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Williams et al.

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(54) **RUBIDIUM SPIN EXCHANGE RELAXATION FREE MAGNETOMETER BASED RECEIVER**

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H01Q 7/08 (2006.01)
H01Q 1/38 (2006.01)

(52) **U.S. Cl.**
CPC ***H01Q 7/08*** (2013.01); ***H01Q 1/38*** (2013.01)

(58) **Field of Classification Search**
CPC .. H01Q 7/08; H01Q 1/38; H01Q 1/36; H01Q 7/00
See application file for complete search history.

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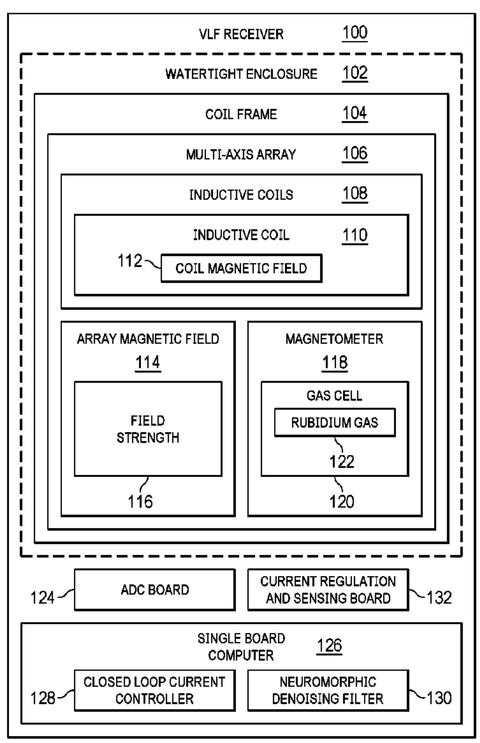
(57) **ABSTRACT**

A very low frequency (VLF) receiver is provided. The VLF receiver comprises a magnetometer that detects a magnetic field, wherein the magnetometer comprises a rubidium gas cell. Processing circuitry receives an electrical signal representative of VLF electromagnetic signals detected by the magnetometer. A multi-axis array encloses the magnetometer. The multi-axis array comprises a number of inductive coils. A closed loop current controller is connected to the inductive coils and runs on the processing circuitry. The closed loop current controller controls the magnetic field strength of the inductive coils to maintain a uniform magnetic field across the rubidium gas cell to allow the processing circuitry to detect the VLF electromagnetic signals.

20 Claims, 7 Drawing Sheets



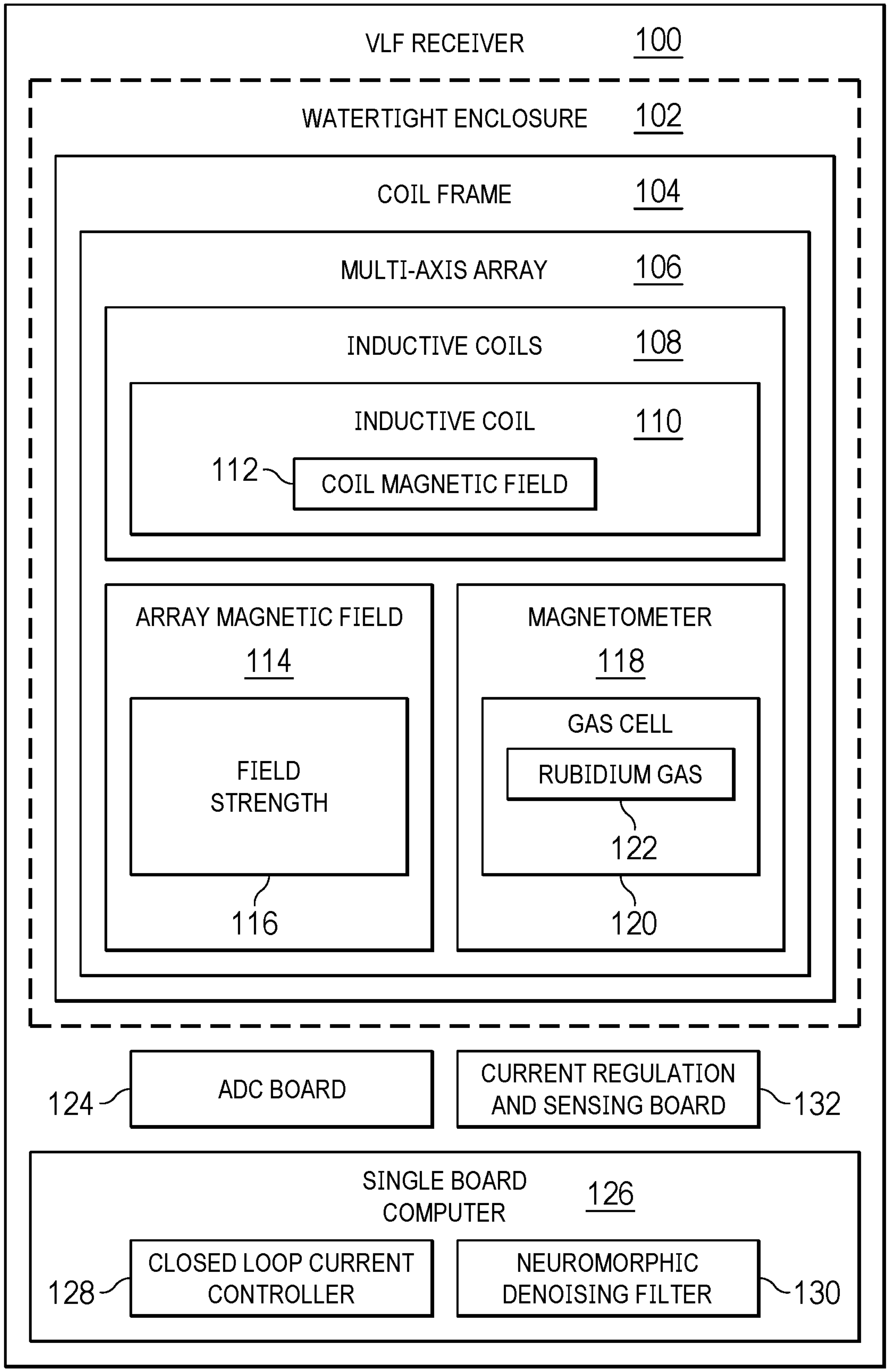

VLF RECEIVER 100
WATERTIGHT ENCLOSURE 102
COIL FRAME 104
MULTI-AXIS ARRAY 106
INDUCTIVE COILS 108
INDUCTIVE COIL 110
112
COIL MAGNETIC FIELD
ARRAY MAGNETIC FIELD 114
FIELD STRENGTH
116
MAGNETOMETER 118
GAS CELL
RUBIDIUM GAS
122
120
124
ADC BOARD
CURRENT REGULATION AND SENSING BOARD
132
SINGLE BOARD COMPUTER 126
128
CLOSED LOOP CURRENT CONTROLLER
NEUROMORPHIC DENOISING FILTER
130

FIG. 1

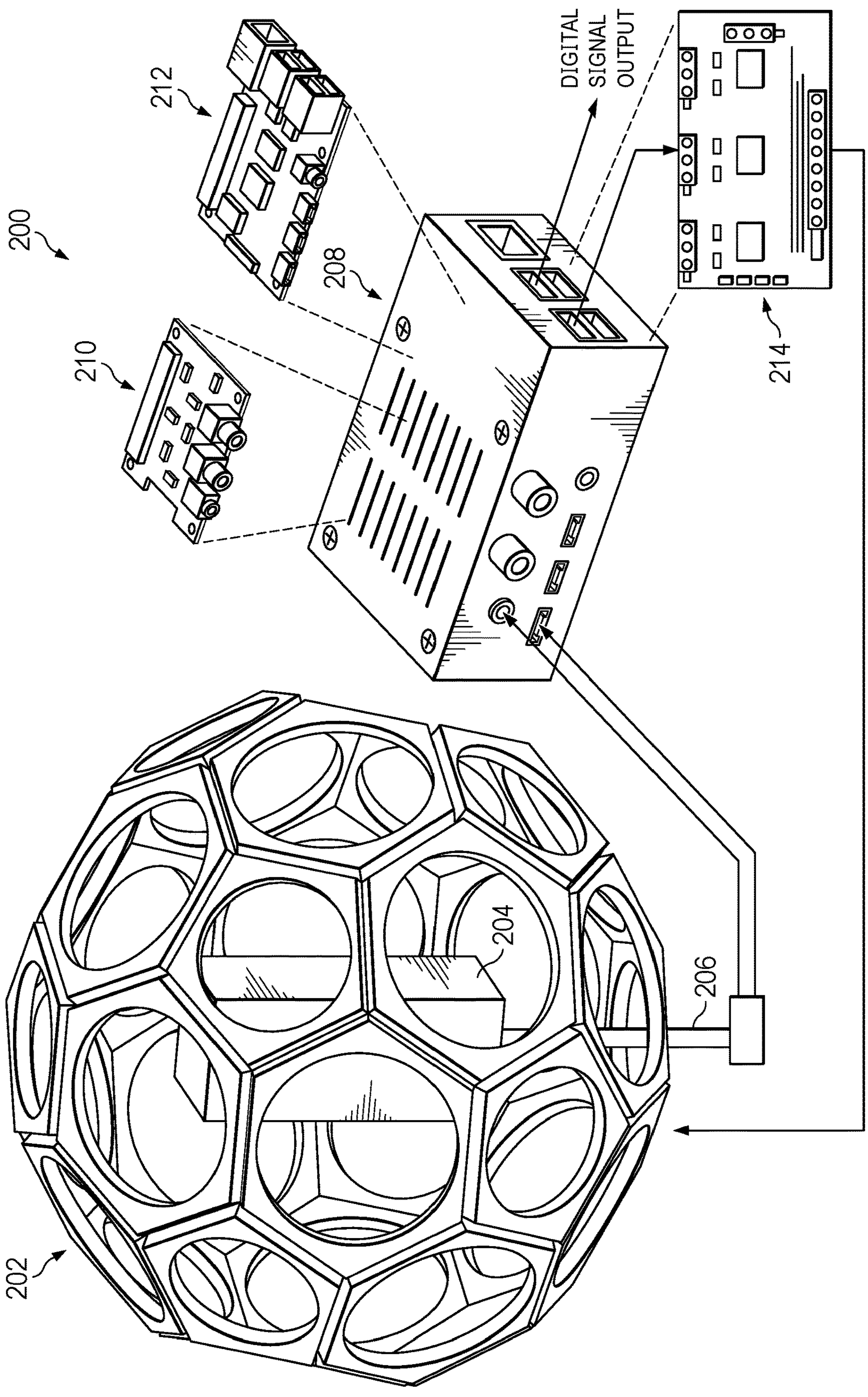


FIG. 2

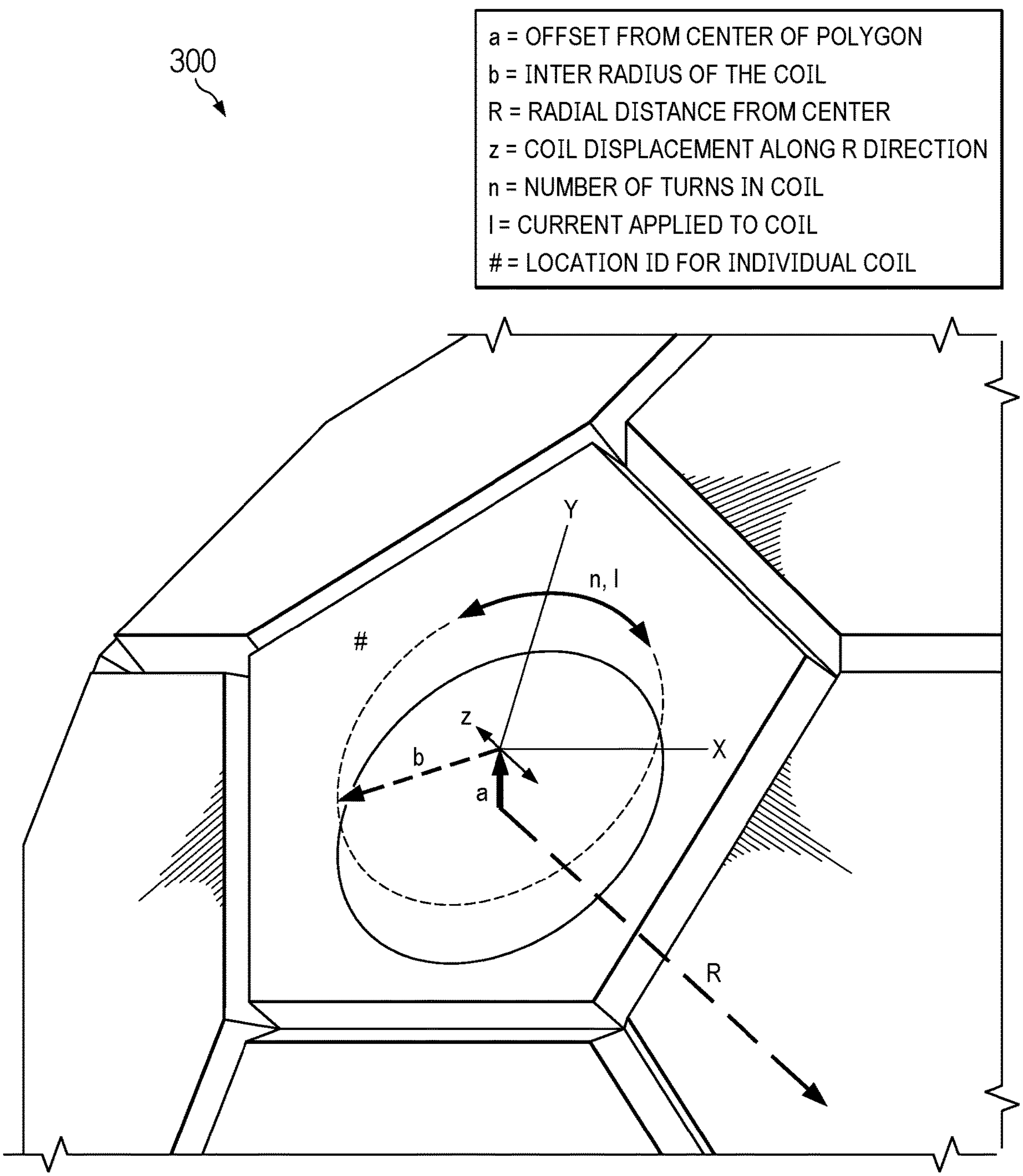

300
a = OFFSET FROM CENTER OF POLYGON
b = INTER RADIUS OF THE COIL
R = RADIAL DISTANCE FROM CENTER
z = COIL DISPLACEMENT ALONG R DIRECTION
n = NUMBER OF TURNS IN COIL
I = CURRENT APPLIED TO COIL
# = LOCATION ID FOR INDIVIDUAL COIL
Y
n, I
#
z
X
b
a
R

FIG. 3

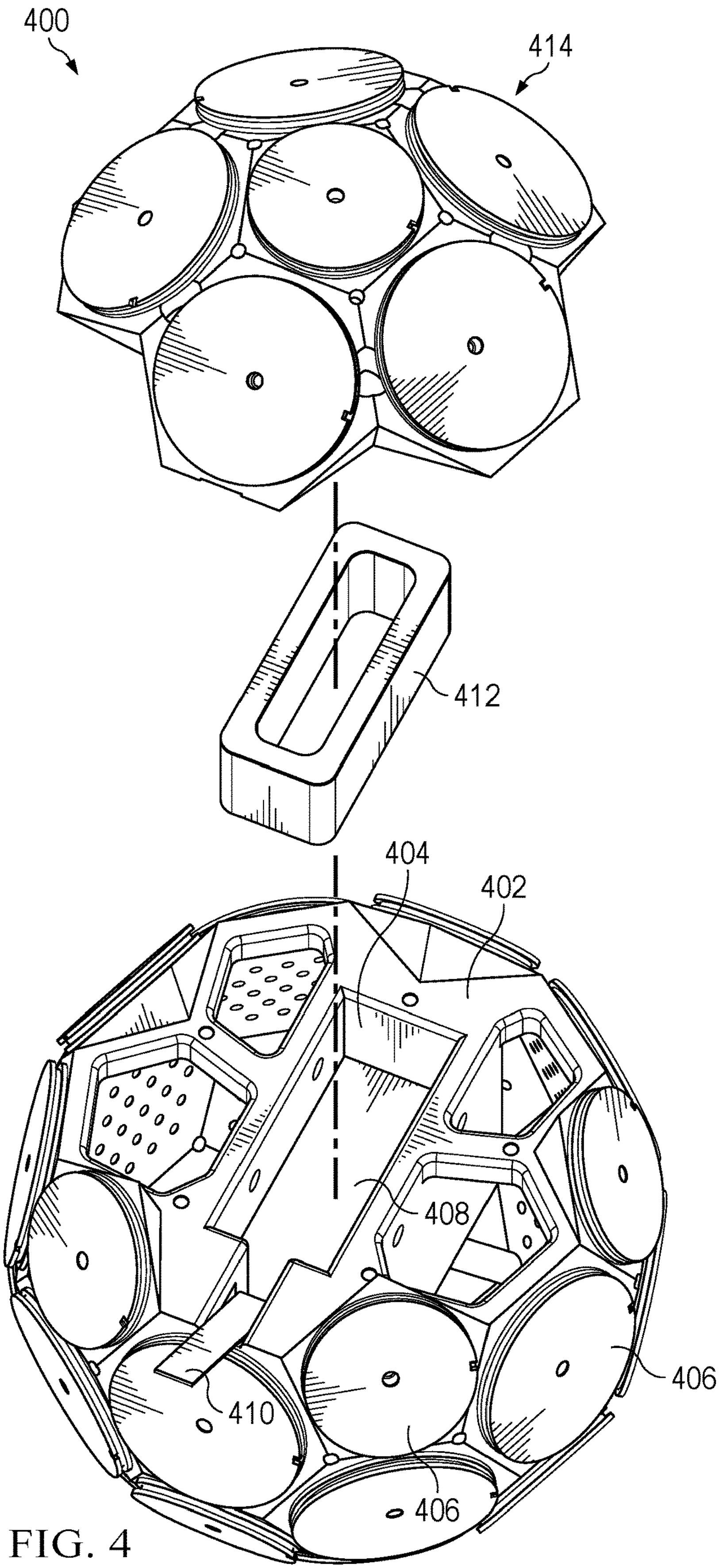


FIG. 4

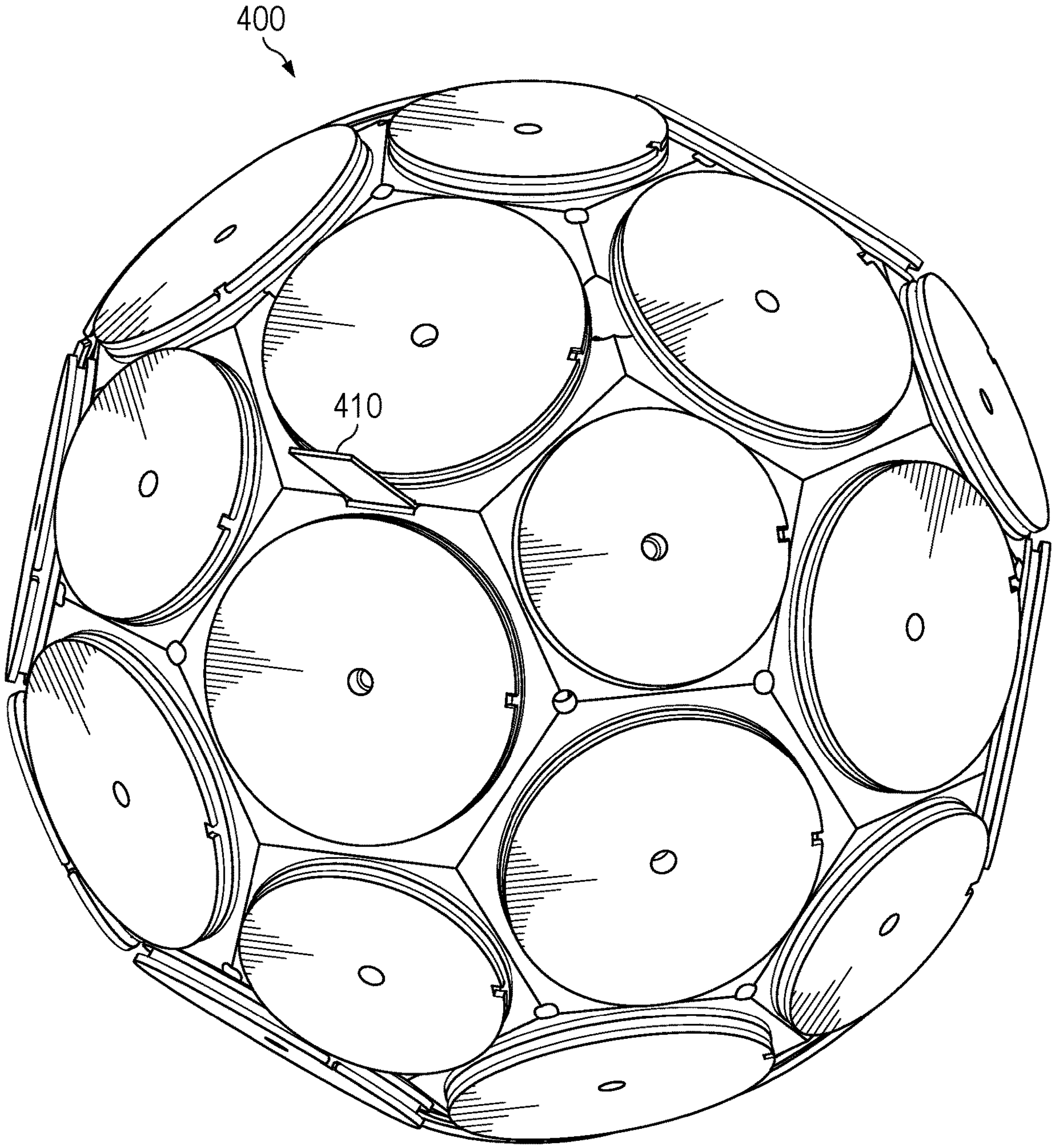


FIG. 5

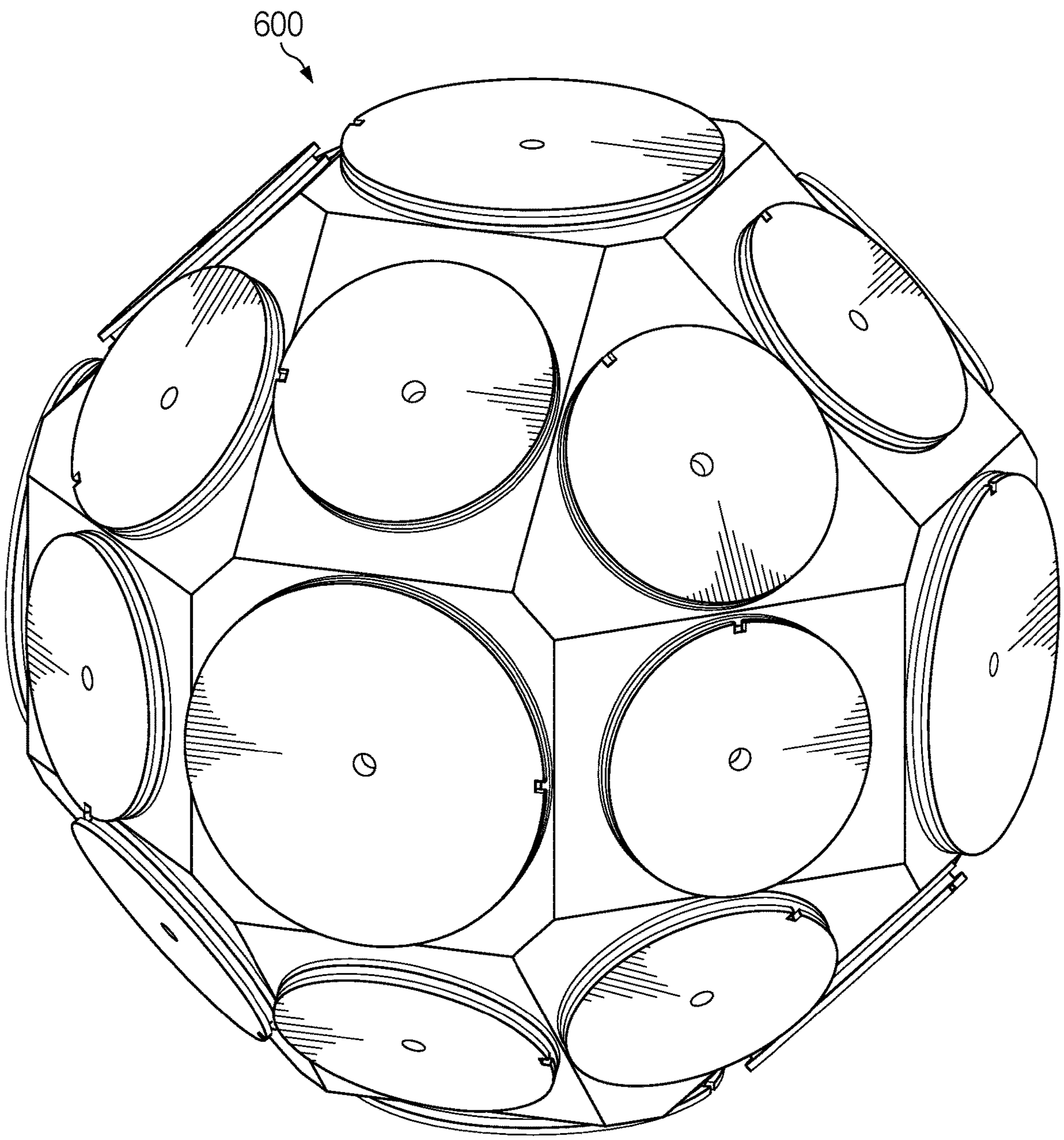


FIG. 6

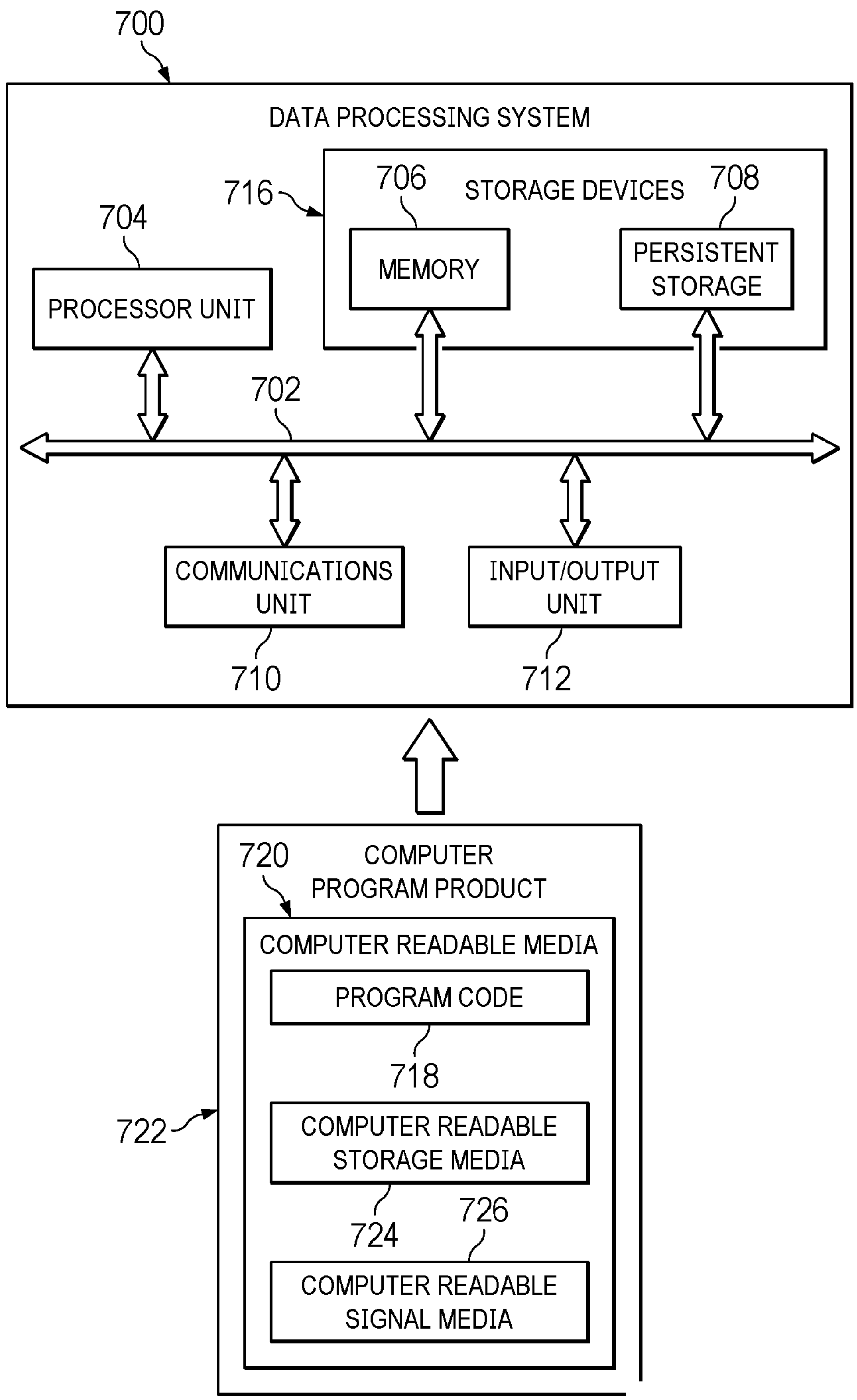

700
DATA PROCESSING SYSTEM
716
706
STORAGE DEVICES
708
704
MEMORY
PERSISTENT STORAGE
PROCESSOR UNIT
702
COMMUNICATIONS UNIT
INPUT/OUTPUT UNIT
710
712
720
COMPUTER PROGRAM PRODUCT
COMPUTER READABLE MEDIA
PROGRAM CODE
718
722
COMPUTER READABLE STORAGE MEDIA
724
726
COMPUTER READABLE SIGNAL MEDIA

FIG. 7

RUBIDIUM SPIN EXCHANGE RELAXATION FREE MAGNETOMETER BASED RECEIVER

BACKGROUND INFORMATION

1. Field

The present disclosure relates generally to electromagnetic receivers, and more specifically to a tuned multi-coil array that maintains a uniform magnetic field.

2. Background

Magnetic induction is the most compact means of recording electromagnetic waves from a distance. Almost all very low frequency (VLF) receivers today are made of loop antennas. Each loop induces current that is amplified by the number of loops and the permeability of the ferrite often placed within them. The received current is coupled to the incident electromagnetic (EM) wave by its magnetic component, not the electric one, allowing insulated loop inductors to receive data. Loop current antennas are typically meters in size and have limited gain. Loop antennas with ferrite cores are smaller, typically a few feet, but still have limited gain.

Therefore, it would be desirable to have a method and apparatus that take into account at least some of the issues discussed above, as well as other possible issues.

SUMMARY

An illustrative embodiment provides a very low frequency (VLF) receiver. The VLF receiver comprises a magnetometer that detects a magnetic field, wherein the magnetometer comprises a rubidium gas cell. Processing circuitry receives an electrical signal representative of VLF electromagnetic signals detected by the magnetometer. A multi-axis array encloses the magnetometer. The multi-axis array comprises a number of inductive coils. A closed loop current controller is connected to the inductive coils and runs on the processing circuitry. The closed loop current controller controls the magnetic field strength of the inductive coils to maintain a uniform magnetic field across the rubidium gas cell to allow the processing circuitry to detect the VLF electromagnetic signals.

Another illustrative embodiment provides a VLF receiver. The VLF receiver comprises a magnetometer that detects a magnetic field, wherein the magnetometer comprises a rubidium gas cell. A buckyball-shaped frame encloses the magnetometer. A number of inductive coils are mounted on the buckyball shaped frame, wherein the inductive coils form a multi-axis array. A high bit resolution analog to digital converter (ADC) receives an electrical signal representative of VLF electromagnetic signals detected by the magnetometer. A single board computer receives a digital signal from the ADC and applies a neuromorphic denoiser to improve signal to noise ratio. A closed loop current controller is connected to the inductive coils and runs on the single board computer, wherein the closed loop current controller controls magnetic field strength of the inductive coils to maintain a uniform magnetic field across the rubidium gas cell to allow the ADC to detect the VLF electromagnetic signals.

Another illustrative embodiment provides a multi-axis inductive coil array. The multi-axis inductive coil array comprises a number of inductive coils and a closed loop current controller connected to the inductive coils, wherein the closed loop current controller controls magnetic field strength of the inductive coils to maintain a uniform magnetic field within the multi-axis array.

The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

FIG. **1** depicts a block diagram of VLF receiver in accordance with an illustrative embodiment;

FIG. **2** depicts a pictorial diagram of a VRSMR in accordance with an illustrative embodiment;

FIG. **3** depicts a diagram illustrating magnetic field optimization in accordance with an illustrative embodiment;

FIG. **4** depicts an exploded view of a VRSMR assembly in accordance with an illustrative embodiment;

FIG. **5** depicts a pictorial diagram of a closed VRSMR assembly in accordance with an illustrative embodiment;

FIG. **6** depicts a pictorial diagram of an alternate VRSMR design in accordance with an illustrative embodiment; and

FIG. **7** is an illustration of a block diagram of a data processing system in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

The illustrative embodiments recognize and take into account a number of different considerations as described herein. The illustrative embodiments recognize and take into account that magnetic induction is the most compact means of recording electromagnetic waves from a distance. Almost all VLF receivers today are made of loop antennas. Each loop induces current that is amplified by the number of loops and the permeability of the ferrite often placed within them. The received current is coupled to the incident electromagnetic (EM) wave by its magnetic component, not the electric one, allowing insulated loop inductors to receive data.

The illustrative embodiments also recognize and take into account that loop current antennas are typically meters in size and have limited gain. Loop antennas with ferrite cores are smaller, typically a few feet, but still have limited gain.

The illustrative embodiments also recognize and take into account that magnetic coupling of light is far more important than most realize. Light absorption does not always affect the primary atomic state (N) but often the secondary states (L and M) by coupling angular momentum from the magnetic component of the EM wave to the electron which in turn induces magnetic transitions within the atom. One could argue that kinetic oscillations (phonon) within an atomic lattice create similar magnetic states. Thus, while momentum transfer in magnetism is more difficult to understand, it is probably the primary means by which light and sound excite the atomic world. Therefore, the ideal measurement of the smallest electromagnetic energy transfer, or EM signal transduction, allowed is the measure of magnetic field.

The illustrative embodiments provide a VLF receiver comprising a quantum magnetometer enclosed in a multi-axis array of inductive coils enclosed into a single, water-tight modular unit. A closed loop controller controls the bias of the inductive coils, and a single board computer runs radio and data analysis.

Currently, the most accurate sensor available at or near room temperature is an alkali gas spin exchange relaxation free (SERF) magnetometer. This device uses light to excite all the atoms in a diffuse gas enclosed within a glass box to a single excited state. When an EM field penetrates the glass box, the atoms within are inductively coupled and their angular momentum (inductive state) is changed. The excitation of angular momentum can be observed in the polarization of the light passed through the cell. Therefore, an EM wave is observed without electronic losses or thermal noise present in conductive materials. Without the losses present in conductors, sensitivities of femtoTesla instead of microTesla can be achieved within a volume 10,000 times smaller than a conventional inductive loop.

At present there are three primary means to communicate effectively in saltwater environments. First is VLF radio transmit and receive. The second is laser communications, and the third is sound wave propagation. Each offers distinct benefits. Blue-green lasers are good point to point communication systems but require precise beam steering and constant location data. Sonic buoys dissipate over long distances, but do not efficiently penetrate the air water barrier efficiently. VLF propagation is range limited in sea water, but propagates long in air, does not require line of sight, and efficiently passes through the air water interface.

Another potential application of a VLF receiver is recording atmospheric disturbances between 300 Hz and 25 kHz. At these frequencies, the Antarctic research stations often record lightning and other short term events for thousands of miles. By strategically placing and timing events over large distances, it is possible to record the plasma generated during the atmospheric reentry of satellites, vehicles, and rockets.

FIG. **1** depicts a block diagram of a VLF receiver in accordance with an illustrative embodiment.

VLF receiver **100**. Multi-axis array **104** comprises a number of inductive coils **108** mounted on a coil frame **104**. Multi-axis array **104** encloses magnetometer **112**. Each inductive coil **110** has a respective coil magnetic field **112** with a respective field strength.

Multi-axis array **106** has an array magnetic field **114** created by the inductive coils **108**. The field strength **116** the of array magnetic field **114** is determined by the shape of the multi-axis array **106** and the coil magnetic field **112** of each individual coil **110**, which can be dynamically tuned by a closed loop current controller **128**. Array magnetic field **114** and its field strength **116** are the sum of the individual coil magnetic fields of the inductive coils **108** in multi-axis array **106**. The inductive coils **108** might comprise three-axis Helmholtz coils that are tuned by the closed loop current controller **128**.

Magnetometer **118** comprises a gas cell **120** containing rubidium gas **122**. Gas cell **120** may be made of glass, silicon, or other nonreactive material with transparent windows to allow for the transmission and recording of optical signals. The magnetometer **118** might comprise a spin exchange relaxation free magnetometer.

An analog-to-digital converter (ADC) board **124** receives an electrical signal representative of VLF electromagnetic signals detected by the magnetometer **118**. The ADC board **126** might comprise a high bit resolution (e.g., 24-bit) sound board that digitizes an analog signal up to 50 KHz.

Single board computer (SBC) **126** reads signal inputs and operates command functions continuously. SBC **126** might comprise, e.g., a Raspberry Pi 4, field programmable gate array (FPGA), or other single board processing unit with similar computing power and memory. SBC **126** is connected to the inductive coils **108** and runs a closed loop current controller **128** which controls the coil magnetic field **112** of each inductive coil **110** to maintain a uniform field strength **116** of array magnetic field **114** across the rubidium gas cell. The closed loop controller **128** nullifies the Earth's magnetic field and spurious local fields across the interior of the gas cell **120** containing the rubidium gas **122**. This uniform field strength allows the ADC board **124** to detect the VLF electromagnetic signals. The closed loop controller **126** might employing machine learning to tune the field strength **116** of array magnetic field **114**.

SBC **126** uses an operating system that can load a software based neuromorphic denoising filter **130** that boosts signal to noise ratio (SNR) by at least 40 dB above the noise floor and decoded.

A current regulation and sensing board **132** regulates current across multiple channels.

For underwater applications, the coil frame **104**, inductive coils **108** and magnetometer **118** can be enclosed in a watertight enclosure **102**.

FIG. **2** depicts a pictorial diagram of a Very Low Frequency (VLF) Rubidium (Rb) Spin Exchange Relaxation Free (SERF) Magnetometer Receiver (VRSMR) in accordance with an illustrative embodiment. VRSMR **200** is an example implementation of VLF receiver **100** in FIG. **1**.

The VRSMR **200** provides several innovations that optimize the system during operation. These innovations improve the overall performance characteristics of the VRSMR receiver module while supporting a low Size, Weight, and Power (SWAP) and performance. The VRSMR of the illustrative embodiments has the ability to record real-time minimum shift key (MSK) signal modulation. The VLF Rb SERF magnetometer of VRSMR is able to detect kHz signals. The VRSMR also optimizes the symmetry of the magnetic field to maintain magnetic field uniformity across the Rubidium gas cell. The VRSMR may also incorporates a neuromorphic denoising filter software installed on a single board computer.

In the present example, VRSMR **200** utilizes a Buckyball design frame **202** for the inductive coil array in which SERF magnetometer **204** in enclosed as shown. The term buckyball is derived from buckminsterfullerene, which is a carbon molecule with a cage-like fused ring structure made of twelve pentagons and twenty hexagons and resembling a soccer ball/football.

Coil placement on the Buckyball frame **202** can be determined using a multi-degree-of-freedom machine learning model and a closed loop optimizer for the current controller, such as closed loop current controller **128** in FIG. **1**.

The illustrative embodiments model various aspects of the three-axis Helmholtz coil design to minimize non-uniformity of the magnetic field within the rubidium cell in magnetometer **204** and improve signal to noise ratio (SNR) by an additional 10 dB. This modeling optimizes the magnetic field amplitude and uniformity across the Rubidium cell required for signal reception. Without field optimization one can record laboratory signals but may not be able to remove local magnetic field biases and noise contributors required to isolate the VLF communication signal.

Compact digitally tunable current sources can be applied to geometric changes in the magnetic field of the coil array to reduce the field variation between the optimized coil inputs. The illustrative embodiments can apply Miller orientations [**100**], [**110**], and throughout the Rubidium cell when biased using 1-, 2-, and 3-dimensional Helmholtz coils. Lightweight magnetic shielding around the coil array reduces local magnetic effects. These approaches reduce the random field noise present in the Rubidium cell by up to 90% over conventional square 3D Helmholtz coil designs.

The improved design optimizes SWAP characteristics and performance of the VRSMR using either current or future RF Alkali gas magnetometers. The overall size of the VRSMR **200** and electronics shown in FIG. **2** can be smaller than a 4" diameter cylinder, 6" tall (~75 in^3) with femtotesla resolution.

The VLF receiver subsystem comprise a magnetometer **204** surrounded by a spherical multi-axis shaped array of inductive coils mounted on frame **202** (see coils **406** in FIGS. **4** and **5**). The inductive coils are driven by a closed loop current controller running on SBC **212** to nullify the Earth's magnetic field and spurious local fields uniformly throughout the interior of the Rubidium (Rb) gas cell, thereby locking the magnetometer **204** (i.e., optimized for settings according to the magnetometer's own internal closed loop control system). The closed loop current controller can use the machine learning algorithm to optimize the operation of more than three inductive coils at once. The addition of more coils provides a more uniform distribution of magnetic field within the cubic Rubidium glass cell of magnetometer **204**, thereby increasing overall sensor sensitivity.

The use of a symmetric coil 3-axis distribution actually focuses the field at the center and not the edges of the Rubidium gas cell. Therefore, the multi-axis array is tailored to "blur" the magnetic field across the gas cell uniformly. Thus, magnetic field variations in corners of the cubic cell, Rb gas condensation sites, and local area non-uniformities in the cell can be optimized for in order to improve the signal to noise ratio of the sensor. This blurring requires solving a parametric problem with at least 7-8, and possibly more than a dozen, parameters. A machine learning approach can be used that utilizes the existing physical model to optimize a solution and compare results to minimize the signal noise floor using real-time closed loop current control.

Magnetic sensor data from the magnetometer **204** is sent via cable **206** to a high bit resolution input analog-to-digital converted (ADC) sound board **210** with a sufficient sampling rate to distinguish the channel of interest for optimal signal processing (i.e., at least 2-4x channel frequency). After analog to digital conversion, the VLF signal is sent to SBC **212** where it can be passed through the Neuromorphic Denoiser to improve signal to noise ratio (SNR) by at least 40 dB above the noise floor and decoded. The SBC **212** processes the message then transmits it to the next subsystems (not shown). SBC **212** might comprise, e.g., a Raspberry Pi 4.0 SBC. ADC board **210** and SBC **212**, along with a current regulation and sensing board **214**, can be housed in a single case **208**.

The denoiser provides an effective improvement to the resolved signal which equates to improved dBfT (femtotesla signal resolution) to resolve weak incoming VLF signals due to electrical storms, solar flares, or depth of the receiver itself. The denoiser may also be able, and particularly with the blind source separator proven with the denoiser for electronic support measures (ESM), to demodulate and decode VLF transmissions. The denoiser has proven itself very effective in recognizing a changing signal, including both phase and amplitude changes as well as de-spreading linear frequency modulations.

A neuromorphic prediction engine uses input signals to predict a small future time-step by minimizing a quadratic objective function that represents reservoir outputs as linear combinations of historical reservoir states. Since noise is random and unpredictable, the predicted signal will be free of noise. To minimize the error function at the input sample rate, the prediction engine can combine online gradient descent with finite element methods, obtaining a discretized de-noising algorithm. For the needs of VLF communications, this may be realized on a Raspberry Pi at 200 kHz. Combining the filtering improvement with the RF magnetometer configuration presented above provides sufficient signal capture capability without the use of high power amplifier electronics.

Some applications might require continuous signal reception. To achieve this requirement in a remote mobile unit, all subsystems are optimized to use the least amount of power. The power to run the neuromorphic filter on a small SBC is estimated to be between 0.9 Watts to 3.6 W. The next highest power consumer is the sensor closed loop current controller **214**, which might require 2.2 Watts for routine operation and up to 5.1 Watts of peak power over a 30 second time period to recalibrate the sensor if it loses lock on the magnetic field. The magnetic coils require approximately 2.1 Watts of constant power to stabilize the sensor for continuous operation. The ADC sound board **210** might require approximately 0.3 Watts of continuous power to meet the program requirements. Thus, the VRSMR **200** might require approximately 5.3 to 7.4 W at 5 V for continuous operation. The energy and power subsystem is designed to have enough capacity to power the VLF subsystem. The entire device weighs less than 1 lb.

FIG. **3** depicts a diagram illustrating magnetic field optimization in accordance with an illustrative embodiment.

The illustrative embodiments employ a spherical coil driver using a spherical multi-axis array approach to reduce the overall size of the magnetic bias coils and improve bias field uniformity across the Rubidium gas cell in the magnetometer. This approach allows for a smaller device with improved sensitivity over all prior Helmholtz based coil models. This design has a minimum of seven (7) parametric variables. There are six variables per coil including: offset (c) from the center of the polygon (c), inner radius (b) of the coil, radial distance (R) from center, coil displacement (z) along the R direction, the number of turns (n) in the coil, and current (I) applied to the coil. Another variable (#) is used to account for the 30± individual coils patterned over the spherical multi-axis array.

A machine learning (ML) can optimize the shape and size of the coil while maintaining the minimum possible variation of magnetic field strength across the interior of the Rubidium gas cell. The structure can be 3D printed in sections and assembled using wrapped bobbins fitted inside 2D polygons.

FIG. **4** depicts an exploded view of a VRSMR assembly in accordance with an illustrative embodiment. FIG. **5** depicts a pictorial diagram of the closed VRSMR assembly **400**.

As shown in the example, inductive coils **406** are fixed over the polygon sections of buckyball frame **402** to form a coil array surrounding the magnetometer **408**. At the center of the frame **402** is a chamber **404** configured to accommodate magnetometer **408**.

A spacer **412** is configured to fit within chamber **404** and hold magnetometer **408** in place. Closure cap **414** is then placed over the chamber **404** to seal the magnetometer **408** inside the frame **402**. As shown in FIG. **5**, when closed, VRSMR assembly is approximately spherical due to the buckyball design of the frame **402**. Cable **410** protrudes from the closed VRSMR assembly to allow connection to the signal and power subsystems (not shown).

It should be emphasized that the method described above of maintaining a uniform magnetic field across an inductive coil array is not limited to the example of a buckyball frame as shown in FIGS. **2**-**5**. The method of the illustrative embodiments can be applied to a variety of complex arrangements of inductive coils. The magnetic field of a coil array can be designed and tuned through closed loop control according to the specific geometric characteristics of the arrangement in question. For example, the frame for the inductive coil array can comprise an elongated shape with bands of additional pentagons and hexagons oriented around a meridian. Other geometric variants such as tubular shapes can also be implemented in the illustrative embodiments with a concomitant increase in required computational resources.

FIG. **6** depicts a pictorial diagram of an alternate VRSMR design in accordance with an illustrative embodiment. In the example, the VRSMR takes the form of a truncated cube deluxe **600**. In this arrangement, faces for inductive coils are equidistant from the center of all the Miller indices (i.e., [**100**], [**110**], [**111**], etc.). The truncated cube design **600** has better symmetry for a cube-lattice structure compared to a buckyball but has more inconsistent face shape dimensions. In contrast, the buckyball arrangement has a more uniform spatial arrangement of coil faces, but the face distances are not equidistant from the center. This arrangement allows the VRSMR to better accommodate small variations in the geometric and magnetic properties of individual cells when using the Buckyball configuration over a 3 axis Helmholtz or even a multi-axis coil aligned directly to Miller Indices. Thus, each type of arrangement has advantages and disadvantages that affect the design and closed loop tuning of the coil array magnetic field.

It should be noted that the use of a tuned coil array is not limited to magnetometers and VLF detection. A tuned induction coiled array as described in the examples above can be used in any application that requires a uniform magnetic field in which to detect signals.

Turning now to FIG. **7**, an illustration of a block diagram of a data processing system is depicted in accordance with an illustrative embodiment. Data processing system **700** may be an example of SBC **128** in FIG. **1**. In this illustrative example, data processing system **700** includes communications framework **702**, which provides communications between processor unit **704**, memory **706**, persistent storage **708**, communications unit **710**, and input/output (I/O) unit **712**. In this example, communications framework **702** takes the form of a bus system.

Processor unit **704** serves to execute instructions for software that may be loaded into memory **706**. Processor unit **704** may be a number of processors, a multi-processor core, or some other type of processor, depending on the particular implementation. In an embodiment, processor unit **704** comprises one or more conventional general-purpose central processing units (CPUs).

Memory **706** and persistent storage **708** are examples of storage devices **716**. A storage device is any piece of hardware that is capable of storing information, such as, for example, without limitation, at least one of data, program code in functional form, or other suitable information either on a temporary basis, a permanent basis, or both on a temporary basis and a permanent basis. Storage devices **716** may also be referred to as computer-readable storage devices in these illustrative examples. Memory **706**, in these examples, may be, for example, a random access memory or any other suitable volatile or non-volatile storage device. Persistent storage **708** may take various forms, depending on the particular implementation.

For example, persistent storage **708** may contain one or more components or devices. Persistent storage **708** may include neuromorphic hardware. Communications unit **710**, in these illustrative examples, provides for communications with other data processing systems or devices. In these illustrative examples, communications unit **710** is a network interface card.

Input/output unit **712** allows for input and output of data with other devices that may be connected to data processing system **700**.

Instructions for at least one of the operating system, applications, or programs may be located in storage devices **716**, which are in communication with processor unit **704** through communications framework **702**. The processes of the different embodiments may be performed by processor unit **704** using computer-implemented instructions, which may be located in a memory, such as memory **706**.

These instructions are referred to as program code, computer-usable program code, or computer-readable program code that may be read and executed by a processor in processor unit **704**. The program code in the different embodiments may be embodied on different physical or computer-readable storage media, such as memory **706** or persistent storage **708**.

Program code **718** is located in a functional form on computer-readable media **720** and may be loaded onto or transferred to data processing system **700** for execution by processor unit **704**. Program code **718** and computer-readable media **720** form computer program product **722** in these illustrative examples. In one example, computer-readable media **720** may be computer-readable storage media **724** or computer-readable signal media **726**.

In these illustrative examples, computer-readable storage media **724** is a physical or tangible storage device used to store program code **718** rather than a medium that propagates or transmits program code **718**. Computer readable storage media **724**, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

Alternatively, program code **718** may be transferred to data processing system **700** using computer-readable signal media **726**. Computer-readable signal media **726** may be, for example, a propagated data signal containing program code **718**. For example, computer-readable signal media **726** may be at least one of an electromagnetic signal, an optical signal, or any other suitable type of signal. These signals may be transmitted over at least one of communications links, such as wireless communications links, optical fiber cable, coaxial cable, a wire, or any other suitable type of communications link.

The different components illustrated for data processing system **700** are not meant to provide architectural limitations to the manner in which different embodiments may be implemented. The different illustrative embodiments may be implemented in a data processing system including components in addition to or in place of those illustrated for data processing system **700**. Other components shown in FIG. **7** can be varied from the illustrative examples shown. The different embodiments may be implemented using any hardware device or system capable of running program code **718**.

As used herein, "a number of" when used with reference to items, means one or more items. For example, "a number of different types of networks" is one or more different types of networks.

Further, the phrase "at least one of," when used with a list of items, means different combinations of one or more of the listed items can be used, and only one of each item in the list may be needed. In other words, "at least one of" means any combination of items and number of items may be used from the list, but not all of the items in the list are required. The item can be a particular object, a thing, or a category.

For example, without limitation, "at least one of item A, item B, or item C" may include item A, item A and item B, or item B. This example also may include item A, item B, and item C or item B and item C. Of course, any combinations of these items can be present. In some illustrative examples, "at least one of" can be, for example, without limitation, two of item A; one of item B; and ten of item C; four of item B and seven of item C; or other suitable combinations.

When one component is "connected" to another component, the connection is a physical connection. For example, a first component can be considered to be physically connected to a second component by at least one of being secured to the second component, bonded to the second component, mounted to the second component, welded to the second component, fastened to the second component, or connected to the second component in some other suitable manner. The first component also can be connected to the second component using a third component. The first component can also be considered to be physically connected to the second component by being formed as part of the second component, an extension of the second component, or both.

The description of the different illustrative embodiments has been presented for purposes of illustration and description and is not intended to be exhaustive or limited to the embodiments in the form disclosed. The different illustrative examples describe components that perform actions or operations. In an illustrative embodiment, a component can be configured to perform the action or operation described. For example, the component can have a configuration or design for a structure that provides the component an ability to perform the action or operation that is described in the illustrative examples as being performed by the component. Further, to the extent that terms "includes", "including", "has", "contains", and variants thereof are used herein, such terms are intended to be inclusive in a manner similar to the term "comprises" as an open transition word without precluding any additional or other elements.

Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different features as compared to other desirable embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. A very low frequency (VLF) receiver, comprising:

a magnetometer that detects a magnetic field, wherein the magnetometer comprises a rubidium gas cell;

processing circuitry that receives an electrical signal representative of VLF electromagnetic signals detected by the magnetometer;

a multi-axis array enclosing the magnetometer, wherein the multi-axis array comprises a number of inductive coils; and

a closed loop current controller connected to the inductive coils and running on the processing circuitry, wherein the closed loop current controller controls magnetic field strength of the inductive coils to maintain a uniform magnetic field across the rubidium gas cell to allow the processing circuitry to detect the VLF electromagnetic signals.

2. The VLF receiver of claim **1**, wherein the magnetometer comprises a spin exchange relaxation free magnetometer.

3. The VLF receiver of claim **1**, wherein the inductive coils comprise three-axis Helmholtz coils that are tuned by the closed loop current controller.

4. The VLF receiver of claim **1**, wherein the processing circuitry comprises a single board computer.

5. The VLF receiver of claim **4**, wherein the single board computer is configured to run a neuromorphic denoiser to improve signal to noise ratio.

6. The VLF receiver of claim **4**, wherein the closed loop current controller runs on the single board computer.

7. The VLF receiver of claim **1**, wherein the processing circuitry comprises an analog to digital converter (ADC).

8. The VLF receiver of claim **7**, wherein the ADC comprises a high bit resolution sound board that digitizes an analog signal up to 50 KHz.

9. The VLF receiver of claim **1**, wherein the closed loop controller employs a machine learning algorithm to optimize operation of more than three inductive coils at once.

10. The VLF receiver of claim **1**, wherein the closed loop controller locks the magnetometer.

11. The VLF receiver of claim **1**, wherein the closed loop controller tunes the inductive coils.

12. The VLF receiver of claim **1**, wherein the closed loop current controller uniformly maintains the uniform magnetic field across the rubidium gas cell by nullifying the Earth's magnetic field and spurious local fields across the interior of the rubidium gas cell.

13. The VLF receiver of claim **1**, wherein the multi-axis array is mounted on a buckyball-shaped frame.

14. The VLF receiver of claim **1**, wherein the magnetometer and multi-axis array are sealed within a watertight enclosure.

15. A very low frequency (VLF) receiver, comprising:

a magnetometer that detects a magnetic field, wherein the magnetometer comprises a rubidium gas cell;

a buckyball-shaped frame enclosing the magnetometer;

a number of inductive coils mounted on the buckyball shaped frame, wherein the inductive coils form a multi-axis array;

a high bit resolution analog to digital converter (ADC) that receives an electrical signal representative of VLF electromagnetic signals detected by the magnetometer;

a single board computer that receives a digital signal from the ADC and applies a neuromorphic denoising filter to improve signal to noise ratio; and

a closed loop current controller connected to the inductive coils and running on the single board computer, wherein the closed loop current controller controls magnetic field strength of the inductive coils to maintain a uniform magnetic field across the rubidium gas cell to allow the ADC to detect the VLF electromagnetic signals.

16. The VLF receiver of claim **15**, wherein the magnetometer comprises a spin exchange relaxation free magnetometer.

17. The VLF receiver of claim **15**, wherein the closed loop controller employs a machine learning algorithm to optimize operation of more than three inductive coils at once.

18. A multi-axis inductive coil array, comprising:

a number of inductive coils; and

a closed loop current controller connected to the inductive coils, wherein the closed loop current controller controls magnetic field strength of the inductive coils to maintain a uniform magnetic field within the multi-axis array.

19. The multi-axis array of claim **18**, wherein the closed loop current controller runs on a single board computer.

20. The multi-axis array of claim **18**, wherein the closed loop controller employs a machine learning algorithm to optimize operation of more than three inductive coils at once.

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