a rotated vertical magnetometer component (M_z) as a function of azimuth from GPS/IMU readings using a fourth-order Fourier-series deviation curve and least squares.

[0046]   Fig. 18 graphically illustrates the steps for solving parameters of horizontal magnetometer components (M_x, M_y) simultaneously by least squares to compensate for both hard and soft iron effects in the horizontal plane.

[0047]   Fig. 19 graphically illustrates the steps for determining a weighted, interpolated delta declination plot for a calibration site.

[0048]   Fig. 20 diagrams processing steps in flow chart form for correcting the declination of cable compass readings from a marine seismic survey.

[0049]   Fig. 21 schematically shows a land-based seismic survey system according to the present disclosure.

DETAILED DESCRIPTION

A. Declination Correction for Seismic Surveys

[0050]   Seismic surveys on land or sea use sensors to obtain seismic signals. An image of a subterranean formation of interest can then be generated when the locations of these sensors are known when the seismic signals are obtained. In many cases, geomagnetic field measurements, such as compass readings, are used to determine the location, orientation, and heading of the seismic sensors. Although declination varies over time and at different locations on the earth, the variance can be more pronounced at certain locations (*e.g.,* arctic latitudes) or during certain events, (*e.g.,* solar storms). Therefore, being able to correct for declination in real-time for a given spatial location on the earth can be beneficial in seismic surveys and can improve the accuracy of the survey results.

[0051]   To that end, a system and method are disclosed for correcting declination both temporally and spatially during seismic surveys, which can be either land-based or marine-based. In Figure 1, a process 10 for correcting declination for a

seismic survey is shown in flow chart form. During the survey, seismic signals are obtained with one or more seismic sensors in a survey area (Block 12). For a marine-based survey, the sensors can be hydrophones disposed along streamers towed behind a vessel, and the seismic signals can be generated by a source, such as air guns also towed behind the vessel. For a land-based survey, the sensors can be geophones disposed at various locations on the ground, and the seismic signals can be generated by a vibrator or other seismic source.

[0052]   To image the formation of interest with the seismic signals, the locations of the sensors relative to the source must be know. For this, local geomagnetic field measurements are obtained relative to the seismic sensors (Block 14). For example, compass readings may be made on the towed streamers during a marine seismic survey. Readings may also be made on the tow vessel or elsewhere. For land-based seismic, compass readings may also be obtained to orient the sensors and sources.

[0053]   As is known, compasses and other similar sensors give a magnetic azimuth, but the positions of various sensors, sources, etc. for imaging the earth are calculated in a geographical reference system, such as latitude and longitude. Therefore, the compass readings need to be translated to the reference system. Unfortunately, the compasses or similar sensors are sensitive to the declination of the local magnetic field in the survey area so that any local discrepancy reduces the accuracy of reconstructed locations of the compasses. To overcome this, the local geomagnetic field measurements are corrected to account for the declination in the survey area.

[0054]   Declination varies over time and across different locations of the earth. As noted previously, this can be especially true in certain areas of the earth or under certain conditions. Thus, the local geomagnetic field measurements (*i.e.*, compass readings) are corrected based on temporal and spatial declination parameters, which have been determined according to the techniques discussed herein (Block 16-17). Ultimately, these corrected measurements can be correlated with the seismic signals obtained so a more accurate seismic image can be produced (Block 18).

[0055]   To correct for declination in a marine seismic survey, for example, the various compass readings obtained from the streamer for locating the sensors can be corrected over time and relative to the current declination measurement of the area of interest. As discussed below, this can involve calibrating a declinometer deployed on the tow vessel to remove hard and soft iron effects so the current declinations can be calculated and used to correct the compass readings along the streamers. Declination calculations from local base stations may also be used to interpolate the current declinations of the survey area.

[0056]   To correct for declination in a land-based seismic survey, for example, the various readings obtained for locating the geophones can be corrected over time and relative to the current declination measurements of the area of interest. As discussed below, this can involve using declinometer measurements at the local sensors and interpolating declination from local base stations near the survey area.

B. Marine Seismic Survey System

[0057]   With an understanding of the overall process of correcting declination in a seismic survey, discussion now turns to details of a marine seismic survey system and the declination corrections that can be performed with it.

[0058]   Figures 2A-2B show a marine seismic survey system 20 having a tow vessel 30 towing a number of streamers 60 with sensors 70. This system 20 can be similar to a conventional marine seismic survey system used in typical waters. However, as particularly shown, the system 20 can be used in icy regions having glacial ice, pack ice, ice floes, or other obstructions or obstacles at the water's surface that can interfere with towed components of the marine seismic survey system. In this particular system 20, an ice breaker vessel 35 breaks ice in advance of the tow vessel 30. Either way, various forms of marine seismic systems that gather information of streamer locations during the survey using geomagnetic field measurements, such as compass and magnetometer readings, can benefit from the declination correction as discussed herein.

[0059]   As the tow vessel 30 tows streamers 60, a supply system 45 operates a source 90, and a control system 40 having a seismic recorder records the seismic data obtained with sensors 70 on the streamers 60. Extending below the vessel's

waterline, an ice skeg 50 keeps the attachment points for towlines 62/92 below the surface of the water. Streamer cables 65 connected to the seismic recorder of the control system 40 extend form the vessel 30, and the skeg 50 directs these streamer cables 65 below the water's surface so that ice will not interfere with or collect around them.

[0060]   The seismic source 90 has a plurality of seismic source elements 91, which are typically air guns. A supply cable 95 connected to the supply system 45 extends from the vessel 30. A towline 92 connects the cable 95 to the ice skeg 50 and helps tow the source 90 behind the vessel 30.

[0061]   As further shown in Figure 2B, paravanes, fins, or doors 64 and a spreader 66 can be used to support multiple streamers 60 behind the tow vessel 30. These paravanes 64 and spreader 66 can also be similar to conventional components used for marine seismic surveying, except that the paravanes 64 preferably tow under the water's surface.

[0062]   During marine seismic surveying, it is desirable to determine, track, and potentially control the positions of the streamers 60 to better acquire and map the seismic data obtained. Determining absolute position can be done using GPS readings of the streamers 60 during the survey.

[0063]   In the marine seismic survey systems 20 of the present disclosure, however, obtaining GPS readings can prove difficult because the system 20 is significantly submerged below the water's surface so that GPS receivers cannot operate to obtain readings. For this reason, the system 20 has deployed devices 80 on the streamers 60 to assist in determining the absolute position of the streamers 60 as well as to actively control their positions. Moreover, various sensor readings of geomagnetic field measurements, such as compass readings along the streamers 60, can suffer from fluctuations in declination over time and over the survey area. For this reason, the system 20 uses declination correction techniques as discussed later.

[0064]   Discussion now turns to several types of deployed or controllable devices 80 that can be used on the streamers 60 to obtain GPS readings and otherwise control the position of the streamers 60 during surveying.

1.   Floating Deployed Device

[0065]   In Figure 2C, the marine seismic survey system 20 is shown having a
first type of deployed device 80A according to the present disclosure. During a
marine seismic survey, the locations of the streamers 60 are controlled and
monitored so that the absolute positions of the array of sensors 70 can be known
for proper data acquisition and analysis. For example, GPS coordinates of the
streamers' tail ends can be used to coordinate the position of each of the sensors
70 on the various streamers 60, and a control system 40 uses these coordinated
positions for data acquisition, analysis, and control. A suitable system for
acquisition, analysis, and control includes ION Geophysical's Intelligent
Acquisition system that can determine the locations of the streamers 60. Such a
system can steer the streamers 60 using DIGIFIN™ streamer steering systems and
ORCA® command control software, which are available from ION Geophysical.
(DIGIFIN is a registered trademark of ION Geophysical, Corporation, and ORCA
is a registered trademark of Concept Systems Holdings Limited.)

[0066]   In the present survey system 20, the streamers 60 travel submerged
below the water's surface using the skeg 50 and other features disclosed herein.
Yet, it is still necessary to determine the locations of the streamers 60. To obtain
the location of a given streamer 60, the system 20 in Figure 2A uses the deployed
device 80A that floats on the water's surface at the tail end of the streamer 60.

[0067]   The deployed device 80A can be a spar type buoy designed to handle ice
impacts and shed ice floes while at the surface. The device 80A includes a GPS
receiver 82 that can obtain GPS coordinates for the deployed device 80A as it is
towed behind the vessel 30 with the streamer 60. Obtaining the GPS coordinates
can use conventional techniques known in the art so that they are not detailed
herein. For example, details related to GPS-based positioning of an underwater
streamer cable 60 can be found in U.S. Pat. No. 7,190,634, which is incorporated
herein by reference.

[0068]   As the vessel 30 tows the streamer 60, the source 90 produces source
signals, and the sensors 70 detect seismic signals. The control system 40 obtains
GPS coordinates from the deployed device 80A using the streamer 60 and other
lines for communication and power to the GPS receiver 82. Then, using
techniques known in the art, the control system 40 determines the location of

streamer 60, sensors 70, source 90, and other components relative to the vessel 30 and physical coordinates of the area being surveyed.

[0069] Although the marine seismic survey system 20 uses the floating deployed device 80A of Figure 2C, this is generally possible as long as the surfaced device 80A is designed to encounter a certain amount of ice floes, obstacle, or the like. Otherwise, the surfaced device 80A can become bogged with ice, damaged by impacts, moved out of place, or lost. Therefore, in some situations, a submersible form of deployed device 80 may be used as described below.

2. Controllable Deployed Devices

[0070] The previous deployed device 80A was intended to float at the surface. Other devices disclosed in incorporated App. Ser. No. 12,719,783 can also be used and can have buoys, drogues, tethers, etc.–Notably, the marine seismic survey system 20 in Figure 2D has a deployed device 80D whose depth can be controlled. During surveying, the controllable deployed device 80D is towed on the end of the streamer 60 below the surface of the water to avoid impacts with ice floes. To obtain GPS readings, the deployed device 80D has a GPS receiver 82d that can be brought to the surface by controlling the depth of the device 80D. Therefore, the deployed device 80D is preferably towed below the surface in line with the streamer 60 and is brought to the surface to obtain GPS readings with the receiver 82d at appropriate times.

[0071] Figures 3A-3B illustrate the previously described deployed device 80D in two operating conditions. In its standard gliding condition of Figure 3A, the deployed device 80D follows behind the streamer 60 underwater. This position is suitable when ice floes, obstructions, or the like are at the surface of the water that can damage or obstruct the deployed device 80D. When a clearing develops at the surface, the deployed device 80D can be raised to the surface so that the GPS receiver 82d can obtain GPS readings. To map the array of streamers 60 and sensors 70 adequately, these GPS readings may need to be made at periodic intervals so the location of the streamers 60 and sensor 70 can be sufficiently tracked.

[0072] The deployed device 80D can be a controllable vehicle, device, or glider. In one arrangement, for example, the deployed device 80D can be a Remotely Operated Vehicle (ROV) having a propulsion system and controllable fins or the like to steer the deployed device 80D to desired positions in the water as it is towed. Alternatively, the deployed device 80D can be a towed glider that moves up or down using buoyancy control, as described in more detail latter. In yet another alternative, the deployed device 80D can be a Remotely Operated Towed Vehicle (ROTV) lacking a propulsion system but having controllable fins, as also described in more detail latter.

[0073] Along these lines, Figures 4-5 illustrate embodiments of deployed device or controllable vehicles 150A-B for the disclosed marine seismic system 20. As shown in Figure 4A and as noted previously, the vehicle 150A attaches to the end of the seismic streamer 60, which provides power and communications for the vehicle 150A. A tether 61 can be used for this purpose. Fins 154/156 on the vehicle 150A may be movable, and the vehicle 150A can have a propulsion system 160, such as a propeller. Alternatively, the fins 154/156 do not need to be movable. Instead, the vehicle 150A uses buoyancy control, as described below. Likewise, the vehicle 150A does not use propulsion, and the system 160 on the vehicle 150A may actually be a brake, as also described later.

[0074] As shown, the vehicle 150A has a detector 165 for detecting surface obstructions. This detector 165 can include sonar, ice profiler, optical sensor, multi-beam fathometer, camera, or the like that is upward looking and monitors for obstructions (or clearings) above the vehicle 150A. Signals from the detector 165 can be integrated with a navigation and/or control system (not shown) for acquiring marine seismic data, such as the Orca® system. In this way, the control system can determine when the surface above the vehicle 150A is free of ice and can signal the vehicle 150A to rise to the water's surface.

[0075] As one example, the detector 165 can use sonar to detect when ice is present at the surface. For example, if ice of a particular thicknesses is present at the surface, the sonar detector 165 may detect this surface ice, and this information can then be used for determining whether the vehicle 150A is raised or not. Although this depends on its capabilities, the sonar detector 165 is

preferably able to detect thinner ice that is at least less than 1-m thick so the vehicle 150A can be protected from most surface ice that may be present.

[0076]   As another example, the detector 165 can be an optical sensor that determines available light at the surface, which may indicate the presence or absence of ice. Along these lines, the detector 165 can be a digital camera that feeds video or images along the streamer 60 to the towing vessel. The tail ends of the streamers 60 can lie a significant distance from the tow vessel, and operators will not be able to determine where the streamers 60 are and what ice may be over the vehicles 150A. Therefore, operators can view the video or images from the camera 165 and determine whether to raise a particular vehicle 150A or not if a clearing is present. This can then be done remotely by activating the vehicles 150A with signals communicated from the vessel to the vehicles 150A via the streamers 60.

[0077]   The vehicle 150A also has a GPS receiver 152. As shown, this GPS receiver 152 can be located on an upward fin 154 so that the antenna 152 can peek above the surface of the water when the vehicle 150A glides to the surface for acquiring GPS readings. Regardless of how the GPS receiver 152 is surfaced, the GPS readings obtained are communicated to the instrument control system for positioning the streamer 60 and determining its location for proper data acquisition and analysis.

[0078]   Because continuous GPS readings may not always be available, the vehicle 150A may include an inertial navigation system to maintain the bearing intermittently determined by GPS readings as noted herein. Moreover, the vehicle 150 may include a declinometer 167, which can be tethered from the end of the vehicle 150A to keep it away from any interfering electronics. The declinometer 167 can use a three-axis magnetometer to calculate declination in the earth's magnetic field, and the declination can then be corrected to a true north reading so the instrument control system can determine the absolute position of the end of the streamer 60 in the absence of more consistent GPS readings usually used for that purpose. Rather than towing the declinometer 167 at the end of the streamer 60, the declinometer 167 can preferably be towed on its own directly behind the vessel 30, typically at a distance of 2-1/2 times the vessel's length, to reduce

interference from the vessel's magnetic field. Even more preferably and as described later, a declinometer can be disposed on the vessel 30 itself.

[0079]   The vehicle 150A intermittently gets GPS readings by going to the surface to obtain GPS data with the GPS receiver 152. Then, diving under the surface, the vehicle 150A can use the previously obtained GPS data along with inertial navigation data, compass readings, and current declinometer data to determine the real-time or near real-time location of the streamer 60 on an ongoing bases until new GPS readings can be obtained.

[0080]   The deployed device or vehicle 150B in Figure 5 reveals some inner details and components. On the vehicle 150B, the fins 154 are not movable, and the vehicle 150B does not use propulsion. Instead, the vehicle 150B uses buoyancy control having a volume (*e.g.,* bladder) 180 in a free-flooded tail of the vehicle 150B. The volume of this bladder 180 can be adjusted using a pumping system 182 or the like so that the buoyancy of the vehicle 150B can be altered in a controlled manner.

[0081]   To change the pitch and roll of the vehicle 150B, a mass 170 can be shifted axially along the length of the vehicle 150B or rotated about an axis. Preferably, the mass 170 is the actual battery used for the vehicle's electronic components, which include servos or other motors for moving the mass 170.

[0082]   In contrast to the GPS receiver of Figure 4, the GPS receiver 152 shown in Figure 5 is located on the end of an extended arm or mast 153. This arm 153 can extend upward at an angle from the vehicle 150B so that the GPS receiver 152 can extend from out of the water when the vehicle 150B glides near the surface. Alternatively, the mast 153 can be pivoted at its base 155 from a streamlined position in line with the vehicle 150B to an upward angled position. When the vehicle 150B is periodically brought to the surface to obtain GPS data, the mast 153 can be activated to pivot the GPS receiver 152 out of the water at this base 155.

[0083]   In general, the vehicle 150B can have features similar to those used for vehicles and drifting profilers that measure subsurface currents, temperatures, and the like in the oceans. As such, the vehicle 150B has a chassis (not shown) holding the variable buoyancy system 180, mass 170, and electronics section 190.

An isopycnal hull 157 suitable for the density of seawater can fit in sections on the chassis. The hull 157 and chassis can then fit within a fiberglass housing 151 having the fins 154 and streamlined shape. The mast 153 for the GPS receiver 152 can connect to the electronics section 190 and can extend from the housing 151.

[0084]   As disclosed in the incorporated application, these and other controllable deployed devices 80 can be used at the tail end of the streamer 60 (as well as other locations). When the tail end devices 80 are brought to the surface, they can obtain GPS readings for determining the location of the streamers.

3. System Using Controllable Deployed Devices

[0085]   As noted previously, the controllable deployed devices 80 can be used on the tail end of the steamers 60 to control position of the streamers 60. As also noted previously, the devices 80 can include Remotely Operated Towed Vehicles (ROTVs) that lack a propulsion system but have controllable fins. Figure 6A illustrates a side view of a marine seismic survey system 20 having a Remotely Operated Towed Vehicle (ROTV) 200 as the controllable device at the tail end of the streamers 60. The ROTV 200 is towed on the end of the streamer 60 below the surface of the water. This ROTV 200 also has a GPS receiver 212 that can obtain GPS readings once the ROTV 200 is brought to the surface.

[0086]   Figure 6B illustrates a plan view of the marine seismic survey system 20 having ROTVs 200 at multiple locations on the streamers 60. In this system, leading ROTVs 200A are towed at the head of the streamers 60, and trailing ROTVs 200B are towed on the end of the streamers 60. The leading ROTVs 200A connect by towlines 62 and streamer cables 65 off the vessel's skeg 50. If desired, even intermediate ROTVs (not shown) may be deployed at intermediate locations along the streamers 60.

[0087]   To achieve three-dimensional (or even 2-D or 4-D) operation, each of the leading ROTVs 200A individually tows a streamer 60. Towlines and streamer cables 62/65 connect the ROTVs 200A to the vessel's skeg 50. During surveying, the position and depth of each ROTV 200A-B can be controlled to maintain an appropriately arranged array of streamers 60 for the seismic survey. In addition, the controlled depth allows the streamers 60 to avoid any ice floes at the surface.

[0088]   Using the ROTVs 200A-B in leading and tailing locations along the streamers 60 can facilitate deployment and retrieval of the streamers 60. Being independent of one another, for example, individual ROTVs 200A-B can guide their streamer 60 down under the other streamers 60 and can bring it up through the middle of the array of streamers 60 in the potentially cleared area behind the vessel 30. The steamer 60 can then be pulled up to the vessel 30 and can avoid the other streamers 60 and towlines 62. This will allow operators to deploy and retrieve the streamers 60 individually and can even allow for repair of a steamer 60 while all of the other streamers 60 remain in the water. Use of a single ROTV 200 on the tail of the streamer 60 as in the system of Figure 6A may also be capable of the same form of deployment and retrieval.

[0089]   Figures 7A-7B show one embodiment of the Remotely Operated Towed Vehicle (ROTV) 200 in more detail. In general, this ROTV 200 is a hybrid type of device incorporating elements of ROVs, AUVs, and gliders. One suitable example for the ROTV 200 is a TRIAXUS Towed Undulator available from MacArtney Underwater Technology Group.

[0090]   For towing the ROTV 200, a tow cable (not shown) having power conductors and communication lines connects to the leading edge 49 of a center foil 227. As shown, the ROTV 200 has four tubulars 210 interconnected in their front section by foils 220/225 and in their trailing section by flaps 230. The foils 220/225 and flaps 230 have a wing shape. Central foils 225 interconnect the leading foils 220 and support the horizontal foil 227 in the front of the ROTV 200. These central foils 225 help keep the ROTV 200 leveled in its roll direction. The trailing flaps 230 are controllable with the upper and lower flaps 230A-B controlling pitch and the right and left flaps 230C-D controlling yaw.

[0091]   Four actuators or motors (not shown) installed in each of the tubulars 210 move these flaps 230A-D to control the pitch and yaw of the ROTV 200 as it is towed. The tubulars 210 have compartments 212 for holding various components besides the motors, gears, and position sensors for the flaps 230A-D. For example, these compartments 212 can have a GPS receiver, an inertial navigation system, a depth sensor, a pitch sensor, a roll sensor, a heading sensor, etc., discussed below.

[0092]   While being towed, the horizontal flaps 230A-B produce up and down

forces to move the ROTV 200 vertically, while the vertical flaps 230C-D

produces starboard and ports force in order to move the ROTV 200 horizontally

(laterally). Typically, the ROTV 200 will be towed in a neutral position with the

flaps 230 being adjusted intermittently to maintain the ROTV 200 as is. Some

situations, such as rising to the surface, will require more aggressive movement of

the flaps, especially when connected to a streamer. Braking for the ROTV 200

can use some of the techniques discussed previously. Additionally or in the

alternative, the flaps 230 can be turned inward or outward to increase the ROTV's

drag while being towed.

[0093]   Figure 8 schematically illustrates elements of a control system 300 for

controlling controllable vehicles (*e.g.,* ROTVs 200) and determining their

locations while being towed in a marine seismic system of the present disclosure.

Vessel components 305 on the vessel 30 include a main control system 310, which

has a main GPS receiver 320 for obtaining GPS readings. As before, this control

system 310 can be an instrumentation control system such as Orca® available from

ION Geophysical. The control system 310 interfaces with (or is integrated with) a

control unit 330, which controls and monitors the various vehicles (*e.g.,* ROTVs)

used for the streamers in the array. An example of a suitable control unit 330 for

an ROTV 200 of Figures 7A-7B is the topside unit used for the TRIAXUS ROTV.

[0094]   Connected by communication and power lines 332, the control unit 330

interfaces with a local controller 350 on a controllable vehicle 340, such as ROTV

200 of Figures 7A-7B, for example, or some other controllable device disclosed

herein. The controller 350 communicates sensor data from the device's sensors

360 to the control unit 330. After interfacing with the navigational information in

the main control system 310, the control unit 330 sends navigational instructions

back to the controller 350, which operates the various fin motors 370

appropriately. Navigating the controllable vehicle 340 can involve both real-time

control and preprogrammed trajectories.

[0095]   The controller 350 communicates with the device's integrated sensors

360 and to the motors 370 for the flaps. The integrated sensors 360 for controlling

the device 340 include a depth sensor, a pitch sensor, a roll sensor, and a heading

sensor. The depth can be measured with a pressure sensor, while pitch and roll can be measure by bi-axial inclinometers. The yaw or heading can be measured using a fluxgate compass, and an altimeter can also be used.

[0096]   In addition to the integrated sensors 360, the controller 350 can connect to position sensors that monitor the motors and flaps to keep track of the positions of these flaps to feedback to the control unit 330. All of these integrated sensors (*i.e.,* pitch, roll, heading, and motor position) provide feedback for the control system 310 to control the flaps to direct the controllable vehicle 340 and keep it from rolling.

[0097]   Aside from these sensors, the controller 350 on the controllable vehicle 340 communicates with a GPS receiver 380. As noted previously, when the controllable vehicle 340 is brought to the surface, the antenna for the GPS receiver 380 can be exposed above the water's surface to obtain GPS readings. Yet, such readings are expected to be intermittently made. Likely, when used in icy or obstructed waters, the controllable vehicle 340 may be towed under ice floes for several continuous hours or even days before it can be resurfaced to obtain GPS readings. Therefore, the controllable vehicle 340 also has an Inertial Navigation System (INS) device 390 used for determining the relative position or location of the controllable vehicle 340 between direct GPS readings with the GPS receiver 380.

[0098]   In general, the INS device 390 can use components known in the art, such as a processor, accelerometers, and gyroscopes, and uses dead reckoning techniques to determine position, orientation, direction, and speed of the controllable vehicle 340 continuously. Depending on how long the controllable vehicle 340 must be dead reckoned in this way, the drift error inherent to the INS device 390's measurement of acceleration and angular velocity becomes increasingly magnified. Accordingly, the navigation is preferably corrected by periodic GPS readings. Even with an error of a fraction of a nautical mile per hour for position and tenths of a degree per hour for orientation, error in the INS device 390's determination can be significant if the controllable vehicle 340 must remain below the surface for extended periods. Discussion below describes a feedback loop that can be used to correct the INS device 390's determination.

4. Control Loop

[0099]   Figure 9 shows an example of a navigational feedback loop 400 for determining the position of a controllable vehicle (*e.g.,* 340; Fig. 8), such as an ROTV, and correcting that position. Initially in the loop 400, the controllable vehicle 340 obtains a direct GPS reading using its GPS receiver 380 (Block 402). This is done while the area above the controllable vehicle 340 is free of ice floes or other obstructions. After the controllable vehicle 340 submerges again, the INS device 390 and control system 310 begin determining the position of controllable vehicle 340 as it is towed (Block 404). This is done by taking the starting location or fix from the GPS reading and measuring direction, speed, and time to calculate the position of the controllable vehicle 340 going forward from that starting position using dead reckoning techniques.

[00100]   Unfortunately, this form of inertial navigation is not precise and drift error accumulates over time. As long as the drift error is low enough, this inertial navigation can continue. At some point, the control system 310 determines whether drift error has exceeded some acceptable range that depends on the implementation (Block 406). If not, then the control system 310 can continue dead reckoning (Block 404) until the drift error is too large.

[00101]   Once the drift error is large (due to a long period of dead reckoning, fast survey speeds, long survey distance, or a combination of the these), the control system 310 seeks to correct the error by either resurfacing the controllable vehicle 340 to obtain a new GPS reading that fixes the device 340's position or by integrating the INS device's dead reckoning with feedback from the vessel's main navigation system. Accordingly, the control system 310 determines from manual input or from the sensors (sonar, ice profiler, fathometer, etc.) on the controllable vehicle 340 whether the device 340 can rise to the surface (Decision 408) to obtain another GPS reading to fix the device's location (Block 402) to repeat the process.

[00102]   If the controllable vehicle 340 cannot surface, then the control system 310 obtains a GPS reading using the on-board GPS receiver 380 of the vessel (Block 410). This GPS reading gives the location of the tow vessel 30. As an additional supplement, the system 310 obtains data from the various in-water

devices (*i.e.,* controllable vehicle 340, streamer, sensors, etc.) (Block 412). This data can be used to determine the relative position of the controllable vehicle 340.

[00103]   For example, Figure 10 shows the marine seismic system 20 having a steamer 60 with cable compasses or sensors 70 positioned thereon for determining the shape of the streamer. Here, the determination uses a GPS reading (x) from the vessel components 305, known sensor locations (Y1-Y5), known controllable vehicle location (Y6) along the streamer 60, and various compass headings from cable compasses 70 or the like. As shown, data about the sensors 70 and controllable vehicle 340 on the streamer 60 (including each of their positions (Y) on the streamer 60, compass headings corrected by declination, and the like) can be used to estimate the location of points on the streamer 60 and derive the streamer's shape. Combined with the vessel's GPS reading (X) using the on-board GPS receiver of the vessel components 305, all of this data can be integrated with the position data from the INS device (390; Figure 9) to correct its drift error and provide more absolute position information about the location of the streamer 60 and its sensors 70 in GPS coordinates or the like.

[00104]   Additionally, acoustic positioning techniques can be used along with the GPS reading using the on-board GPS receiver of the vessel components 305 to correct drift error of the INS device and provide more absolution position information. As shown in Figure 11, for example, different arrangements of acoustic systems for performing acoustic cross-bracing are shown for the system 20. Such acoustic cross-bracing can be used to determine the streamers' positions.

[00105]   Additionally, a short base line can be obtained by using a transducer on the vessel 30 to "ping" an acoustic sensor on the controllable vehicle 340 toward the tail end of the streamer 60 to determine the vehicle's position. Also, a long base line can be obtained by using one or more other transducers on the seabed (a minimum of two transducers are needed for a long base line system) to "ping" a sensor on the controllable vehicle 340 to determine its position. Finally, even the control sensor readings from the controllable vehicle 340 and the movements directed to the controllable vehicle 340 by the vessel components 305 (*i.e.,* control unit 330) can be integrated with the on-board GPS reading (X) to determine the

absolute position of the controllable vehicle 340. These and other techniques available in the art can be used.

[00106]   Regardless of how the INS device's position is integrated with feedback from other navigation components, the vessel components 305 corrects the dead reckoned (relative) position of the controllable vehicle (*See* Block 414 in Figure 9) so the system can continue using the INS device 390 with less drift error. The entire process of dead reckoning and correcting the drift error may continue as long as the controllable vehicle 340 remains submerged below the surface. Eventually, should conditions allow it, the controllable vehicle 340 is directed to the surface to obtain a direct GPS reading to fix its location once again (Block 402 in Figure 9). This new GPS reading provides a new starting point that can then be used for dead reckoning and correcting while the controllable vehicle 340 remains submerged in further surveying.

C. Declination Correction for Marine Seismic Survey

[00107]   As noted previously, position information of streamers 60 in a seismic survey can be obtained using one or more compasses, acoustic measurements, or the like to determine positions of the streamers 60 and their relation to one another. Although reference is made to cable compasses, the teachings of the present disclosure can be used to correct any geomagnetic field measurement device, such as correcting a magnetic heading device to true north. The position measurements can be performed using instruments or sensors mounted in the streamers 60 themselves, and the measurements can be used in standard marine surveys with a closed traverse or in surveys in icy waters with an open traverse. In the end, either form of marine survey may benefit from the correction techniques disclosed herein.

[00108]   As noted previously, measuring instantaneous declination is useful for correcting the magnetically determined positions of the streamers 60 that are obtained from cable compasses or the like. This correction is especially useful at higher latitudes because more magnetic variation may occur at high latitudes due to atmospherics. Finally, ice in the water inhibits the use of tail buoys and limits measurements of GPS readings at the end of the streamers 60 as discussed previously so declination corrections can improve accuracy.

[00109]   As noted above, one way to obtain needed GPS readings at the tail of the streamer 60 involves using floating or tethered buoys (*e.g.,* 82 in Fig. 2A) or involves moving a controllable device to the surface to obtain GPS readings when able (Figs. 2D, 3A-3B, 4, 5, and 6A-6B). Dead-reckoning and inertial navigation can then be used to track the location of the streamers 60 between periodic GPS readings as described with reference to Figures 7A-7B, 8, and 9. Part of these calculations may be based on a declinometer in the controllable device at the tail end of the streamer 60 as described previously with reference to Figures 2B and 4.

[00110]   When used, a declinometer can correct the compass readings of the cable compasses used for positioning the streamers 60. Towing a declinometer behind the vessel 30, such as on the tail end of a streamer 60 or in a controllable device on the streamer 60, positions the declinometer away from the vessel 30. In this position, the declinometer can avoid issues with the vessel's magnetic field. Rather than towing the declinometer at the end of the streamer 60, the declinometer can be towed on its own directly behind the vessel 30, typically at a distance of 2-1/2 times the vessel's length to reduce interference from the vessel's magnetic field.

[00111]   Preferably, the declinometer uses vector-based magnetometers to measure directional components of the earth's magnetic field relative to the magnetometers' spatial orientation. Towing the declinometer on the streamer 60 or behind the vessel 30 moves the magnetometer so continual correction for the magnetometers' spatial orientation using inertial measurements and the like may be required. This is especially true when the magnetometer in the declinometer is a 3-axis strapdown-type of magnetometer as opposed to a scalar-type of magnetometer that measures only total field.

[00112]   In most situations, however, any induced magnetism from the vessel 30 compared to the increased motion of such a towed magnetometer may not be worth the tradeoff so that towing the declinometer behind the vessel 30 is less desirable. For these reasons, the towing vessel 30 may have a declinometer system installed thereon. Being on the vessel 30, however, the declinometer system must compensate for the hard and soft iron effects caused by the vessel 30. The discussion that follows provides details for calibrating and using a

declinometer system on the vessel 30 for performing a marine seismic survey.
Again, the survey may or may not be done in icy or obstructed waters where GPS
readings of the streamers 60 are hard or impossible to obtain on a continual basis.

[00113]   Figures 12A-12B schematically illustrate a control system 500 for a
vessel 30 towing streamers 60. Although the vessel 30 is shown towing one
streamer 60 from a skeg 50 in Figure 12A, more streamers 60 may be used as
represented in Figure 12B. Each streamer 60 has a number of magnetic heading
devices or cable compasses 65 disposed along its length for determining and
controlling the streamer's location during towing. Using a declinometer system
520, the control system 500 obtains declination readings at the vessel 30 and
corrects the readings of the cable compasses 65 spatially and temporally based on
the declination readings. Moreover, the control system 500 can use features of an
instrumentation control system such as Orca® available from ION Geophysical
and can use similar features as discussed previously for controlling the positions
of the streamers 60.

[00114]   The control system 500 has a control unit 510 that controls and monitors
the various streamers 60 in the array as well as other sensors. Although not
illustrated in detail, it will be appreciated that the control unit 510 can use
components known in the art, such as processors, storage devices, memory,
software, user interfaces, and the like.

[00115]   To control the streamers 60, for example, the control unit 510 interfaces
with towed vehicles, controllable devices, fins, vanes, and other components (not
shown) for steering and directing the streamers 60 as disclosed herein and used in
the art. To monitor position and determine declination, the control unit 510
interfaces with the cable compasses 65 on the streamers 60 and interfaces with a
magnetometer 550, an inertial measurement unit 560, and a GPS heading device
570 of the declinometer system 520 on the vessel 30. The GPS heading device
570 obtains GPS readings at the towing vessel 30, and the magnetometer 550
obtains three directional magnetic components and can be a fluxgate
magnetometer, a strapdown-type of magnetometer, or the like. The GPS heading
device 570 can preferably have two GPS receivers (not shown) to obtain GPS

readings and calculate a geodetic bearing according to techniques known and used in the art.

[00116]　The inertial measurement unit 560 obtains three directional components of the vessel's motion. For example, the unit 560 can have a pitch sensor, a roll sensor, and a heading sensor. Pitch and roll can be measured by bi-axial inclinometers. The yaw or heading can be measured using a fluxgate compass, and other devices can also be used.

[00117]　To help illustrate the various orientations used herein, discussion turns to Figures 12C-12D showing geomagnetic and vessel coordinate systems. Figure 12C schematically shows elements of the geomagnetic field for a point in space. The elements include a north component X_e, an east component Y_e, and a vertical component Z_e. From these, a horizontal intensity H, a total intensity F, an inclination angle I, and a declination angle D (measured clockwise from true north to the horizontal component) can be derived.

[00118]　Figure 12D schematically shows a vessel's coordinate system with attitude angles measured relative to geographical north and a horizontal plane. As conventionally done, the vessel's inertial coordinate system has an x-component X_s (measured positive to the bow), a y-component Y_s (measured positive to starboard), and a z-component Z_s (measured positive down to the keel). As the vessel moves, it can have various attitude angles in its coordinate system relative to geographical coordinates. Heading　is measured about the vertical axis (Z_s), while roll　is measured about the longitudinal axis (X_s). Pitch　is measured about the cross axis (Y_s).

[00119]　Coupled to the vessel's motion, the magnetometer 550, which can be a three-axis strapdown-type of magnetometer, measures the geomagnetic field relative to the vessel's spatial orientation. Because of this, the magnetometer's measurements must be unrotated for proper referencing to an absolute coordinate system (i.e., true north, latitude, longitude, etc.) using techniques known in the art.

[00120]　Figure 13 illustrates a general flow diagram of a seismic survey 600 using declination determined at a vessel 30 with the control system 500 of Figures 12A-12B. To conduct the seismic survey, operators initially calibrate the on-board declinometer system 520 on the vessel 30 (Block 602). As described

below, the calibration process allows the control system 500 to account for magnetic effects of the vessel 30 in making magnetometer readings and the like.

[00121]   Once calibration is done, operators start the seismic survey (Block 604). As noted previously, the survey involves the tow vessel 30 towing one or more streamers 60 in an array behind the vessel 30 over an area of interest. Source signals reflect from formation features, and the acoustic sensors on the streamers 60 obtain seismic signals for analysis. To combine all of the data and ultimately image the area of interest, the seismic signals must be correlated to information about the location of the sensors on the streamer 60 and the time when signals are received during the survey. This can use many of the known techniques for marine seismic surveying.

[00122]   As is customary during the marine seismic survey, the control unit 510 obtains compass readings from the streamers' cable compasses 65 (Block 608) and obtains GPS readings from one or more GPS receivers. For example, the various cable compasses 65 on the streamers 60 obtain compass readings at points along the streamers 60, and the GPS receiver 570 on the tow vessel 30 obtains GPS readings of the vessel's location. If possible, GPS receivers (not shown) on tail buoys or other controllable devices towed on the streamers 60 can also obtain GPS readings, although this may be intermittent as discussed previously.

[00123]   The readings from the cable compasses 65 are then corrected for current declination, which can be accounted for using the calibration and calculation techniques described in more detail below (Block 610). Briefly, raw compass readings from the streamer's compasses 65 are typically stored without being corrected for current declination determined at the vessel 30. To make this correction, the control unit 510 determines differences in a first geodetic heading derived using GPS data from the GPS heading device 570 versus a second geodetic heading derived using the 3-component magnetometer data of the magnetometer 550. From this, the control unit 510 computes a magnetic declination. Additionally, the control unit 510 applies motion compensation from the 3-component inertial measurement unit 560 to the magnetic declination. The magnetic declination can then be applied to the raw compass readings from the

compasses 65, and the resulting data can be stored as corrected compass readings in the system's database 542.

[00124]   Using navigating software and knowing the arrangement of the streamers 60, spacing of the sensors and compass readings, cross-bracing determinations, and the like, the control unit 510 can control the location of the streamers 60 as desired for the survey (Block 612). All of the relevant data on the streamers' locations, acoustic sensor readings from the steamers 60, compass readings, GPS readings, declination, and the like can then be stored in the database 542 for later processing and analysis common to marine seismic surveying so that the area of interest can be imaged.

[00125]   Given this general overview of a seismic survey that determines declination with a declination system 520 on the vessel 30, discussion now turns to particulars involved in calibrating the vessel's declination system 520 to determine and use declination to correct compass readings on the streamers 60.

1. Calibration Techniques

[00126]   Before correct magnetic declination can be determined with the control unit 510 on the towing vessel 30, various calibrations steps must be performed. In one calibration, the control unit 510 calibrates for hard and soft iron effects by simultaneously solving the 3D hard and soft iron effects of the steel towing vessel 30 on the various data readings obtained with the devices 550, 560, and 570 on the vessel 30.

[00127]   To do this, the control unit 510 is calibrated for induced magnetization to compensate for the induced magnetic forces caused by the vessel's orientation within the earth's magnetic field. This calibration uses a Fourier series deviation curve. Additionally, the control unit 510 performs interpolated infield referencing from remote base stations or observatories to estimate the correct magnetic declination at the calibration location. Here, the control unit 510 uses data from base stations situated some distance away from the calibration location. Each of these calibration steps is described in detail below.

a. Calibration Processes

[00128]   Calibrating for hard and soft iron effects from the tow vessel 30 with the control unit 510 is based on the known characteristics of the earth's magnetic field

and the ferromagnetism of the steel vessel 30. As is known, the earth's geomagnetic field has a magnitude, an inclination with respect to horizontal, and a declination with respect to true north. These field components can be decomposed into the geometrical components of M_x, M_y, and M_z, which can be obtained with the system's magnetometer 550. These components correspond to the typical coordinate system or frame convention for magnetometers. This frame convention is often referred to as NED, in which the X-axis points North in the horizontal, the Y-axis points East in the horizontal, and the Z-axis point down vertically.

[00129]   The earth's total magnetic field (B) at a particular location comprises the sum of three physical components: the main field (B_m) in the core of the earth, the crustal field (B_c) near the crust's surface, and the most variable atmospheric field (B_d). These three fields B_m, B_c and B_d are accounted for during calibration of the declinometer.

[00130]   The vector of the earth's magnetic field B has components defined in a geodetic coordinate system. As noted previously in Figure 12D, the geodetic coordinate system for the earth's geomagnetic field has an x-component X_e (measured positive to the north), a y-component Y_e (measured positive to the east), and a z-component Z_e (measure positive down towards the center of the earth). The main field (B_m) is the largest component of the total magnetic field (B), comprising about 98%, and it can be predicted with a number of models. Some typical models include International Geomagnetic Reference Field (IGRF), World Magnetic Model (WMM), Enhanced Magnetic Model (EMM), and BGS Global Geomagnetic Model (BGGM). One or more of these models are used in the calibration procedure outlined below.

[00131]   For its part, the crustal field (B_c) can only be known through local magnetic surveys, which in most cases would not be available. This can be dealt with by calibrating in the water as deep as possible to minimize B_c. The variable atmospheric field (B_d) can be estimated by interpolation from the data provided by magnetic observatories established in the region being surveyed. Such observatories are strategically located around the world and data from them can be used to estimate the variable atmospheric field (B_d) in the region of interest.

[00132] Two types of ferromagnetism are of interest in the calibration of the system 500. First, the towing vessel 30 is constructed of iron while in the magnetic field of the earth so that the vessel 30 acquires remnant or permanent magnetism during the physical process of its construction. This ferromagnetism is called "hard iron" magnetism and is constantly aligned with the vessel 30 even as its orientation changes. Thus, as the magnetometer 550 obtains readings, the hard iron magnetism of the vessel 30 constantly adds to the output of each axis of the magnetometer 550.

[00133] The second type of ferromagnetism of interest is induced magnetism created by the interaction of the earth's magnetic field and the iron of the vessel 30. This induced magnetism is called "soft iron" magnetism, and it varies (fluctuates) as the vessel 30 changes orientation in the earth's magnetic field. Computing the soft iron effects is more intensive than hard iron effects and involves determining an angle (phi) at which the horizontal magnetometer readings M_x/M_y are rotated in the horizontal. The computing also involves determining a ratio (R) of major to minor axes in the deviated, horizontal magnetometer readings M_x/M_y. When combined, the angle (phi) and the ratio (R) compensate for induced magnetism (soft iron) in the horizontal plane. Particular equations for indentifying the angle, magnitude of the major axis, rotation matrices, and scale factor for the major axis are known in the art and are not restated in fine detailed herein for the sake of brevity.

[00134] Both of these types of ferromagnetisms have effects in both the horizontal planes (M_x, M_y) and the vertical plane (M_z). Therefore, the calibration process preferably compensates for the hard and soft iron magnetism in both the horizontal and the vertical planes to determine correction parameters.

b. Flow Chart

[00135] Figure 14 shows a calibration process 630 in flow chart form, which can be implemented as software or the like in a programmable processor of a control unit as disclosed herein. The calibration process 630 solves for an azimuth of the declinometer system 520 with respect to magnetic north. To do this, the process 630 uses rotated, compensated components of an observed magnetic field obtained by magnetometer readings (M_x, M_y and M_z) as the vessel 30 traverses a calibration pattern. The magnetic azimuth from this observed magnetic field is

then compared to the azimuth obtained with the GPS/IMU devices 560/570 with respect to true north, which gives a declination for correcting the various compass readings on the streamers 60.

[00136]   Initially, operators perform a calibration run with the vessel 30 to calibrate the declinometer system 520 (Block 632). Here, the vessel 30 is sailed in a circular pattern so that the vessel's heading passes through all azimuths, where azimuth refers to the angle in a horizontal plane measured clockwise from a north bearing. Two patterns 620/625 for the vessel 30 can be used as shown in Figures 15A-15B. As the vessel 30 sails the pattern 620/625, the control system 510 records calibration data, including GPS/IMU heading, pitch and roll from the inertial measurement unit 560; the 3-axis readings of M_x, M_y and M_z from the magnetometer 550; the GPS readings of latitude and longitude from the GPS receiver 570; and time stamps for each of the preceding data (Block 634). This calibration data is then stored for processing as detailed below to derive parameters for correcting future readings (Block 636).

[00137]   For the calibration, the control unit 510 rotates the raw magnetometer data to horizontal using the GPS/IMU data obtained (Block 638). Once this is done, various calculations are performed to find calibration parameters that can be used to correct compass readings and seismic data based on changes in declination experienced during a seismic survey. As part of these calculations, the control unit 510 determines calibration parameters for hard and soft iron effect in the vertical orientation (Block 640) and in the horizontal orientation (Block 642).

[00138]   With the calibration parameters calculated, the control unit 510 also performs calculations that can compensate for atmospheric difference in the earth's magnetic field (Block 644). This can be done using infield referencing of data from surrounding observatories as explained in more detail later. In the end, once calibration is done, the control unit 510 can use the calibration parameters for data acquisition and processing for the streamer compasses to account for changes in declination when performing or analyzing a seismic survey (Block 646).

c. First Calibration Stage

[00139]   With an understanding of the overall calibration process 630 described above, discussion now turns to Figure 16A, which shows a first calibration stage 650 in more detail. (The steps of the stage 650 can be implemented as software or the like in a programmable processor of a control unit as disclosed herein.) After the vessel 30 traverses the pattern (620/625 of Figs. 15A-15B) and obtains readings in all azimuths as noted previously, the control unit 510 first rotates the raw magnetometer data (M_x, M_y, M_z) from the magnetometer 550 to horizontal using the pitch and roll obtained from the inertial measurement unit 560 (Block 652). To do this, a rotation is applied to the magnetometer data to remove the roll (i.e., bank angle between Y-axis and horizontal), and another rotation is applied to remove the pitch (*i.e.,* elevation angle between the X-axis and horizontal). This rotation aligns the local x-y horizontal plane with a reference X-Y horizontal plane and can use rotation matrices and calculations known in the art.

[00140]   After this, the control unit 510 solves for the rotated vertical M_z component as a function of GPS/IMU azimuth using a fourth-order Fourier-series deviation curve and least squares. This curve fitting determines vertical soft iron parameters (9 coefficients) to compensate for soft iron effects in the vertical plane (Block 654).

[00141]   Figure 17 graphically illustrates this step to solve for the rotated vertical component M_z as function of the azimuth from the GSP/IMU readings using a fourth-order Fourier-series deviation curve and least squares. Here, the raw vertical component M_z is shown as line 680, and the rotated vertical component M_z is shown as line 682. The solved curve for the rotated vertical component M_z is shown as line 684 with the nano-Teslas of the rotated vertical component M_z graphed as a function of IMU azimuth from the inertial measurement unit 560. As a result of these steps, the calibration process 630 obtains parameters to compensate for the induced magnetism (soft iron effects) in the vertical caused by the vessel 30. The vertical soft iron parameters come from the nine coefficients of the Fourier series of the best-fit line 684.

[00142]   Returning now to Figure 16A, the control unit 510 iterates over several steps (Blocks 656 to 665) after solving the vertical soft iron parameters to then

determine parameters for compensating for remnant magnetism (hard iron effects) in the vertical.

[00143] While iterating over a sequence of vertical adjustment factors M_{z0adj} and for every data point in the calibration circle traversed by the vessel 30, the process solves for M_{z0} = Fourier (a function of azimuth) minus the adjustment factor M_{z0adj} and divides M_{z0} by cos(pitch)*cos(roll) (Block 636). (In the calculations, M_{z0adj} represents the value of the remnant magnetization in the vertical that minimizes the standard deviation (SD) of the horizontal ellipse (M_h) in nanoTeslas). This operation essentially "unrotates" the vertical azimuth M_{z0} to the vessel's orientation. Additionally, the absolute value of unrotated vertical azimuth M_z is decreased by unrotated azimuth M_{z0}. The decrease in M_z alters the rotated M_x and M_y components. Therefore, the control unit 510 rotates the magnetometer data (raw M_x, raw M_y, decreased M_z) to horizontal with pitch and roll obtained from the inertial measurement unit 560 (Block 638).

[00144] The horizontal magnetometer components M_x and M_y form a horizontal field component. When graphed in the horizontal plane of M_x as a function of M_y, the horizontal field component of the observed magnetic field is characterized as an ellipse. In the calibration, the horizontal component should be "circular" if it has not been distorted by soft and hard iron effects from the vessel 30. Because the magnetometer data has been distorted, however, the horizontal component of the observed magnetic field has been altered and has an offset, rotated, and elliptical shape when graphed in a horizontal plane of M_x and M_y. By understanding how the horizontal field's ellipse M_h is distorted from an ideal circular shape, various parameters describing the soft and hard iron effects of the vessel 30 on the magnetometer readings in the horizontal plane can be determined.

[00145] Once the magnetometer data is rotated (Block 658), the control unit 510 solves for the parameters of the horizontal field's ellipse M_h simultaneously by least squares (Block 640). Doing this involves solving for two translations (X_0 and Y_0), an orientation angle (phi), and a ratio (R) of the major to minor axes of the ellipse M_h by which the ideal shape for the magnetometer readings has been distorted in the actual magnetometer data obtained.

[00146] The translation X_0 is the translation in the X-direction of the horizontal field, and the translation Y_0 is the translation in the Y-direction of the horizontal field. These two translations (X_0 and Y_0) compensate for remnant magnetism (hard iron) in the horizontal. In essence, these translations (X_0 and Y_0) indicate what offsets to apply to the horizontal field's ellipse M_h after correction for pitch and roll to compensate for the hard-iron's offsetting effects in the horizontal plane. The angle (phi) is the angular orientation of the horizontal field's ellipse M_h in the horizontal, and the ratio (R) is a ratio of the major to minor axes of the horizontal field's ellipse M_h. When combined, both the angle (phi) and the ratio (R) compensate for induced magnetism (soft iron) in the horizontal plane.

[00147] Then, the process translates and "circles" the horizontal field's ellipse M_h—*i.e.,* the process finds what parameters would make the horizontal field's ellipse M_h conform to the ideal circular shape if the magnetometer's data was not subject to distortions from the soft and hard iron effects (Block 642). Here, the process iteratively solves for parameters that define the distortion of the hard and soft iron effects on the magnetometer data by choosing an adjustment factor M_{z0adj} value that minimizes the standard deviation (SD) of the horizontal field (M_h) from the ideal.

[00148] In particular, the process solves for the translations (X_0 and Y_0) that shift the horizontal field's ellipse M_h to (0,0) in the M_x/M_y horizontal plane. The process also solves for the angle (phi) that rotates the horizontal field's ellipse M_h so the process can solve for the ratio (R) of the major and minor axis to increase the minor axis to make the ellipse circular. Once the ratio is determined, the process can then rotate the horizontal field's ellipse M_h back by the angle (*i.e.,* − phi) to restore this orientation.

[00149] At this point in the iterative process of Figure 16A, the control unit 510 computes the standard deviation for all data points based on the parameters that have been used for the current iteration of the solution (Block 664). In particular, for all data points, the control unit 510 computes the standard deviation (SD) of the horizontal field's ellipse M_h as the square root of $(M_x^2 + M_y^2)$. Then, the control unit 510 chooses the M_{z0adj} adjustment factor that minimizes the standard deviation (SD) of horizontal field's ellipse M_h from the ideal circular shape (Block

665). This value of the M_{z0adj} adjustment factor is associated with the specific parameters of the translations (X_0, Y_0), rotation angle (phi), and axis ratio (R). There are also nine coefficients of the Fourier series for the vertical component M_z. The process then repeats as needed until an optimized declination value is computed for the declination at the location (Block 666).

[00150] Figure 18 graphically illustrates these steps. The raw horizontal magnetometer readings M_x, M_y are shown by horizontal field's ellipse 690, and the pitch and roll data from the inertial measurement unit 560 is shown by circle 692. If no distortion were present, the magnetometer's horizontal readings M_x, M_y if turned through 360° would plot as a circle in the horizontal M_x/M_y plane centered around (0, 0). Of course, external magnetic influences from hard or soft-iron effects distort the magnetometer 550's readings M_x, M_y from the ideal. In general, hard-iron effects cause the magnetometer's readings M_x, M_y to offset from the center (0, 0). Thus, the raw magnetometer readings M_x, M_y are shown as ellipse 690 offset from the center. For its part, the soft-iron effects warp the ideal circle of the readings M_x, M_y into a more elliptical shape. Therefore, the raw magnetometer readings M_x, M_y are shown by the ellipse 690. Naturally, as both effects can exist concurrently, the resulting readings M_x, M_y in the ellipse 690 exhibits both disturbances.

[00151] In the calibration calculations, the raw magnetometer data (690) is rotated to horizontal using the pitch and roll data (692) from the IMU device 660. To do this, the steps use translations to shift the ellipse (690) of the raw magnetometer data to (0,0) in the horizontal Mx/My plane and to rotate the ellipse (690) by the angle (phi). The steps also increase the minor axis b of the ellipse (690) by a particular ratio (R) (thus "circling" the ellipse), and rotates the ellipse (690) back by the angle (phi). Finally, the steps solve for the least squares, which is represented by the circle (696). The standard deviation (SD) described previously is represented here as the difference between circle (694 and 696).

d. Second Stage of the Calibration Process

[00152] The first calibration stage 660 in Figure 16A is sufficient to solve for an azimuth with respect to magnetic north. However, the first stage 660 does not compensate for the earth's atmospheric magnetic variation B_d. To accomplish

this, a second calibration stage is performed as shown in Figure 16B that interpolates magnetic observatory data using infield referencing to estimate declination during calibration. The steps of the stage 650 can be implemented as software or the like in a programmable processor of a control unit as disclosed herein.

[00153] Here, the control unit 510 obtains the 3-component magnetometer data for the day of the calibration from one or more regional magnetic observatories (Block 670). Using a magnetic model (e.g., Enhanced Magnetic Model (EMM) or the like), the predicted declinations for the observatories (670) are then known. For a given calibration location or survey area, several observatories (670) may be available relative to the calibration site for this process.

[00154] The control unit 510 subtracts the computed declination (668) from the interpolated observatory declinations (670) (Block 672). Figure 16C schematically illustrates a vessel 30 in a survey area relative to observatory stations 670. For each of the observatories (670), for example, a time series of a delta-declination can be obtained where the delta declination is the observed declination at the observatory (670) minus the predicted declination for the day. Weighting based on distance from the calibration site (i.e., vessel 30) to the observatories (670) and based on relative strengths of their horizontal magnetic fields, the calibration process interpolates a delta-declination time series for the calibration site (Block 674).

[00155] Figure 19 graphically illustrates these steps. Delta-declination plots for four observatories are shown by lines 695_{1-4}. Weighting based on distance from the calibration site (vessel 30) to the observatories (670) and based on relative strengths of their horizontal magnetic fields, the process interpolates a delta-declination time series for the calibration site, which is represented by line 697.

[00156] The second calibration stage in Figure 16B then adds this interpolated delta declination (670) to the predicted declination from the model to produce a time series of declination at the calibration site. As functions of time and magnetic azimuth of the vessel 30, the declinations computed above are then subtracted from the observatory time series to provide a declination adjustment as a function of azimuth (Block 672). This adjustment is solved as a function of

magnetic azimuth with a fourth-order Fourier-series deviation curve (also called a "deviation curve") using least squares (Block 674). The result is nine coefficients of the Fourier series for the declination adjustment, which compensate for atmospheric variation in declination at the time and place of the calibration.

[00157]   Finally, after the calibration calculation, the control unit 510 sends the various declination parameters to be used in processing of data acquired during surveying (Block 676). The parameters include:

- the soft iron parameters—*i.e.,* the 9 coefficients of the Fourier series for vertical component M_z that compensate for induced magnetism (soft iron) in the vertical;

- the hard iron parameters—*i.e.,* the M_{z0adj} adjustment factor, which in combination with Fourier series for the vertical component M_z (above) forms the component M_{z0} to compensate for remnant magnetism (hard iron) in the vertical;

- the translation matrix X_0 for translating in the X direction of the horizontal field;

- the translation matrix Y_0 for translating in the Y direction of the horizontal field, which with X_0 compensates for remnant magnetism (hard iron) in the horizontal;

- the orientation angle (phi) that the horizontal field's ellipse M_h of the magnetometer data has in the horizontal;

- the ratio (R) of the major to minor axes that the horizontal field's ellipse M_h has, which with the angle (phi) compensates for induced magnetism (soft iron) in the horizontal; and

- the nine coefficients of the Fourier series for the declination adjustment (also called a "deviation curve"), which compensates for atmospheric variation in declination at the time and place of the calibration.

2. Processing Flow

[00158]   Having the calibration parameters, the control unit 510 can then process declination data at the vessel 30 to correct the compass readings for current declination. Figure 20 diagrams this processing in flow chart form and uses many of the same steps as outline previously. As before, the processing can be

implemented as software or the like in a programmable processor of a control unit as disclosed herein. Here, the processing uses the previous declination parameters determined through calibration to determine a correct magnetic declination of cable compasses and sensors and to report to the control system's navigation components.

[00159]   Initially, the control unit 510 computes M_{zF} from the raw azimuth M_z, M_{z0adj}, heading, pitch, roll and nine Fourier coefficients of the vertical soft iron parameters (Block 702) and rotates M_x, M_y, M_{zF} to horizontal with pitch and roll (Block 704). The unit 510 translates the horizontal components M_x/M_y (*i.e.,* the horizontal field's ellipse M_h) to (0,0) with the transformations X_0 and Y_0 (Block 706) and circles the horizontal field's ellipse M_h with the previously determined angle (phi) and ratio (R) (Block 708). The control unit 510 then computes the magnetic azimuth from M_x and M_y (Block 710) and computes the declination from the magnetic azimuth and the GPS/IMU heading (Block 712).

[00160]   To finish the second part of the process and account for magnetic atmospheric variations B_d, the control unit 510 computes the delta-declination from magnetic azimuth and the nine Fourier coefficients for the atmospheric correction (Block 714). Finally, the control unit 510 corrects magnetic declination with delta-declination and reports the result to the navigation system for controlling the streamers 60 and for recording for later processing in correcting the cable compass readings as detailed herein (Block 716).

D. Declination Correction for Land-Based Seismic Survey

[00161]   As disclosed herein, the declination system can be used in marine seismic surveys, and especially in surveys where it is impractical to attach tail buoys to the end of streamer cables, such as in ice covered areas, in congested areas, and in applications where the cable is towed too deep for practical connection to a tail buoy (deep tow geometry, slanted cable geometry, etc). However, the declination system can be used in other situations. In general, the disclosed system can be used in marine seismic surveys where additional precision is required from the compasses or other magnetic heading sensors, even though there may be no hindrance to having a tail buoy for obtaining GPS readings in a closed traverse. The disclosed system can also be used in marine

seismic surveys where the survey crosses a wide expanse in which magnetic declination is expected to change or where environmental conditions indicate fluctuations in declination.

[00162]   Rather than marine applications, the declination system can further be used in multi-component land surveys where the main orientation sensor is a compass or other magnetic heading sensor and can be used at times when the earth's magnetic field is in a state of extreme change either spatially or temporally over time (e.g., at arctic latitudes or during solar storms). Thus, the disclosed system can be used in seismic data acquisition to measure the real-time magnetic declination of a particular area. Moreover, the disclosed system can be used in both land and marine seismic surveys to be applied to any magnetic heading device for correction to true north and can be used to compensate for the magnetic influence of a marine-based or land-based device, such as a steel platform, a vessel, a vehicle, or the like. In one example, rather than a marine-based vessel, a land-based vehicle can have a magnetometer, navigation device, and controller comparable to those disclosed above for marine surveying albeit for land surveying.

[00163]   As another example, Figure 21 schematically shows a plan view of a land-based seismic survey system 800 having a source 810, a plurality of sensors 820, and a central controller 830. Spaced in array to measure geophysical information, the sensors 820 can use 3-component sensors for obtaining 3-dimensional energy known as 3D seismic and can include accelerometers, velocity geophones, microphones, or the like. In use, the seismic source 810 imparts acoustic energy into the ground, and the sensors 820 receive energy after reflection and refraction at boundaries in subsurface structures. The central controller 830 receives the seismic information and processes it so image information can be generated.

[00164]   As shown, various isogonic lines of the geomagnetic field's declination may pass through the survey area. These isogonic lines are typically expressed in degrees for correcting compass readings to true north. The degrees of the isogonic lines change over the geographic location and also change over time. Therefore, geomagnetic field measurements from compasses or the like associated with each

of the sensors 820 may have errors due to fluctuations in declination. For this reason, the system 800 uses the techniques disclosed herein for obtaining the declination both temporally and spatially for the various sensor locations so the associated geomagnetic field measurements can be corrected and the corrected measurements can provide better correlated information for imaging.

[00165] As also shown, declination at the sensors 820 can be determined by interpolation from one or more remote base stations S1-S2 so that spatial and temporal corrections for declinations can be calculated for the various sensor locations using infield referencing as detailed previously. Additionally or in the alternative, declination at the sensors 820 can be individually calculated using a declination system and techniques as disclosed herein so that individual geomagnetic readings at the different sensor locations can be corrected in real time for declination.

[00166] The techniques of the present disclosure can be implemented in digital electronic circuitry, or in computer hardware, firmware, software, or in combinations of these. Apparatus for practicing the disclosed techniques can be implemented in a computer program product tangibly embodied in a machine-readable storage device for execution by a programmable processor; and method steps of the disclosed techniques can be performed by a programmable processor executing a program of instructions to perform functions of the disclosed techniques by operating on input data and generating output. Suitable processors include, by way of example, both general and special purpose microprocessors. Generally, the processor receives instructions and data from a read-only memory and/or a random access memory, including magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and optical disks. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM disks. Any of the foregoing can be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

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[00167]   The foregoing description of preferred and other embodiments is not intended to limit or restrict the scope or applicability of the inventive concepts conceived of by the Applicants. The teachings of the present disclosure can apply to 2-D, 3-D, and 4-D seismic surveying in icy or obstructed waters, as well under normal marine seismic conditions. Although described for offshore use, the magnetic declination correction to true north disclosed herein can be used in both land and marine seismic surveys. Moreover, aspects and techniques discussed in conjunction with one particular embodiment, implementation, or arrangement disclosed herein can be used or combined with aspect and techniques discussed in others disclosed herein. In exchange for disclosing the inventive concepts contained herein, the Applicants desire all patent rights afforded by the appended claims. Therefore, it is intended that the appended claims include all modifications and alterations to the full extent that they come within the scope of the following claims or the equivalents thereof.

WHAT IS CLAIMED IS:

1.   A seismic survey method, comprising:

obtaining one or more seismic signals with one or more seismic sensors in
        a survey area;

obtaining one or more local geomagnetic field measurements relative to
        the one or more seismic sensors;

measuring temporal and spatial declination parameters;

correcting the one or more local geomagnetic field measurements based on
        the declination parameters; and

correlating the one or more corrected geomagnetic field measurements
        with the one or more seismic signals.

2.   The method of claim 1, wherein the seismic survey is a land-based or a
marine-based seismic survey.

3.   The method of claim 1, wherein measuring the temporal and spatial
declination parameters comprises obtaining one or more base geomagnetic field
measurements from one or more base locations and interpolating the temporal and
spatial declination parameters based thereon.

4.   The method of claim 3, wherein the one or more base locations are
spatially separate from the one or more local geomagnetic field measurements,
and wherein the one or more base geomagnetic field measurements are obtained
over time.

5.   The method of claim 1, wherein obtaining the one or more seismic signals
with the one or more seismic sensors comprises towing at least one streamer
having the one or more seismic sensors behind a vessel.

6.   The method of claim 5, wherein measuring the temporal and spatial
declination parameters comprises obtaining global positioning system

measurements of the vessel and determining a geodetic bearing of the vessel therefrom.

7.   The method of claim 5, wherein obtaining the one or more geomagnetic field measurements relative to the one or more seismic sensors comprises obtaining one or more compass readings on the at least one streamer.

8.   The method of claim 5, wherein measuring the temporal and spatial declination parameters comprises measuring declination at the vessel over time during the seismic survey.

9.   The method of claim 8, wherein measuring declination at the vessel comprises calibrating a declinometer on the vessel by traversing a calibration pattern with the declinometer in the survey area.

10.   The method of claim 9, wherein calibrating the declinometer on the vessel comprises supplementing the calibration with one or more predicted declinations of the survey area interpolated from one or more base stations.

11.   The method of claim 8, wherein measuring declination at the vessel comprises compensating for at least one iron effect of the vessel on the one or more local geomagnetic field measurements.

12.   The method of claim 11, wherein compensating comprises compensating for soft and hard iron parameters of the vessel for vertical and horizontal planes in the geomagnetic field.

13.   The method of claim 12, wherein compensating for soft and hard iron parameters of the vessel for vertical and horizontal planes in the geomagnetic field comprises
simultaneously solving for soft and hard iron parameters in a least-squares adjustment.

14.   The method of claim 5, further comprising:

at least intermittently tracking an absolute position of the at least one
streamer; and

correlating the one or more corrected geomagnetic field measurements
with the absolute position.

15.   The method of claim 14, wherein at least intermittently tracking the
absolute position of the at least one streamer comprising intermittently—

bringing a device on the at least one streamer toward the surface, and

obtaining absolute position information of the at least one streamer with
the device while brought toward the surface.

16.   The method of claim 15, wherein tracking the absolute position of the at
least one streamer comprises:

obtaining relative position information of the at least one streamer while
towed under the surface of the water; and

determining the absolute position of the at least one streamer using the
relative position information and the intermittently obtained
absolute position information.

17.   A programmable storage device having program instructions stored
thereon for causing a programmable control device to perform a method of ice
threat monitoring method for a target marine structure according to claim 1.

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18.   A seismic data acquisition apparatus, comprising:

at least one seismic sensor measuring one or more seismic signals in a

survey area;

at least one geomagnetic heading device associated with the at least one

seismic sensor and making one or more local geomagnetic field

measurements;

at least one magnetometer;

a controller operatively coupled to the at least one seismic sensor, the at

least one geomagnetic heading device, and the at least one

magnetometer, the controller configured to:

determine temporal and spatial declination parameters from

measurements with the at least one magnetometer;

correct the one or more local geomagnetic field measurements

based on the declination parameters; and

correlate the one or more corrected geomagnetic field

measurements with the one or more seismic signals.

19.   The apparatus of claim 18, wherein the apparatus comprises a land-based
device for performing a land-based seismic survey.

20.   The apparatus of claim 18, wherein the apparatus comprises a marine-
based device for performing a marine-based seismic survey.

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21. A vessel declinometer calibration method, comprising:

traversing a pattern in the geomagnetic field with the vessel;

obtaining a plurality of magnetometer measurements while traversing the

pattern;

obtaining a plurality of heading measurements while traversing the pattern;

computing a declination in the geomagnetic field using the magnetometer

measurements and the heading measurements;

calibrating for soft and hard iron effects of the vessel by simultaneously

solving for soft and hard iron parameters in a least-squares

adjustment; and

correcting the computed declination based on the soft and hard iron

parameters.

10

| OBTAIN SEISMIC SIGNALS |
12

| OBTAIN LOCAL GEOMAGNETIC FIELD
MEASUREMENTS RELATIVE TO SEISMIC SENSORS |
14

| CORRECT THE LOCAL GEOMAGNETIC FIELD
MEASUREMENTS BASED ON SPATIAL DECLINATION PARAMETERS |
16

| CORRECT THE LOCAL GEOMAGNETIC FIELD
MEASUREMENTS BASED ON TEMPORAL DECLINATION PARAMETERS |
17

| CORRELATE THE CORRECTED MEASUREMENT
WITH SEISMIC SIGNALS |
18

FIG. 1

FIG. 2A

FIG. 2B

FIG. 2C

FIG. 2D

FIG. 3A

FIG. 3B

FIG. 4

FIG. 5

FIG. 6A

FIG. 6B

6/17

FIG. 7A

FIG. 7B

FIG. 8

400

┌───┐ ⌐402
│ OBTAIN DIRECT GPS READING WITH GPS RECEIVER ON │
│   CONTROL DEVICE WHILE AT SURFACE   │
└───┘

┌───┐ ⌐404
│   DEAD RECKON POSITION OF CONTROL DEVICE   │
│   WHILE SUBMERGED   │
└───┘

DRIFT
ERROR THRESHOLD   ⌐406
EXCEEDED   NO
?

YES

CONTROL
DEVICE CAN SURFACE   ⌐408   YES
?

NO

┌───┐ ⌐410
│   OBTAIN GPS READING WITH ON-BOARD GPS   │
│   RECEIVER   │
└───┘

┌───┐ ⌐412
│   OBTAIN DATA FOR IN-WATER DEVICES   │
└───┘

┌───┐ ⌐414
│ CORRECT DEAD RECKONED POSITION OF CONTROL   │
│ DEVICE USING GPS READING AND OBTAINED DATA   │
└───┘

FIG. 9

FIG. 10

FIG. 11

FIG. 12A

FIG. 12B

FIG. 12C

FIG. 12D

600

602

CALIBRATE DECLINOMETER
READINGS

604

START SEISMIC SURVEY

606

OBTAIN CABLE COMPASS
READINGS

608

OBTAIN GPS/COMPASS
READINGS

610

CORRECT COMPASS
READINGS FOR DECLINATION

612

CONTROL AND MONITOR
STREAMER LOCATIONS

614

STORE DATA

FIG. 13

630

632

PERFORM CALIBRATION RUN

634

OBTAIN MAGNETOMETER READINGS AND GPS/IMU
READINGS DURING RUN

636

STORE RAW MAGNETOMETER DATA AND GPS/IMU DATA

638

ROTATE RAW MAGNETOMETER DATA TO HORIZONTAL
WITH GPS/IMU DATA

640

DETERMINE CALIBRATION PARAMETERS FOR HARD AND
SOFT IRON EFFECTS IN VERTICAL

642

DETERMINE CALIBRATION PARAMETERS FOR HARD AND
SOFT IRON EFFECTS IN HORIZONTAL

644

COMPENSATE FOR ATMOSPHERIC DIFFERENCES IN
MAGNETIC FIELD

646

USE CALIBRATION PARAMETERS FOR DATA ACQUISITION
AND PROCESSING OF STREAMER COMPASSES

FIG. 14

620

FIG. 15A

625

FIG. 15B

Calibration Flow Chart

650

| MAGNETOMETER MX, MY, MZ | — 550 |

| GPS/IMU HEADING, PITCH, ROLL | — 560,570 |

| ROTATION TO HORIZONTAL | — 652 |

| FOURIER OF MZ VERSUS HEADING | — 654 |

| MZ=MZ-(FOURIER–MZ0ADJ)/COS(PITCH)/COS(ROLL) | — 656 |

| ROTATION TO HORIZONTAL | — 658 |

| ITERATE ON MZ0ADJ UNTIL SD MINIMUM | 665 |

| SOLVE X0, Y0, PHI, RATIO | — 660 |

| TRANSLATE, CIRCLE MH ELLIPSE | — 662 |

| COMPUTE SD OF MH | — 664 |

| COMPUTE DECLINATION | — 666 |

FIG. 16A

FIG. 16C

FIG. 16B

FIG. 17

FIG. 18

FIG. 19

16/17
Processing Flow Chart

700

COMPUTE MZF FROM MZ, MZ0ADJ, HEADING, PITCH, ROLL AND 9 FOURIER COEFFICIENTS — 702

ROTATE MX, MY, MZF TO HORIZONTAL WITH PITCH AND ROLL — 704

TRANSLATE MX/MY TO (0,0) WITH X0/Y0 — 706

CIRCLE MX/MY (MH) ELLIPSE WITH PHI AND RATIO — 708

COMPUTE MAGNETIC AZIMUTH FROM MX & MY — 710

COMPUTE DECLINATION FROM MAGNETIC AZIMUTH AND GPS/IMU HEADING — 712

COMPUTE Δ DECLINATION FROM MAGNETIC AZIMUTH AND 9 FOURIER COEFFICIENTS — 714

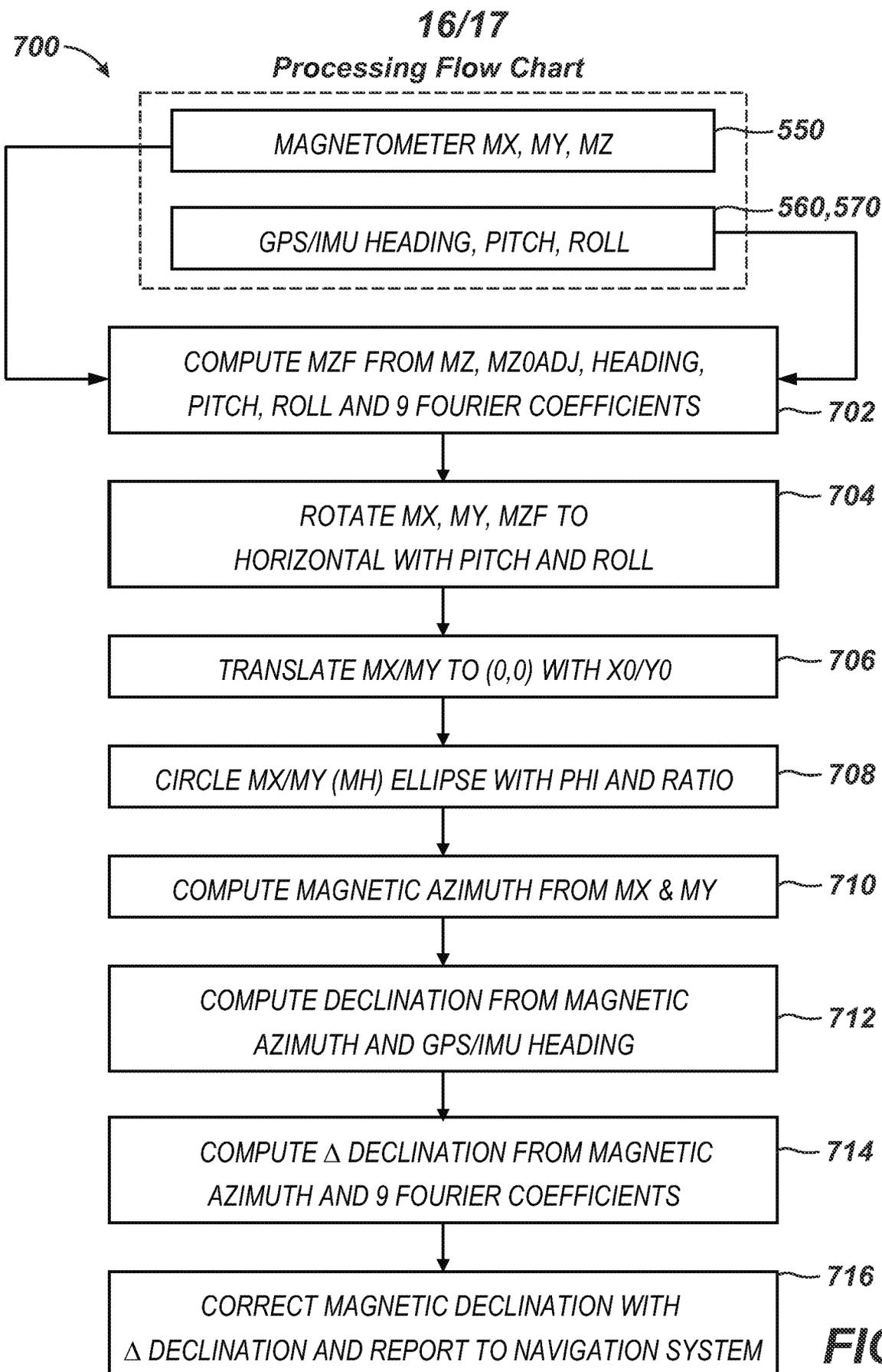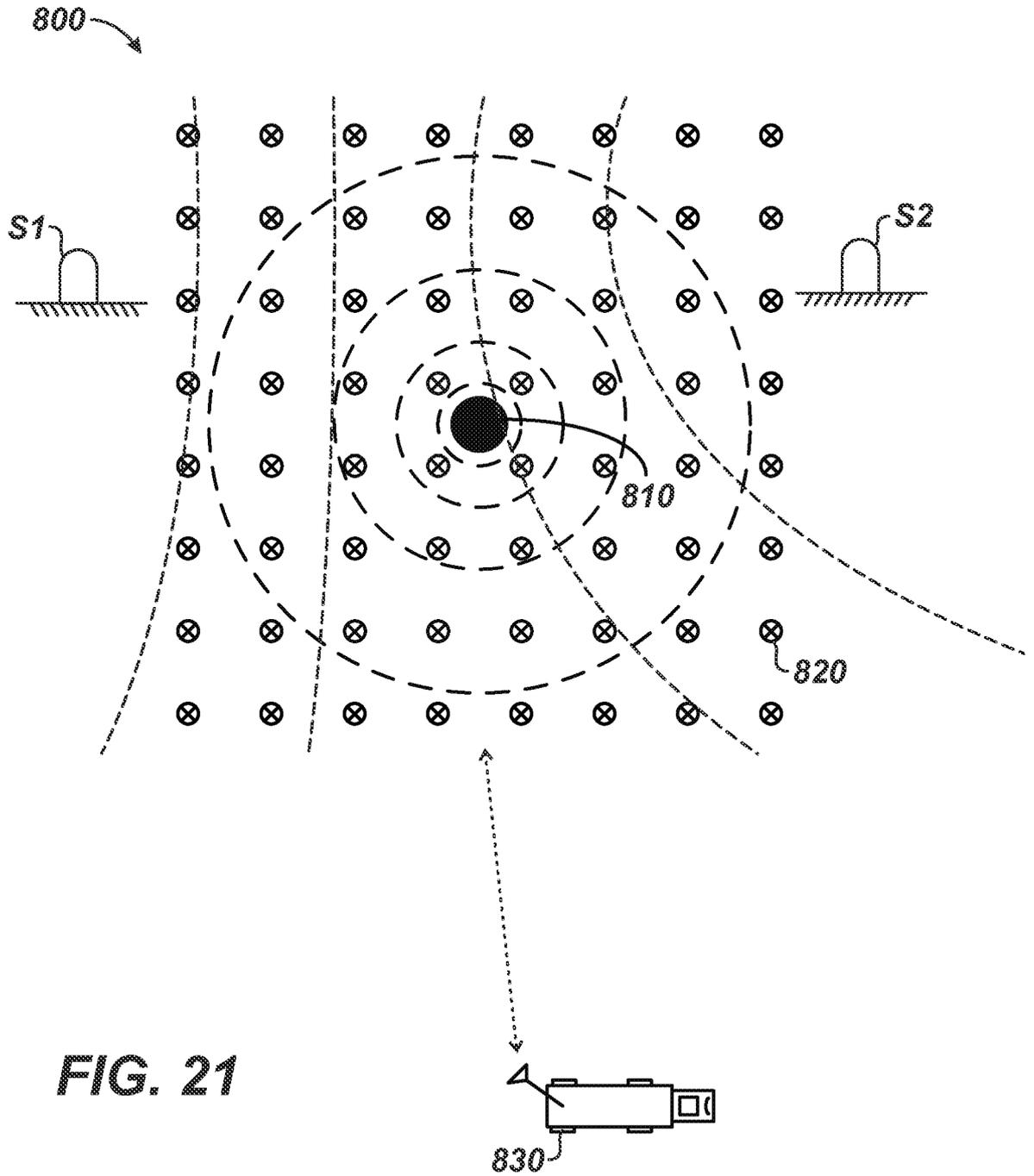CORRECT MAGNETIC DECLINATION WITH Δ DECLINATION AND REPORT TO NAVIGATION SYSTEM — 716

FIG. 20

FIG. 21

Geophysical Information
Processed for Imaging