

(19) **United States**

(12) **Patent Application Publication**
Maas et al.

(10) **Pub. No.: US 2015/0043308 A1**
(43) **Pub. Date: Feb. 12, 2015**

(54) **INTEGRATED SEISMIC MONITORING
SYSTEM AND METHOD**

Publication Classification

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(51) **Int. Cl.**
G01V 1/18 (2006.01)
G02B 6/44 (2006.01)

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(52) **U.S. Cl.**
CPC **G01V 1/18** (2013.01); **G02B 6/4415**
(2013.01)
USPC **367/37**

(21) Appl. No.: **14/383,207**

(57) **ABSTRACT**

(22) PCT Filed: **Mar. 15, 2013**

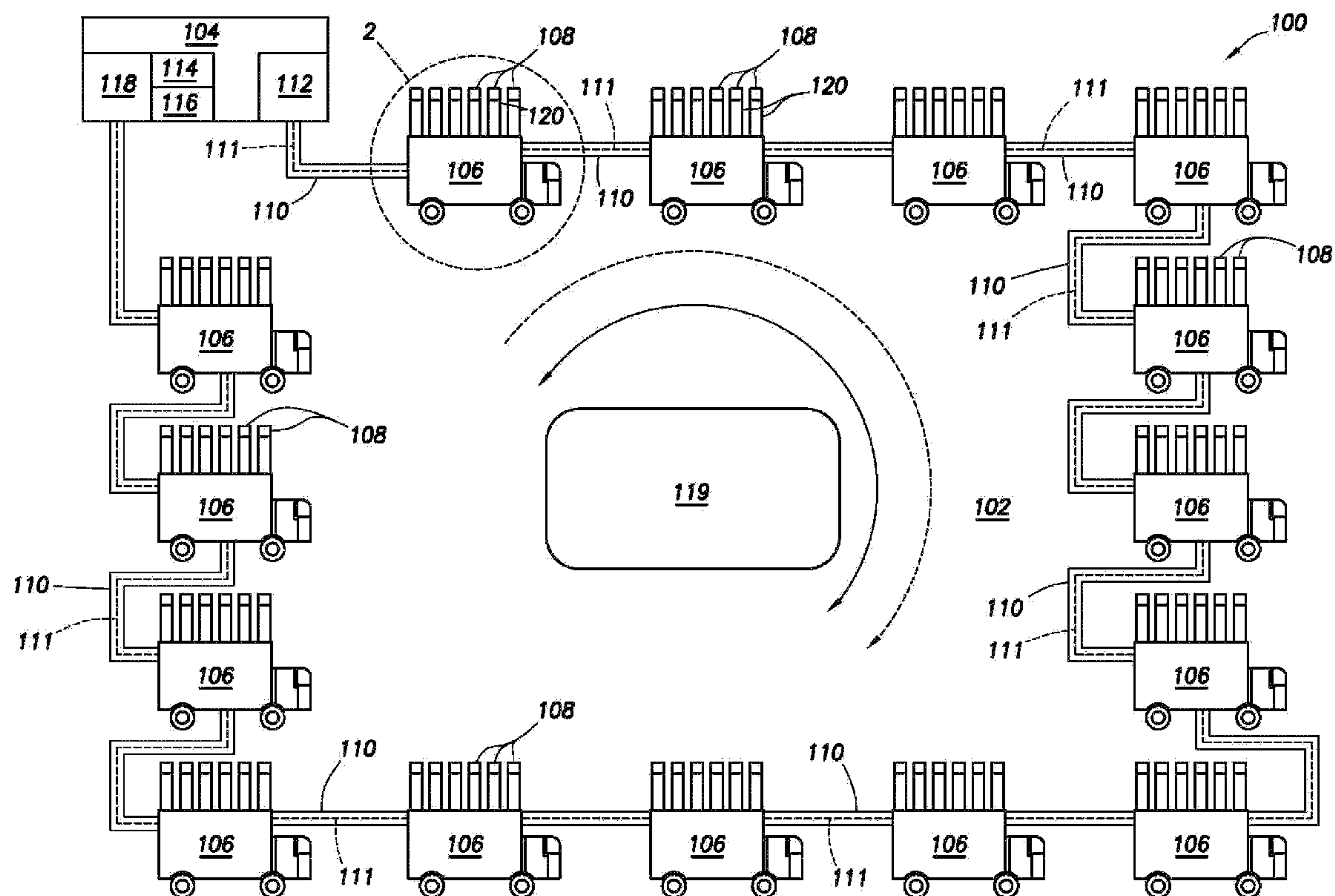
An integrated seismic system and method for monitoring seismic parameters of a subsurface structure is provided. The integrated seismic system includes a plurality of mobile satellite nodes, a seismic cable and a base station. Each of the mobile satellite nodes has sensor stations operatively connectable thereto for collecting seismic data from the subsurface structure. The seismic cable operatively links the plurality of mobile satellite nodes and the sensor stations. The base station includes a seismic acquisition unit for receiving seismic signals from the mobile satellite nodes via the seismic cable and generating seismic parameters therefrom.

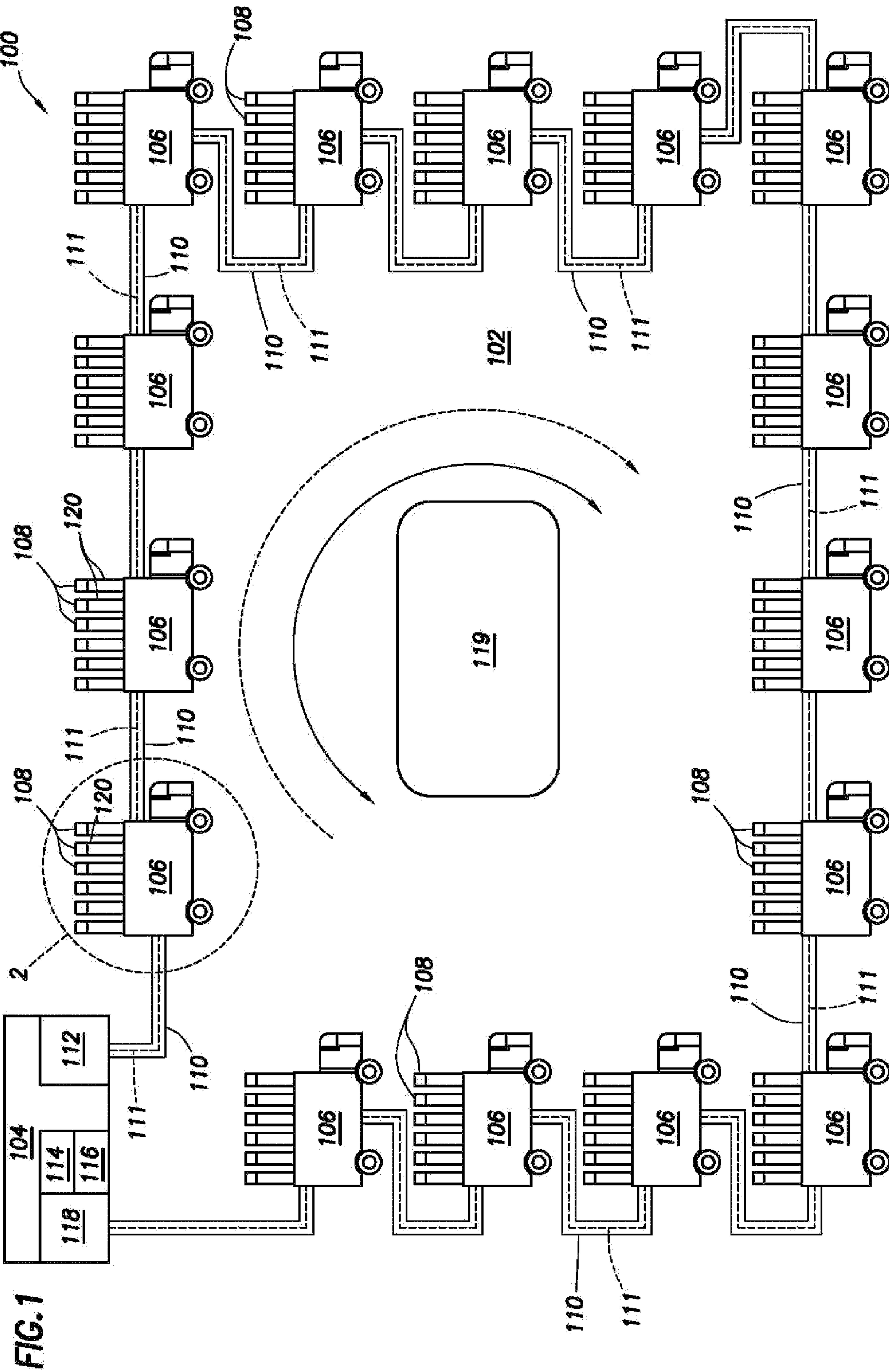
(86) PCT No.: **PCT/US2013/028997**

§ 371 (c)(1),
(2) Date: **Sep. 5, 2014**

Related U.S. Application Data

(60) Provisional application No. 61/608,345, filed on Mar. 8, 2012.





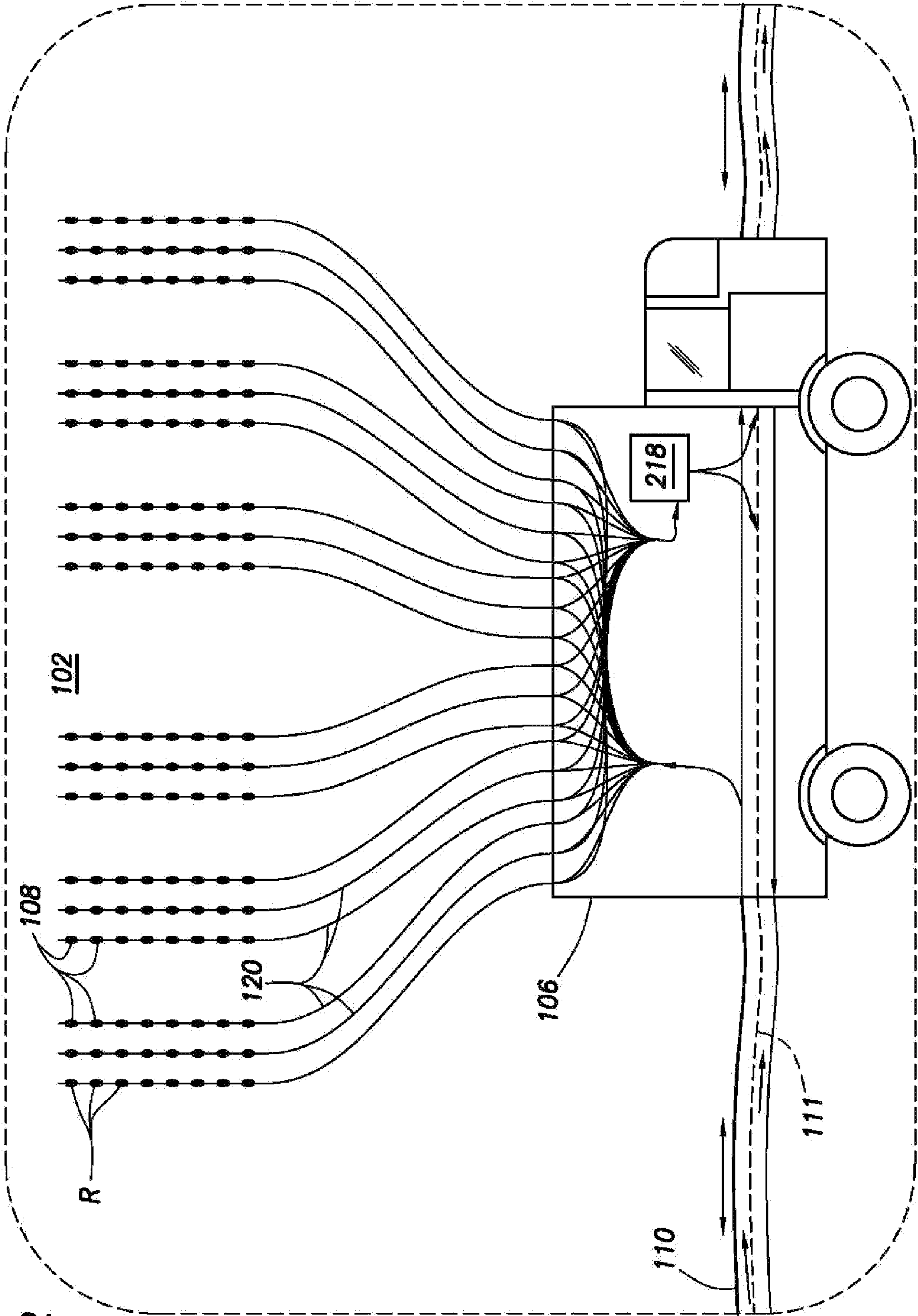


FIG. 2

118/218

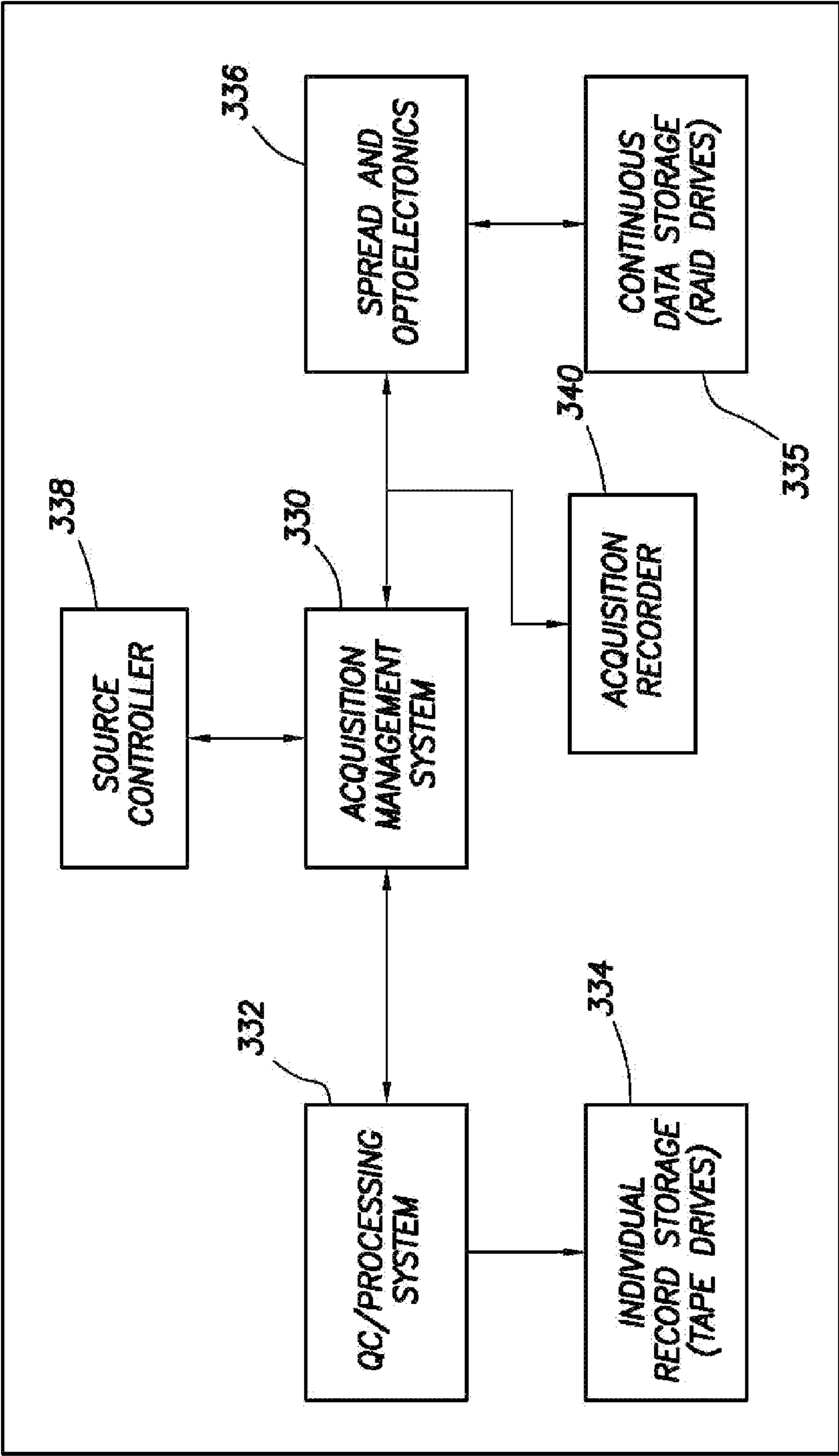
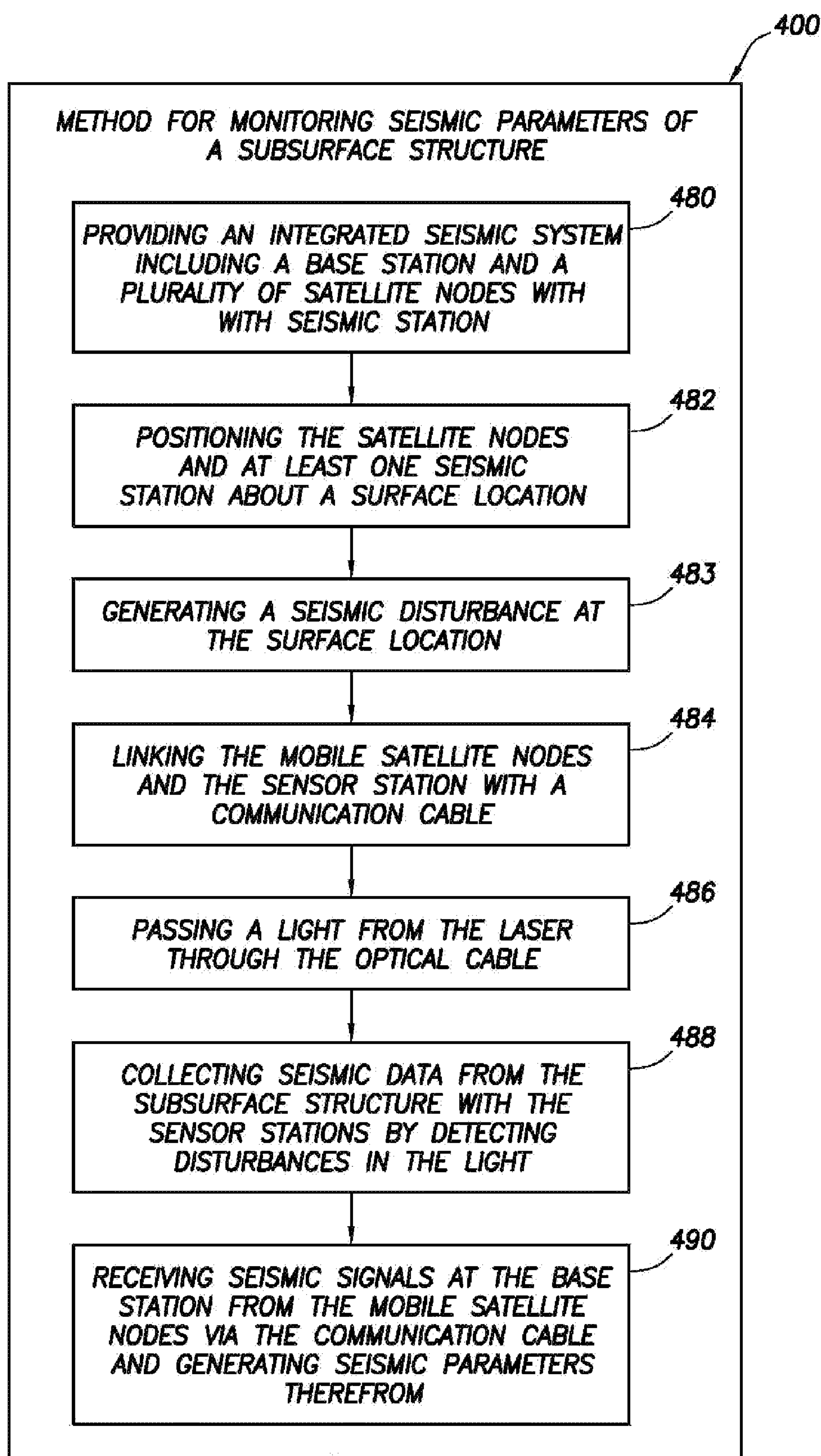


FIG.3

**FIG. 4**

INTEGRATED SEISMIC MONITORING SYSTEM AND METHOD

[0001] This application claims the benefit of priority of U.S. Provisional Patent Application No. 61/608,345, filed on Mar. 8, 2012, the disclosure of which is incorporated by reference herein in its entirety.

BACKGROUND

[0002] The present disclosure relates generally to techniques for investigating subsurface structures. More specifically, the present disclosure relates to optical monitoring systems for measuring seismic parameters of subsurface structures.

[0003] The exploration of oil and gas may involve the investigation of subsurface structures, such as geological formations and/or reservoirs. Seismic sensing systems may be positioned about a surface location for sensing properties of the subsurface structures. Such properties may include physical properties, such as pressure, motion, energy, etc. Such properties may occur naturally, or may be generated by imparting a force to the surface using a seismic energy source (e.g., a seismic vibration truck). Examples of seismic vibration trucks used for generating seismic vibrations are provided in US Patent Application No. 2009/0238038. The reflected seismic waves generated by the seismic energy source may be collected and analyzed to determine characteristics of the subsurface structures.

[0004] Techniques have been developed for sensing seismic parameters. Examples of such techniques are provided in US Patent/Application Nos. 20080062815, 20080060310, and 20080060311. Some seismic sensing systems may be, for example, optical systems including seismic trucks distributed about a location for independently collecting seismic data. Each seismic truck may have fiber optic cables with optical sensors distributed about a surface of a subsurface structure. The seismic trucks may also have a light source for emitting a laser through the fiber optic cables. The light source distributes light to and collects light from the optical sensors positioned along the fiber optic cables. The seismic truck may have devices for detecting changes in the light. Such changes may be used to determine information about and generate images of the subsurface structures. Examples of optical systems and sensors are provided in U.S. Pat. Nos. 7,622,706, 7,222,534, 7,154,082, and 6,549,488.

[0005] Despite the development of advanced techniques for optical seismic monitoring, there remains a need to provide advanced techniques for performing optical seismic monitoring. The present subject matter is directed to fulfilling these needs in the art.

SUMMARY

[0006] The present disclosure relates to an integrated seismic monitoring system positionable about a surface location to form an integrated network for collecting seismic data relating to subsurface structures. The integrated seismic monitoring system includes a base station, a plurality of mobile satellite nodes, and a seismic cable. The plurality of mobile satellite nodes has sensor stations operatively connectable thereto for collecting seismic data from the subsurface structure. The seismic cable operatively links the plurality of mobile satellite nodes and the sensor stations. The base station includes a seismic acquisition unit for receiving seismic

signals from the mobile satellite nodes via the seismic cable and generating seismic parameters therefrom.

[0007] The seismic cable may include a fiber optic cable and the base station may include a light source for sending and receiving a light through the fiber optic cable. The seismic cable may link the base station to the mobile satellite nodes in series. The satellite nodes may be seismic trucks. The fiber optic cable may include fiber optic sections coupled together. The seismic acquisition unit may include recording media (e.g., tape drives and/or raid drives), a source controller, an acquisition management system, spread & opto-electronics, and/or a generic acquisition system. The seismic cable may link the satellite nodes to the base station in a looped, a linear, a star, and/or a concentric ring configuration. The sensor stations may be connected to the satellite node by array cables.

[0008] The present disclosure also relates to an integrated method for monitoring seismic parameters of subsurface structures. The method involves providing an integrated seismic system including a base station and a plurality of mobile satellite nodes (each of the satellite nodes has sensor stations operatively connectable thereto), linking the mobile satellite nodes and the sensor stations with a seismic cable, collecting the seismic data from the subsurface structure with the sensor stations, and receiving seismic signals at a base station from the mobile satellite nodes via the seismic cable and generating seismic parameters therefrom.

[0009] The method may also involve sending and receiving a light from a light source at the base station through the seismic cable and to the sensor stations, positioning the mobile satellite nodes and the sensor stations about the subsurface location, analyzing the measured seismic parameters, processing the measured seismic parameters, generating a seismic disturbance at the surface location, and correlating a position of the sensor station (e.g., a GPS location) with the seismic parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] A more particular description of the subject matter, briefly summarized herein, may be had by reference to the embodiments thereof that are illustrated in the appended drawings. The figures are not necessarily to scale, and certain features and certain views of the figures may be shown exaggerated in scale or in schematic in the interest of clarity and conciseness.

[0011] FIG. 1 shows a schematic view of an integrated seismic system for monitoring seismic parameters of a subsurface structure, the system including a base unit, mobile satellite nodes and sensor stations linked by a fiber optic cable.

[0012] FIG. 2 shows a schematic view of a portion 2 of the system of FIG. 1 depicting the mobile satellite node and sensor stations in greater detail.

[0013] FIG. 3 shows a schematic view of a seismic acquisition unit.

[0014] FIG. 4 is a flow chart depicting a method of monitoring seismic parameters of a subsurface structure.

DETAILED DESCRIPTION

[0015] The description that follows includes exemplary apparatuses, methods, techniques, and instruction sequences

that embody techniques of the subject matter. However, it is understood that the described embodiments may be practiced without these specific details.

[0016] Systems and methods for integrated seismic monitoring are provided. The integrated system includes a base unit, a plurality of mobile satellite nodes, and a plurality of sensor stations. A fiber optic cable joins the base unit to the multiple mobile satellite nodes distributed about a surface location for interactive operation therebetween. Each of the mobile satellite nodes has sensor stations for collecting seismic data relating to a subsurface formation. A single light source at the base unit may be used to send and receive a laser light to each seismic satellite node. The information from each of the seismic satellite nodes may be collected and manipulated at the base station.

[0017] FIG. 1 schematically depicts a system 100 for monitoring seismic parameters of a subsurface structure 102. The system 100 includes a base station (or camp) 104, multiple mobile satellite nodes 106 and multiple sensor stations 108. The base station 104 may be a consolidated or centralized location for controlling operations throughout the system 100. Operators may be stationed at the base station 104 for performing manual and/or automatic operations throughout the system 100. The mobile satellite nodes 106 may optionally be unmanned with operators located at the base station 104 for controlling operations at each of the satellite nodes 106.

[0018] The satellite nodes 106 may be seismic trucks or other mobile devices or vehicles deployable to various surface locations about the subsurface structure 102. Each satellite node 106 may have array (or seismic array) cables 120 linked to multiple sensor stations 108 for collecting seismic data. A seismic cable 110 extends from the base station 104 and to each of the satellite nodes 106. The seismic cable 110 may be deployed from the base station 104 on a reel and extended to each of the sensor stations 108 for communication therewith. A communication network may be formed by linking the base station 104 to the satellite nodes 106 and the sensor stations 108 via the seismic cable 110. The seismic cable 110 may be a unitary cable, or multiple cables joined together to form a single cable. Connectors for joining cables are described in U.S. Pat. No. 6,827,597.

[0019] Any cable capable of communicating between the base station 104 and the sensor stations 108 may be used. The seismic cable 110 may be, for example, a conventional fiber optic cable used in seismic surveying. Conventional fiber optic cables, such as a steel armored optical cable with optical fibers inside gel-filled stainless steel tubes, may be used. In some cases, portions of the integrated seismic system may have additional or other communication links using wired or wireless communication links therebetween.

[0020] The base station 104 may have a light source 112 including a laser for emitting a laser light 111 through the seismic cable 110. Examples of techniques for passing laser light through a fiber optic cable are described in U.S. Pat. No. 7,622,706. A seismic detector 114 may be provided for detecting changes in the laser light 111. A processor 116 may also be provided for analyzing the changes and determining seismic parameters therefrom. A seismic acquisition unit 118 may be provided at the base station 104 for receiving the light 111 and determining seismic parameters therefrom as will be described further herein. The satellite nodes 106 may be provided with the same capabilities of the base station 104 for operating independently thereof as desired.

[0021] A selected length of optical cable 110 may be used to carry light from the light source, which is distributed to the various sensor stations 108 in the seismic system 100. The light in the sensor stations 108 experiences a change or phase shift related to the physical property being measured. Changes in optical characteristics of the optical fibers causes changes in the properties of the applied light which may be detected by one of a number of different optical measurement techniques. Optical signals from the sensor stations 108 are then collected and returned to a receiving device for demultiplexing and analyzing the signals from each sensor station 108.

[0022] Examples of fiber optic cables are provided in U.S. Pat. No. 6,850,461. The fiber optic cable may use wavelength-division multiplexing (WDM) and/or frequency division multiplexing (FDM) techniques in which optical splitting of source light from an input bus to individual sensors and recombination of signals from the individual sensors are made in discrete modules, such that optical splicing and splitting or recombining components are mechanically isolated from other portions of the cable. Portions of the cable and/or sensor stations may be replaceable to address any failures that may occur in the system.

[0023] A seismic source 119 may be provided for producing impact, vibration, explosion or other seismic events to generate seismic waves through the subsurface structure 102. Conventional seismic sources, such as a seismic vibration truck may be used (see, e.g., US Patent Application No. 2009/0238038). In some cases, the seismic satellite nodes 106 may be capable of generating seismic waves in the subsurface structure 102. The integrated seismic system 100 may be positioned about the seismic source 119 and/or subsurface structure 102 for measuring seismic parameters generated by the seismic source 119.

[0024] A data network ring may be set up from the base station 104 to the satellite nodes 106 to communicate the status of the system 100 during the seismic acquisition. The integrated seismic system 100 may form a seismic network about the surface of the subterranean structure. One or more satellite nodes 106 may be linked to the base station 104 to form the network. The satellite nodes 106 may be positioned at various locations about the surface of the subsurface structure 102. The seismic cable 110 may extend from the base station 104 to the satellite nodes 106 in series or in discrete intervals.

[0025] As shown in FIG. 1, the satellite nodes 106 form a continuous loop extending from the base station 104 to each of the satellite nodes in series and back to the base station 104. The satellite nodes 106 may be positioned in various configurations, such as the loop (or ring), a star, a linear, and/or other configurations. Various combinations of continuous and/or linear configurations may be used to provide a variety of configurations. The light source 112 at the base station 104 may emit a light 111 for passing through each of the satellite nodes 106 and returning to the base station 104. In a continuous configuration, such as a loop, ring or star, the light 111 may pass through the fiber optic cable 110 and continue to the seismic acquisition unit 118 therein as indicated by the dashed arrow. In a linear configuration, the light source 112 may emit a light 111 therethrough and receive it back there-through. As indicated by the two way solid arrow, data may pass both ways through system 100 via the seismic cable 110.

[0026] The satellite nodes 106 may be processing units with, for example, about a 72,000 channel capacity. Acquisi-

tion survey needs may require systems having about one million or more channels. Multiple satellite nodes **106** may be deployed for providing the necessary channel capabilities. The integrated network formed by the system **100** may be used to operate the channels provided by multiple satellite nodes **106** from a single location. The seismic acquisition unit **118** may be used to receive and process the data from the multiple nodes and to perform necessary quality control (QC) and operational control. The integrated configuration provided by the system **100** may be used to compare data from multiple sources, eliminate redundancies, and provide an integrated analysis of the data.

[0027] FIG. 2 shows a schematic view of a portion **2** of the seismic system **100** of FIG. 1. This figure also shows one of the satellite nodes **106** (depicted as a seismic truck) and the sensor stations **108** in greater detail. As shown, multiple array cables **120** extend from the satellite node **106**, with each array cable **120** having multiple sensor stations **108**. The sensor stations **108** may be operatively connectable to the satellite node **106** for interaction therewith. The sensor stations **108** may be carried by the seismic cable **110**, or connected thereto at the surface locations. The sensor stations **108** may be conventional optical sensors positionable about the surface locations for measuring seismic parameters of the subsurface structure **102**. The optical sensors may be, for example, hydrophones, accelerometers, or geophones, for sensing physical properties, such as subsurface motion, energy or changes in pressure. The sensor stations **108** may have radio frequency identification (RFID) tags **R** containing information, such as identifiers, for each sensor station.

[0028] The sensor stations **108** may be connected to a sensor pad on the seismic cable **110**. By way of example, the sensor pads may be located about every 25 m along the seismic cable **110**. The sensor stations **108** may be positioned at various locations and used to generate an optical signal in response to the sensed physical properties. The optical signal may be, for example, a change in wavelength, a change in phase or an interference pattern in response to changes in the physical parameter. Examples of optical sensor stations are provided in U.S. Pat. Nos. 7,154,082, and 6,549,488. Multiple sensor stations **108** may be multiplexed from the light source **112** at the base station **104** and signal return optical fibers using optical telemetry systems.

[0029] As shown in FIG. 2, the seismic cable **110** enters the satellite node **106** from the base station **104** and is split out into the array cables **120**. The seismic cable **110** continues through the satellite node and on to the next satellite node(s) and back to the base station **104**. Communication with the base station **104** may be provided with the satellite node **106** and/or sensor stations **108** for determining seismic parameters. The laser light **111** may pass through the seismic cable **110**, through the satellite node **106** and out on to the base station **104** as indicated by the dashed arrows. The laser light **111** is also directed through the sensor cables and returned back to the satellite node **106**. When the laser light **111** passes from the base station **104** to the satellite nodes **106**, the satellite nodes **106** collect, amplify and redistribute the light.

[0030] The seismic cable **110** may also be used to pass data between the satellite node **106** and back to the base station **104** as indicated by bidirectional arrows. The data may be directed to the seismic acquisition unit **118** of FIG. 1. The satellite node **106** may house its own seismic acquisition unit **218** for collecting and recording seismic data for its sensor stations **108**. The seismic acquisition units **118** and/or **218**

may receive the light **111** that passes to the sensor stations **108** and is returned therefrom, and may determine seismic parameters as will be described further herein. The seismic acquisition unit **218** may have part or all of the functionality of the seismic acquisition unit **118** of FIG. 1.

[0031] FIG. 3 is a schematic view of system architecture that may be used as the seismic acquisition unit **118** of the base station **104** of FIG. 1 and/or the seismic acquisition unit **218** of the satellite node **106** of FIG. 2. The seismic acquisition unit **118/218** includes electronic components including an acquisition management system **330**, a QC/Processing System **332**, recording media **334**, **335**, spread & optoelectronics **336**, a source controller **338**, and an acquisition recorder (or generic acquisition system (sometimes referred to as “gAS?”)) **340**. Various links may be provided between the electronic components for operative connection therebetween.

[0032] The source controller **338** provides communication between an operator at the base station and the satellite nodes **106**. Data from the satellite nodes **106** is passed from the source controller **338** to the acquisition management system **330**. The acquisition management system **330** provides communication between an operator at the base station **104** and the satellite nodes **106**. Data from the satellite nodes **106** is passed back to the acquisition management system **330**. The acquisition management system may also communicate with the source controller **338** to provide vibrator information to be stored along with the data. The acquisition management system **330** acts as a central processing unit (CPU) for processing all of the data of the seismic acquisition unit **118/218**. The acquisition management system **330** also communicates with the QC/Processing system **332** and the spread & optoelectronics **336**. The QC/Processing system **332** may be a network computer used for data manipulation, such as signal processing, visualization of data, etc. Data from the QC/Processing system **332** may be passed to an individual record storage **334** for recording. The individual record storage **334** may be a recording media, such as tape drives for storing the data.

[0033] The spread & optoelectronics **336** receives signals from the satellite nodes **106** and converts the signals into seismic data for recording. The seismic data may be passed from the spread & optoelectronics **336** to the acquisition recorder **340** for formatting by an Ethernet connection. The acquisition recorder **340** formats the seismic data for recording. The formatted data may be passed to a recording media **335**, such as a continuous data storage, for recording. The data storage **335** may be a recording media, such as a raid drive for storing the data.

[0034] The system architecture enables the seismic acquisition and QC functions to take place in the centralized base station **104**. The satellite nodes **106** may also perform certain functions, such as initial quality control (QC) functions, at the seismic acquisition unit **218** and report status back the seismic acquisition unit **118** of the base station **104** where the main control takes place. Information may be provided at multiple levels to provide redundancy, cross-checks, and interpretation.

[0035] The seismic acquisition unit **118/218** may also be used to collect information from the RFID tags **R** of the sensor stations **108**. The computers in the system and/or additional RFID units may be provided to communicate with and/or collect information from the RFID tags. The RFID tags **R** may be scanned by an RFID unit (not shown) during or after

deployment to the field **102** to identify the RFID unit by location along the surface location **102**. The RFID unit may also have an RFID sensor for receiving data from and logging the sensor stations. This information may be used with the data collected by the seismic cable **110** and/or sensor stations **108** to, for example, correlate seismic data with location and/or sensor information specific to the identified sensor station **108**.

[0036] The seismic acquisition unit **118/218** may have processors/computers to provide such correlations. For example, the seismic acquisition unit **118/218** may have a global positioning satellite (GPS) tracker that gathers information from the RFID tags that may be used to plot a position of the sensors using. Information concerning a location of each sensor may be determined using conventional GPS technology linked to an output from each sensor station **108**. The GPS data may provide position data in a three dimensional axis. Z-axis data may provide elevation information so that the sensor stations may be corrected to a similar flat datum. X-axis and Y-axis data may position data so that digital filters can be provided to remove additional error. The gathered GPS data for each sensor station may be correlated with the data collected by the sensor station for further analysis. The analyzed information may be used to determine subsurface properties at a given location.

[0037] In operation, dense wavelength division multiplexing (DWDM) may be used in the integrated seismic system **100** to optically power the sensor stations **108**. By way of example, an optoelectronic cabinet may be assembled using **10** wavelengths with the capacity to run 960 sensor or 240 4C channels. Multiplexed and modulated light **111** may be sent into the seismic cable **110** and the array cables **120** to the sensor stations **108**. The light **111** returning from the sensor stations **108** may be demultiplexed and demodulated. A phase modulated laser light **111** passes through an interferometer in the sensor station **108**. Stress from the outside world causes a phase shift in the light **111** as it passes through the interferometer. Using the seismic acquisition system **118/218**, the phase information is extracted from the returning light to output a signal equivalent to the stress input at the sensor station **108**. This provides a passive system with no electronics.

[0038] The light source **112** generates the optical power for the array of sensor stations **108**, and processes the returned optical signals to extract the seismic information. Light **111** returning from the sensor array cables **120** may be routed to a select group of demodulation boards to process the optical data, and outputs a 'word' (e.g., a 32-bit digital word) equal to the seismic data. The data may be processed by the seismic acquisition unit **118** (e.g., a network interface card), where it is put into data packets, and sent to the data storage **334, 335**.

[0039] FIG. 4 is a flowchart depicting a method **400** of monitoring seismic parameters of a subsurface structure **102**. The method **400** involves providing an integrated seismic system such as the system **100** of FIG. 1 (e.g., including a base station **104** and a plurality of satellite nodes **106** and a plurality of sensor stations **108**). The method also involves positioning **(482)** the satellite nodes and the sensor station about a surface location, generating **(483)** a seismic disturbance at the surface location, linking **(484)** the mobile satellite nodes and the sensor station with a seismic cable, passing **(486)** a light from the laser through the optical cable, collecting **(488)** seismic data from the subsurface structure with the sensor station by detecting disturbances in the light, and receiving

(490) seismic signals at the base station from the mobile satellite nodes via the seismic cable and generating seismic parameters therefrom.

[0040] The method may also involve analyzing the measured seismic parameters. Other steps may also be performed, such as performing a quality control check, and/or capturing and/or correlating information from the sensed RFID tags with the subsurface data collected by the sensor stations. The steps may be performed automatically or manually, in any order and repeated as desired.

[0041] While the present disclosure describes configurations, numerous modifications and variations will become apparent to those skilled in the art after studying the disclosure, including use of equivalent functional and/or structural substitutes for elements described herein. For example, aspects of the subject matter may include two or more seismic trucks (or nodes) connected by one or more seismic cables, and have one or more sensor stations.

[0042] Plural instances may be provided for components, operations or structures described herein as a single instance. In general, structures and functionality presented as separate components in the exemplary configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be implemented as separate components.

1. An integrated seismic system for monitoring seismic parameters of a subsurface structure, the integrated seismic system comprising:

a plurality of mobile satellite nodes, each of the plurality of mobile satellite nodes having sensor stations operatively connectable thereto for collecting seismic data from the subsurface structure;

a seismic cable operatively linking the plurality of mobile satellite nodes and the sensor stations; and

a base station comprising a seismic acquisition unit for receiving seismic signals from the plurality of mobile satellite nodes via the seismic cable and generating seismic parameters therefrom.

2. The integrated seismic system of claim 1, wherein the seismic cable comprises a fiber optic cable and wherein the base station comprises a light source for sending and receiving a light through the fiber optic cable.

3. The integrated seismic system of claim 2, wherein the fiber optic cable comprises a plurality of fiber optic sections coupled together into a continuous fiber optic cable.

4. The integrated seismic system of claim 1, wherein the seismic cable links the base station to the plurality of mobile satellite nodes in series.

5. The integrated seismic system of claim 1, wherein the plurality of mobile satellite nodes comprise a plurality of seismic trucks.

6. The integrated seismic system of claim 1, wherein the seismic acquisition unit comprises recording media for collecting the measured seismic parameters.

7. The integrated seismic system of claim 1, wherein the seismic acquisition unit comprises a source controller.

8. The integrated seismic system of claim 1, wherein the seismic acquisition unit comprises an acquisition management system.

9. The integrated seismic system of claim 1, wherein the seismic acquisition unit comprises spread and optoelectronics.

10. The integrated seismic system of claim 1, wherein the seismic acquisition unit comprises an acquisition recorder.

11. The integrated seismic system of claim **1**, where the seismic cable links the plurality of mobile satellite nodes to the base station in one of a looped configuration, a linear configuration, a star configuration, a concentric ring configuration and combinations thereof.

12. The integrated seismic system of claim **1**, where each of the sensor stations are connected to the plurality of mobile satellite nodes by an array cable.

13. The integrated seismic system of claim **1**, wherein each of the sensor stations comprises a radio frequency identification tag.

14. An integrated method for monitoring seismic parameters of a subsurface structure, comprising:

providing an integrated seismic system comprising a base station and a plurality of mobile satellite nodes, each of the plurality of mobile satellite nodes having sensor stations operatively connectable thereto;
linking the plurality of mobile satellite nodes and the sensor stations with a seismic cable;

collecting seismic data from the subsurface structure with the sensor stations; and

receiving seismic signals at a base station from the plurality of mobile satellite nodes via the seismic cable and generating seismic parameters therefrom.

15. The method of claim **14**, further comprising sending and receiving a light from a light source at the base station through the seismic cable and to the sensor stations

16. The method of claim **14**, further comprising analyzing the measured seismic parameters.

17. The method of claim **14**, further comprising processing the measured seismic parameters.

18. The method of claim **14**, further comprising generating a seismic disturbance at the surface structure.

19. The method of claim **14**, further comprising correlating a position of the sensor stations with the seismic data.

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