



(51) International Patent Classification:

E21B 47/00 (2012.01) *G01V 1/46* (2006.01)
G01V 1/40 (2006.01)

(21) International Application Number:

PCT/US2015/027449

(22) International Filing Date:

24 April 2015 (24.04.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/003,292 27 May 2014 (27.05.2014) US

(71) Applicant: **BAKER HUGHES INCORPORATED**
[US/US]; P.O. Box 4740, Houston, Texas 77210-4740
(US).

(72) Inventors: **MARTIN, Carl S.**; 2929 Allen Parkway, Suite
2100, Houston, TX 77019-2118 (US). **HALL, Travis S.**;
2929 Allen Parkway, Suite 2100, Houston, TX 77019-
2118 (US). **HARRIS, Shane D.**; 2929 Allen Parkway,
Suite 2100, Houston, TX 77019-2118 (US).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,

DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a
patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the
earlier application (Rule 4.17(iii))

Published:

- with international search report (Art. 21(3))

(54) Title: A METHOD OF CALIBRATION FOR DOWNHOLE FIBER OPTIC DISTRIBUTED ACOUSTIC SENSING

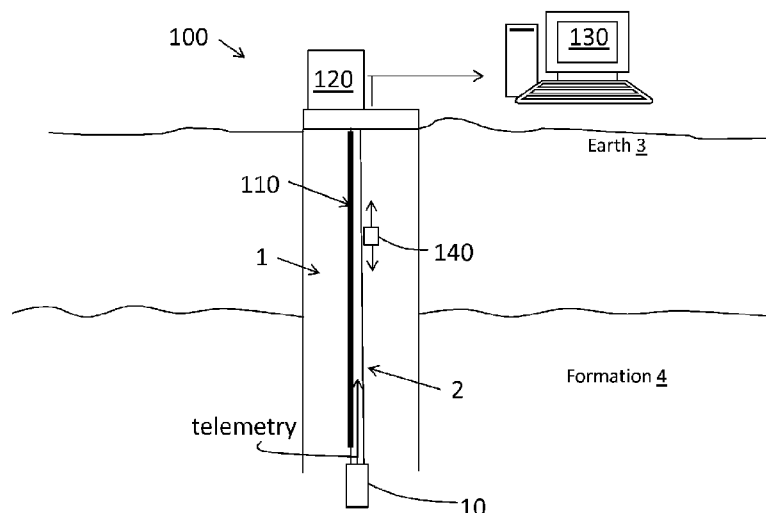


FIG. 1

(57) Abstract: A method of operating a distributed acoustic sensing (DAS) system and a DAS system are described. The method includes disposing the DAS system to measure acoustic signals in a borehole, positioning a vibration tool at a specified depth in the borehole, and obtaining two or more DAS signals, obtaining at least one of the two or more DAS signals while the vibration tool is activated at a respective specified frequency and a respective specified amplitude. The method also includes calibrating the DAS system based on the two or more DAS signals, and the specified depth, the respective specified frequency, and the respective specified amplitude.



A METHOD OF CALIBRATION FOR DOWNHOLE FIBER OPTIC DISTRIBUTED ACOUSTIC SENSING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Application No. 62/003292, filed on May 27, 2014, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] In downhole exploration and production efforts, many sensors and measurement systems are used to ascertain information about the downhole environment. Some of these include pressure sensors, temperature sensors, and nuclear magnetic resonance (NMR) sensors used to determine information about a formation, for example. Distributed acoustic sensing (DAS) systems facilitate the identification of downhole events based on changes in vibration or noise, for example.

SUMMARY

[0003] According to an embodiment of the invention, a method of operating a distributed acoustic sensing (DAS) system includes disposing the DAS system to measure acoustic signals in a borehole; positioning a vibration tool at a specified depth in the borehole; obtaining two or more DAS signals, obtaining at least one of the two or more DAS signals while the vibration tool is activated at a respective specified frequency and a respective specified amplitude; and calibrating the DAS system based on the two or more DAS signals, and the specified depth, the respective specified frequency, and the respective specified amplitude.

[0004] According to another embodiment, a distributed acoustic sensing (DAS) system includes an optical fiber disposed in a borehole; a light source configured to inject light into the optical fiber; a sensor configured to obtain a DAS signal based on the light; a vibration tool disposed in the borehole at a specified depth, the vibration tool configured to output a vibration signal at one or more specified frequencies and one or more specified amplitudes; and a processor configured to calibrate the DAS system based on two or more DAS signals, at least one of the two or more DAS signals obtained while the vibration tool is activated at a respective specified frequency and a respective specified amplitude, and the specified depth, the respective specified frequency, and the respective specified amplitude.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Referring now to the drawings wherein like elements are numbered alike in the several Figures:

[0006] FIG. 1 is a cross-sectional view of a borehole including a DAS calibration system according to an embodiment of the invention;

[0007] FIG. 2 is a cross-sectional view of a borehole including a DAS calibration system according to another embodiment of the invention;

[0008] FIG. 3 details the DAS calibration system shown in FIG. 1 according to one embodiment of the invention;

[0009] FIG. 4 is a process flow of a method of calibrating a DAS system according to embodiments of the invention; and

[0010] FIG. 5 is a process flow of a method of identifying an acoustic event based on a calibrated DAS system according to embodiments of the invention.

DETAILED DESCRIPTION

[0011] As noted above, DAS systems are among the types of sensors used to gather information about a downhole environment. These systems typically involve the use of an optical fiber, light injected into the optical fiber as an interrogation signal, photodetectors that receive light intensity return signals (from Rayleigh backscatter, for example), and a processor that processes the return signals to ascertain the acoustic information. The optical fiber may be longer than only the portion disposed downhole and may be coiled or otherwise deviate from a straight line such that a specific length of the optical fiber does not correspond with a specific depth in the downhole environment. As a result, current DAS systems cannot easily associate a downhole acoustic event with a specific depth. In addition, the response of a DAS system in a test environment may be slightly or drastically different than the response in the downhole environment based on many factors. As a result, current DAS systems indicate relative acoustic levels (such that an occurrence of an event may be recognized) but cannot quantify the acoustic event. Embodiments of the methods and systems discussed herein relate to calibration of a DAS system to facilitate quantified acoustic detection and depth identification.

[0012] FIG. 1 is a cross-sectional view of a borehole 1 including a DAS system 100 according to an embodiment of the invention. As shown in FIG. 1, the borehole 1 is a completion well, a well ready for production or injection following a drilling process. The DAS system 100 includes an optical fiber 110 and an interrogation unit 120. In the

exemplary embodiment shown by FIG. 1, the interrogation unit 120 is on the surface, and the optical fiber 110 is disposed along a carrier 2. The DAS system 100 also includes a calibration component comprising a vibration tool 140 that outputs vibrations at a specified frequency and amplitude. As indicated in FIG. 1, the vibration tool 140 may be moved along the carrier 2 to a specified location within the completion well 1. While the DAS system 100 may be used in other environments and in other sub-surface arrangements, the exemplary DAS system 100 shown in FIG. 1 is arranged to calibrate acoustic levels in the borehole 1 (completion well) penetrating the earth 3 including a formation 4. A set of tools 10 may be lowered into the borehole 1 by a carrier 2. In embodiments of the invention, the carrier 2 is a completion string and may be a casing string, production string, an armored wireline, a slickline, coiled tubing, or a work string. Information from the sensors and measurement devices included in the set of tools 10 may be sent to the surface for processing by the surface processing system 130 via a fiber link or telemetry. The surface processing system 130 (e.g., computing device) includes one or more processors and one or more memory devices in addition to an input interface and an output device.

[0013] FIG. 2 is a cross-sectional view of a borehole 1 including a DAS system 100 according to another embodiment of the invention. The exemplary embodiment of FIG. 2 shows a cased well that includes casing 5 on the inside of the borehole 1. The optical fiber 110 is shown disposed along the casing 5 in FIG. 2. To be clear, the position of the optical fiber 110 is not limited by the exemplary illustrations. For example, the optical fiber 110 may be disposed along the borehole 1 wall in the open well shown in FIG. 1 or may be disposed along the carrier 2 in the cased well of FIG. 2. In addition, the vibration tool 140 may be disposed in a different location within the borehole 1 (e.g., to move along the casing 5) than the exemplary location shown in FIGs. 1 and 2.

[0014] FIG. 2 details the DAS system 100 shown in FIG. 1 according to one embodiment of the invention. The DAS system 110 includes an interrogation unit 120 with a light source 310 and one or more photodetectors 320 to receive the scatter (e.g., Rayleigh backscatter) from the optical fiber 110. The interrogation unit 120 may additionally include a processing system 330 with one or more processors and memory devices to process the scatter resulting from illuminating the optical fiber 110. Alternately, the photodetectors 320 may output the reflection information to the surface processing system 130 for processing. The interrogation unit 120 typically includes additional elements such as a circulator (not shown) to direct light from the light source 310 into the optical fiber 110 and scatter or reflection generated in the optical fiber 110 to the one or more photodetectors 320. Although

the one or more photodetectors 220 are shown at the surface as part of the interrogation unit 120 in FIG. 1, other sensors (e.g., geophones 340) may instead be distributed at different depths along the borehole 1 (e.g., along the casing 5 or carrier 2). The specific arrangement of the DAS system 110 is not limited in any way based on the exemplary embodiments discussed herein.

[0015] The light source 310 may be a coherent light source in which light waves are in phase with one another. According to one embodiment, the light source 310 may be a laser and may emit pulses of light at the same wavelength and amplitude. According to an alternate embodiment, the light source 310 may be a swept-wavelength laser and may emit pulses of light having a range of wavelengths. The photodetector 320 detects a DAS signal resulting from the incident light pulses being emitted into the optical fiber 110. According to an embodiment of the invention, the DAS signal is a measure of interference among the Rayleigh scatter originating from multiple nearby points in the optical fiber 110 over time (a number of samples of interference signals from a particular length of the optical fiber 110). According to alternate embodiments, the DAS signal may be a measure of interference among scatter resulting from Stokes or anti-Stokes Raman scatter or reflections resulting from or fiber Bragg gratings (FBGs) within the optical fiber 110. The DAS signal is processed to determine the acoustic information.

[0016] The DAS signal may be received and processed continuously at a specified interval or may be received and processed based on some trigger. During the calibration process, the vibration tool 140, which is also part of the DAS system 100, is lowered into the borehole 1 to a known depth. The vibration tool 140 may be locked into the carrier 2 at the known depth with slips, a nipple locator, or another type of locking device. The vibration tool 140 may be operated electrically, hydraulically, or by another method such that a known frequency and amplitude are emitted. DAS signals are obtained by the photodetector 320 both with and without the vibration tool 140 being activated or with the vibration tool 140 activated at different amplitudes and frequencies. That is, two or more DAS signals are obtained to perform the calibration. According to one embodiment, a DAS signal is obtained when the vibration tool 140 is not activated and then a two or more DAS signals are obtained after the vibration tool 140 is activated. According to another embodiment, one or more baseline DAS signals are obtained when the vibration tool 140 is activated and then a DAS signal is obtained when the vibration tool 140 is not activated. According to yet another embodiment, two or more DAS signals are obtained when the vibration tool 140 is activated at known amplitude and frequency values. The vibration tool 140 may be moved to one or

more other known depths and the process of obtaining DAS signals may be repeated. Based on the DAS signals (with or without vibration tool 140 activation), the acoustic output of the DAS system 110 is calibrated using the known frequency, amplitude, and depth of the vibration tool 140 output. The calibration itself (how the DAS signals and known values are used) is according to one or more known techniques. Once the DAS system 110 is calibrated, the vibration tool 140 may be removed from the borehole 1. As noted above, at this point, the DAS system 110 may be used to detect an acoustic event in the borehole 1. Because of the calibration process, the DAS system 110 is able to quantify the event and also discern the depth of the event.

[0017] FIG. 4 is a process flow of a method of calibrating a DAS system 110 according to embodiments of the invention. At block 410, disposing the DAS system 110 to measure acoustic signals in the borehole 1 may be as shown in FIG. 1, for example. Positioning the vibration tool 140 at block 420 includes moving the vibration tool 140 to different depths in the borehole 1. This may be done by moving the vibration tool 140 along the carrier 2 or casing 5 and locking the vibration tool 140 in place at a specified depth. At block 430, obtaining a DAS signal includes the DAS system 110 receiving interference signals based on Rayleigh scatter, for example, while the vibration tool 140 is not activated. At block 440, activating the vibration tool includes emitting a signal with a specified frequency and amplitude. At block 450, obtaining the DAS signal measuring vibration tool 140 output includes receiving interference signals based on Rayleigh scatter, for example, while the vibration tool 140 is activated. According to an alternate embodiment, a DAS signal may not be obtained while the vibration tool 140 is not activated (at block 430). Instead, two or more DAS signals may be obtained with the vibration tool 140 being activated at two or more different amplitude or frequency values (at block 450), as noted above. According to another alternate embodiment, one or more DAS signals may be obtained with the vibration tool 140 activated (at block 450) and then a DAS signal may be obtained with the vibration tool 140 being deactivated. At block 460, using the DAS signals (obtained at blocks 430, 450, or both) and the known vibration tool 140 output to calibrate the DAS system 110 facilitates determination of quantitative acoustic level and depth of origin of an acoustic event. As indicated in FIG. 4, blocks 420 through 450 may be repeated. That is, DAS signals may be obtained with the vibration tool 140 located at different depths. The number of depths at which the vibration tool 140 is operated may improve the resolution of the DAS system 110 calibration.

[0018] FIG. 5 is a process flow of a method of identifying an acoustic event based on a calibrated DAS system 110 according to embodiments of the invention. At block 510, calibrating the DAS system 110 is as discussed above. Obtaining acoustic information with the calibrated DAS system 110 at block 520 may include removing the vibration tool 140 from the borehole 1 and obtaining and processing DAS signals periodically or based on a trigger. Because of the calibration, the acoustic information obtained from the DAS signals is quantified (a specific vibrational force is identified, for example) and a depth of the origin of the acoustic information is obtained. Identifying an event (cause of the acoustic information) and a depth based on the acoustic information, at block 530, may be according to a database of known acoustic events, for example. That is, a specific range of amplitudes may be associated with breach of water flow into the borehole 1, for example. Thus, a lookup table may be implemented to identify the cause of an acoustic event, for example.

[0019] While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation.

CLAIMS:

1. A method of operating a distributed acoustic sensing (DAS) system, the method comprising:
 - disposing the DAS system to measure acoustic signals in a borehole;
 - positioning a vibration tool at a specified depth in the borehole;
 - obtaining two or more DAS signals, obtaining at least one of the two or more DAS signals while the vibration tool is activated at a respective specified frequency and a respective specified amplitude; and
 - calibrating the DAS system based on the two or more DAS signals, and the specified depth, the respective specified frequency, and the respective specified amplitude.
2. The method according to claim 1, wherein the disposing the DAS system includes disposing an optical fiber in the borehole, disposing a light source to inject light into the optical fiber, and disposing one or more photodetectors, the one or more photodetectors detecting interference resulting from the light in the optical fiber.
3. The method according to claim 2, wherein the detecting interference includes detecting interference among Rayleigh scatter originating at two or more points along the optical fiber.
4. The method according to claim 3, further comprising processing the interference to obtain a DAS signal and obtaining acoustic information based on the DAS signal.
5. The method according to claim 2, wherein the disposing the light source and the disposing the one or more photodetectors is at a surface location.
6. The method according to claim 1, wherein the obtaining the two or more DAS signals includes obtaining at least one of the two or more DAS signals while the vibration tool is inactive.
7. The method according to claim 1, further comprising disposing two or more geophones at different locations within the borehole to obtain the baseline DAS signal and the calibration DAS signal.
8. The method according to claim 1, wherein the positing the vibration tool includes affixing the vibration tool to a carrier disposed in the borehole at the specified depth.
9. The method according to claim 1, further comprising removing the vibration tool from the completion well following the calibrating.

10. The method according to claim 1, further comprising quantifying an acoustic event and determining a depth of the acoustic event based on obtaining a post-calibration DAS signal after the calibrating.

11. The method according to claim 10, further comprising identifying a cause of the acoustic event based on the quantifying and a lookup table.

12. A distributed acoustic sensing (DAS) system, comprising:
an optical fiber disposed in a borehole;
a light source configured to inject light into the optical fiber;
a sensor configured to obtain a DAS signal based on the light;
a vibration tool disposed in the borehole at a specified depth, the vibration tool configured to output a vibration signal at one or more specified frequencies and one or more specified amplitudes; and

a processor configured to calibrate the DAS system based on two or more DAS signals, at least one of the two or more DAS signals obtained while the vibration tool is activated at a respective specified frequency and a respective specified amplitude, and the specified depth, the respective specified frequency, and the respective specified amplitude.

13. The system according to claim 12, wherein the sensor is a photodetector configured to obtain the DAS signal based on detecting interference among Rayleigh scatter originating at two or more points along the optical fiber.

14. The system according to claim 13, wherein the processor processes the interference to obtain the DAS signal and processes the DAS signal to obtain acoustic information.

15. The system according to claim 12, wherein the sensor is disposed at a surface location.

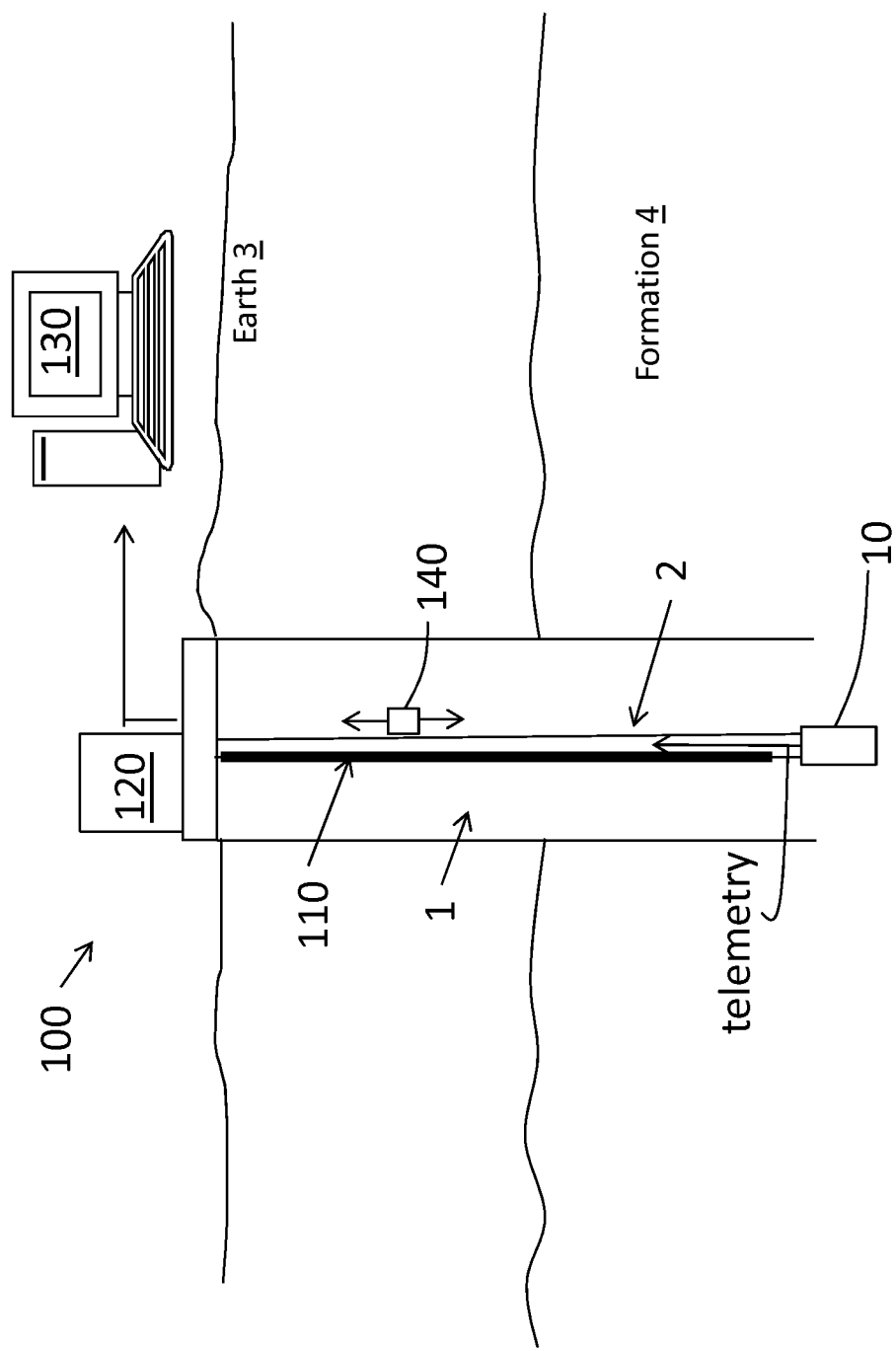


FIG. 1

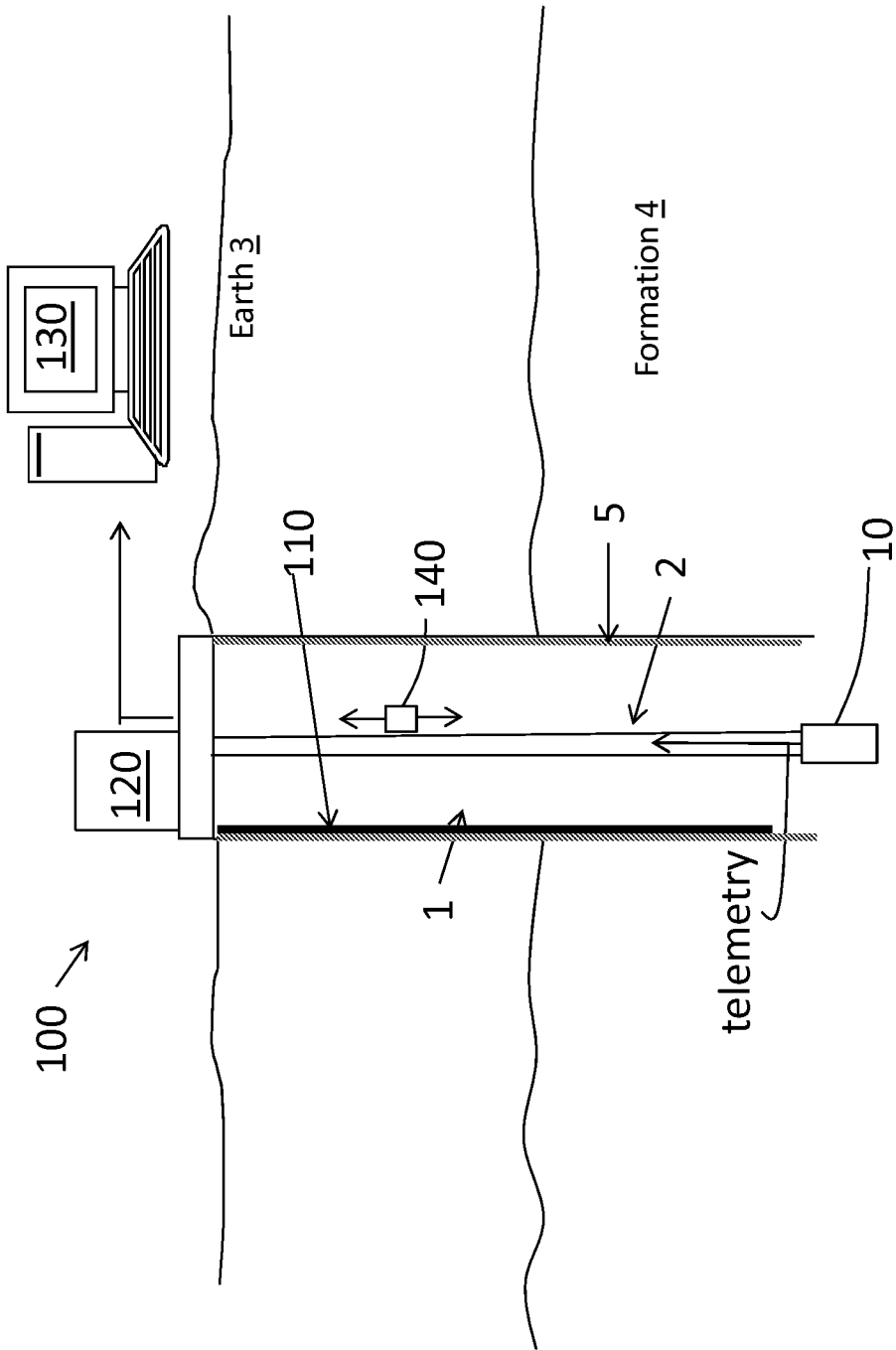


FIG. 2

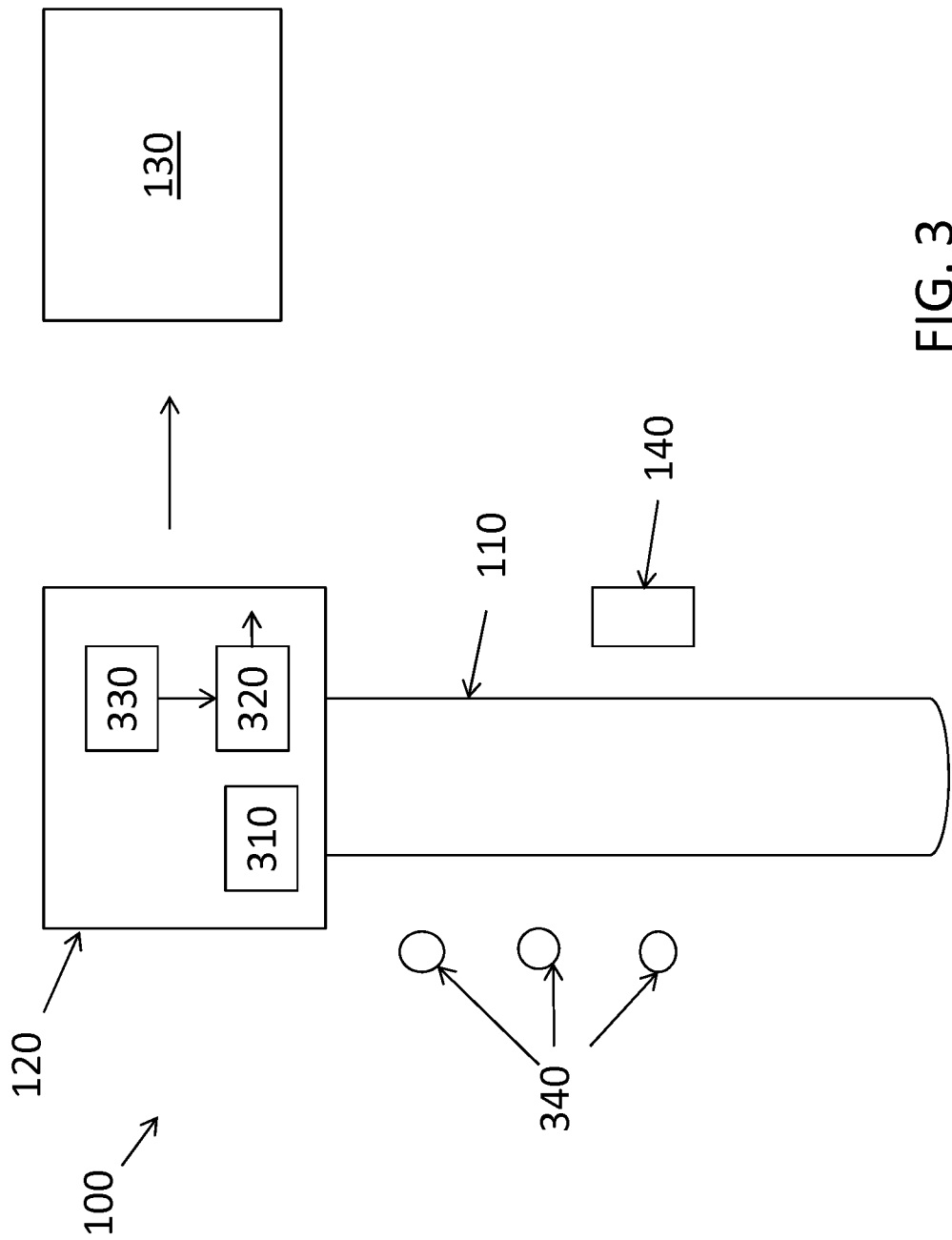


FIG. 3

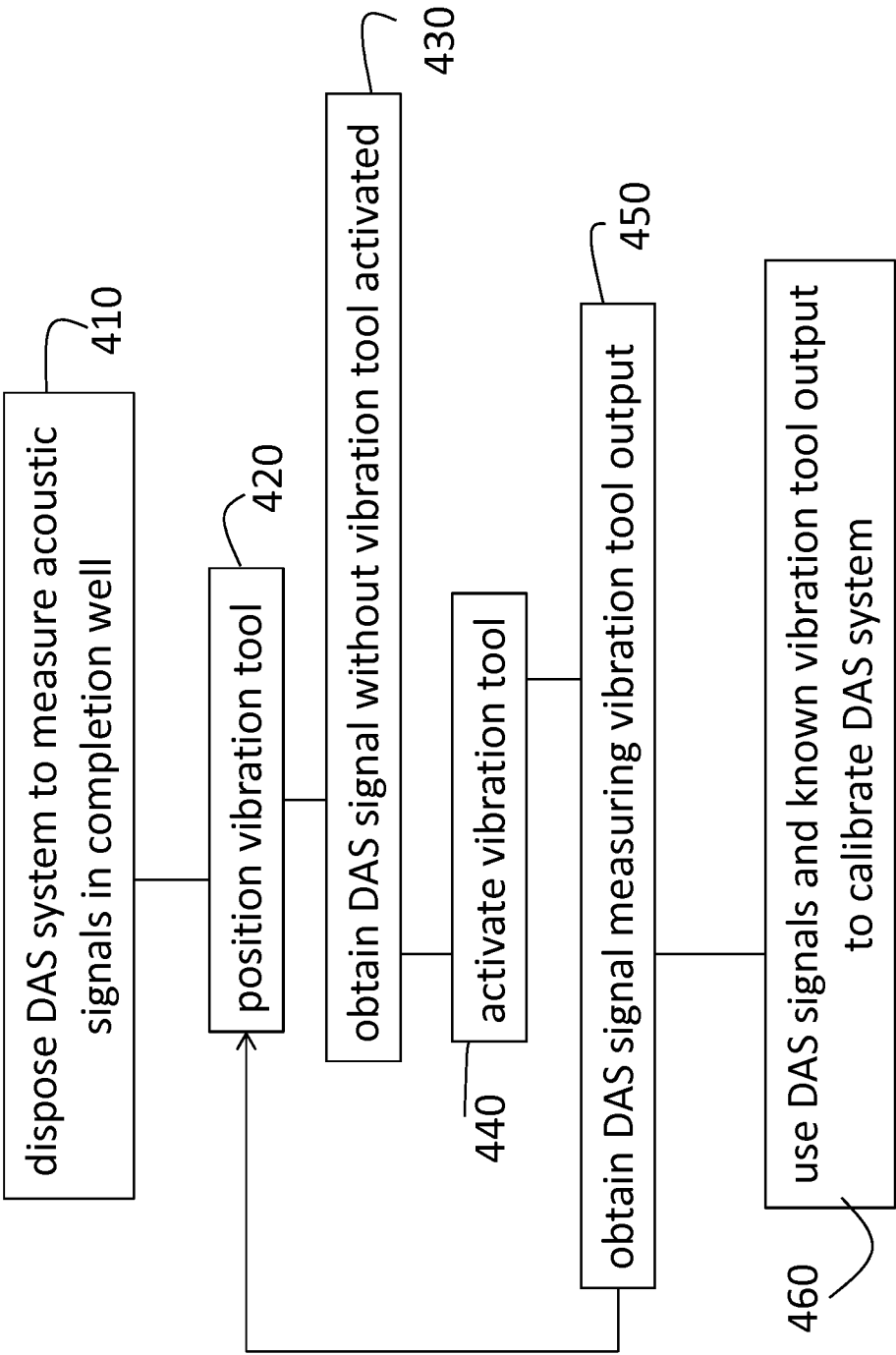


FIG. 4

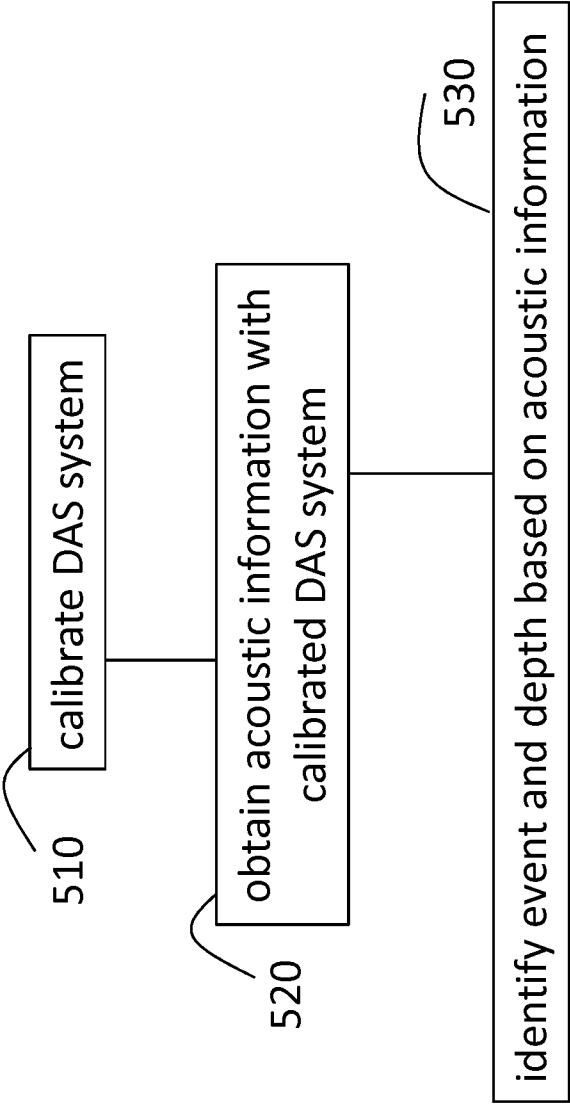


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/027449**A. CLASSIFICATION OF SUBJECT MATTER****E21B 47/00(2006.01)i, G01V 1/40(2006.01)i, G01V 1/46(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 47/00; G01F 25/00; E21B 49/00; G01F 1/66; G01V 1/48; G01V 1/52; G02B 6/00; G01V 1/40; G01V 1/46

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: distributed acoustic sensing, optical fiber, calibration, vibration tool, interference, Rayleigh scatter, and photodetector

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013-0298635 A1 (GODFREY, ALASTAIR) 14 November 2013 See paragraphs [0044], [0049]-[0051], claims 1, 13 and figure 2.	1-15
A	US 2012-0257475 A1 (LUSCOMBE et al.) 11 October 2012 See paragraphs [0015]-[0018], [0037]-[0039] and figures 1, 9.	1-15
A	US 2010-0038079 A1 (GREENAWAY, ROBERT) 18 February 2010 See paragraphs [0019]-[0029] and figure 1.	1-15
A	US 2011-0292763 A1 (COATES et al.) 01 December 2011 See paragraphs [0051]-[0056] and figure 6.	1-15
A	US 2012-0111104 A1 (TAVERNER et al.) 10 May 2012 See paragraphs [0025]-[0028] and figure 2.	1-15

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

21 July 2015 (21.07.2015)

Date of mailing of the international search report

22 July 2015 (22.07.2015)

Name and mailing address of the ISA/KR

International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
Republic of Korea

Facsimile No. +82-42-472-7140

Authorized officer

HWANG, Chan Yoon

Telephone No. +82-42-481-3347



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/027449

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013-0298635 A1	14/11/2013	CA 2826630 A1 EP 2678641 A1 WO 2012-114067 A1	30/08/2012 01/01/2014 30/08/2012
US 2012-0257475 A1	11/10/2012	AU 2012-238471 A1 CA 2830141 A1 CO 6781531 A2 EP 2695001 A2 MX 2013011661 A WO 2012-136951 A2 WO 2012-136951 A3	19/09/2013 11/10/2012 31/10/2013 12/02/2014 01/11/2013 11/10/2012 10/05/2013
US 2010-0038079 A1	18/02/2010	US 8020616 B2 WO 2010-019823 A2	20/09/2011 18/02/2010
US 2011-0292763 A1	01/12/2011	EP 2561382 A2 US 2014-064028 A1 US 8605542 B2 WO 2011-149613 A2 WO 2011-149613 A3	27/02/2013 06/03/2014 10/12/2013 01/12/2011 02/02/2012
US 2012-0111104 A1	10/05/2012	CA 2743696 A1 CA 2743696 C CA 2858016 A1 EP 2418466 A2 EP 2418466 A3	17/12/2011 04/11/2014 17/12/2011 15/02/2012 05/03/2014