ABSTRACT
Using distributed acoustic sensing (DAS) fiber optic cable for borehole surveying and/or well ranging.
DAS FOR WELL RANGING

PRIOR RELATED APPLICATIONS

[0001] This application is a non-provisional application which claims benefit under 35 USC §119(e) to U.S. Provisional Applications Ser. No. 62/305,758 filed Mar. 9, 2016, entitled “LOW FREQUENCY DISTRIBUTED ACOUSTIC SENSING,” and Ser. No. 62/305,777 filed Mar. 9, 2016, entitled “PRODUCTION LOGS FROM DISTRIBUTED ACOUSTIC SENSORS,” each of which is incorporated herein in its entirety.

FEDERALLY SPONSORED RESEARCH STATEMENT

[0002] Not applicable.

FIELD OF THE DISCLOSURE

[0003] The invention relates to drilling oil and gas wells, and in particular to methods of well ranging using distributed acoustic sensors.

BACKGROUND OF THE DISCLOSURE

[0004] In the oil and gas industry, “well ranging” or “wellbore surveying” or “borehole surveying” is the art of determining exactly where an underground well is so that the next well can either be intersected or avoided, as needed.

[0005] Only under ideal conditions will the path of a drilled hole follow the original dip (or inclination) and azimuth (or direction) established at the top of the hole. It is more typical that the borehole will be deflected from the intended direction as a result of weathering in the rock, the variation in the hardness of the layers, and the angle of the drill bit relative to these layers.

[0006] Because one of the purposes of a borehole is to obtain information in the third dimension—i.e. at depth—the location is just as important as the information itself. Most often the information consists of the geology of the drill core or assays of the core at selected depths. If the hole has deviated significantly, then that information cannot be properly assigned to a location in 3-dimensional space beneath the earth’s surface. Conclusions about geological structure or models of the size, shape, tonnage and average grade of ore-bodies based on the ‘mis-placed’ information will be incorrect.

[0007] Furthermore, in crowded fields it may be necessary to avoid drilling in already tapped payzones and/or to avoid existing wells. Alternatively, it may be desired to intersect a given well at a particular depth and angle. Indeed with unconventional oil development, unusual well configurations are often needed to realize the value of a play and may be the norm rather than the exception.

[0008] Thus, determining the distance and direction between wellbores is critical in many applications. In addition to being used for relief-well applications, parallel twinning for developments such as steam-assisted gravity drainage (SAGD) and coalbed methane (CBM) horizontal-to-vertical intersections use ranging technology. As more fields mature, ranging technology can be used in other applications such as plug and abandonment wells, true recovery, and for infill applications where anti-collision and relative wellbore positioning between multiple wells is of concern.

[0009] In the early years drilling was more of an art than a science. The general principals of geology and exploration were understood and followed, but the effects of formation changes and dip on bit deflection and hence borehole trajectory were not clearly understood and largely ignored. This perpetuated state of ignorance lead to many unresolved lease disputes, where wells drilled and brought on stream, close to an adjacent lease, would often result in diminished production rates on the adjacent lease wells. However, wells already in production were cased and the magnetic compass based survey instruments available could not provide post-completion trajectory data. Throughout this time, many inclination-only devices were developed, later versions of which were accurate to 1 or 2 degrees throughout their operating range.

[0010] In 1929 gyroscopes were designed that would provide the inclination of the borehole and the direction of that inclination within casing. The first gyro used by the industry had no means of inner gimbal/spin axis control, but the surveyor could determine its approximate position from the film record at each survey station. These gyro were originally intended for use up to 20-30 degrees inclination. However, as borehole inclinations increased, hardware improvements were made and operational techniques were developed that enabled these tools to be used successfully beyond 60 degrees inclination.

[0011] Since then, numerous borehole surveying devices have been developed, none of which are perfect. Reasonably accurate results are possible by properly using the right tool in the right hole, but all devices have their limitations. Surveying a borehole is usually accomplished by moving a probe along the hole and sensing the movement of the probe relative to one or more frames of reference, which may include the earth’s gravitational field, magnetic field or other inertial reference, and/or by sensing the distortion or bending of the housing of the probe itself.

[0012] Different methods have their own advantages and limitations. Some have the ability to operate inside steel casing, and others cannot. Some methods are time consuming and others are fast. Some are relatively simple to use and others are complex to operate. Other considerations are accuracy, cost, distance between measurements, ruggedness and reliability.

[0013] Thus, there remains a continuing need in the art for ever-improved borehole surveying methods, systems and devices to increase the accuracy of borehole surveying. The ideal method would be fast, easy to use, and cost effective, but without sacrificing accuracy, ruggedness and reliability.

SUMMARY OF THE DISCLOSURE

[0014] Driven by the needs for ever-faster broadband transmission, optical fiber technology has improved dramatically and now approaches theoretical limits in terms of attenuation and precision manufacturing. Taking advantage of such refinements, non-transmission applications have now come to the forefront and optical fibers are increasingly deployed as sensing elements in numerous industries and applications.

[0015] In one embodiment, Distributed Acoustic Sensing (DAS) provides near real-time measurement utilizing optical fiber by taking advantage of its low attenuation and long reach in addition to its dielectric nature and immunity to radio frequency and electromagnetic interference. DAS converts the optical fiber into a lengthy sensor element (up to 50 km) and detects events with very high resolution over the
entire distance. With a spatial resolution of 1 meter, for example, there will be 10,000 synchronized sensors along a 10,000 meter fiber.

As used herein, “DAS” or “Distributed Acoustic Sensing” refers to Rayleigh scatter based distributed fiber optic sensing, wherein a coherent laser pulse is sent along an optic fiber, and scattering sites within the fiber cause the fiber to act as a distributed interferometer with a gauge length approximately equal to the pulse length. The intensity of the reflected light is measured as a function of time after transmission of the laser pulse. When the pulse has had time to travel the full length of the fiber and back, the next laser pulse can be sent along the fiber. Changes in the reflected intensity of successive pulses from the same region of fiber are caused by changes in the optical path length of that section of fiber. This type of system is very sensitive to both strain and temperature variations of the fiber and measurements can be made simultaneously at all sections of the fiber.

Before the next laser pulse can be transmitted the previous one must have had time to travel to the far end of the fiber and for the reflections from there to return, otherwise reflections would be returning from different sections of the fiber at the same time and the system would not operate properly. For a fiber 50 km long the maximum pulse rate is just over 2 kHz. Therefore strains can be measured which vary at frequencies up to the Nyquist frequency of 1 kHz. Shorter fibers clearly enable higher acquisition rates.

As used herein, the “Reference Well” is the well equipped with a DAS cable that is operatively coupled to a C-OTDR or equivalent equipment. In some embodiments more than one Reference Well may be used, e.g., in triangulation applications.

As used herein, the “Active Well” is that provides the acoustic signals for sensing by the Reference Well. Also, a “test” well.

The invention includes any one or more of the following embodiments, in any combination(s) thereof:

A method of well ranging comprising:

- providing a first distributed acoustic sensing (DAS) fiber optic cable in a first reference well, said DAS cable operably connected to a Optical Time Domain Reflectometer (OTDR);
- providing a second distributed acoustic sensing (DAS) fiber optic cable in a second reference well, said DAS cable operably connected to a Optical Time Domain Reflectometer (OTDR);
- generating a laser light signal in said first and second DAS fiber optic cables;
- generating an acoustic signal in a test well;
- receiving a perturbed light signal in said first and second DAS cables;
- recording said received signal using said OTDR (s);
- processing said recorded signal using a computer having a signal processing program therein;
- determining a distance between said test well and said reference well based on said processed signal.

A method as herein described, wherein said OTDR is a coherent-OTDR (C-OTDR).

A method as herein described, each said first and second DAS cable has a separate OTDR or share an OTDR, in which case the signals can be separated by time or frequency.

A method as herein described, wherein said test well is within 100 m, 50 m, 10 m or 1 m or said reference well. Alternatively or in addition, the test well can follow a preplanned drilling pathway and eventually intersect said reference well according to the preplanned drilling pathway. In another embodiment, the active well purposely does not intersect.

A method of drilling a preplanned wellbore pathway, comprising:

- providing a distributed acoustic sensing (DAS) fiber optic cable in a reference well, said DAS cable operably connected to a Optical Time Domain Reflectometer (OTDR);
- generating a light signal in said DAS cable;
The use of the word “a” or “an” when used in conjunction with the term “comprising” in the claims or the specification means one or more than one, unless the context dictates otherwise.

The term “about” means the stated value plus or minus the margin of error of measurement or plus or minus 10% if no method of measurement is indicated.

The use of the term “or” in the claims is used to mean “and/or” unless explicitly indicated to refer to alternatives only or if the alternatives are mutually exclusive.

The terms “comprise”, “have”, “include” and “contain” (and their variants) are open-ended linking verbs and allow the addition of other elements when used in a claim.

The phrase “consisting of” is closed, and excludes all additional elements.

The phrase “consisting essentially of” excludes additional material elements, but allows the inclusions of non-material elements that do not substantially change the nature of the invention.

The following abbreviations are used herein:

<table>
<thead>
<tr>
<th>ABBREVIATION</th>
<th>TERM</th>
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<tbody>
<tr>
<td>LWD</td>
<td>Logging while drilling</td>
</tr>
<tr>
<td>MWID</td>
<td>Measurement while drilling</td>
</tr>
<tr>
<td>C-OTDR</td>
<td>Coherent Optical Time Domain Reflectometer</td>
</tr>
<tr>
<td>DTS</td>
<td>Distributed Temperature Sensing</td>
</tr>
<tr>
<td>OTDR</td>
<td>Optical Time Domain Reflectometer</td>
</tr>
<tr>
<td>IU</td>
<td>Interrogator Unit</td>
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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1. The principle operation of Distributed Acoustic Sensor (DAS).

FIG. 2. OTDR configuration shows pulsed light injected into distributed fiber sensor. The resulting trace resulting from the Rayleigh backscatter in the fiber is shown as the black curve. If the laser is highly coherent, the trace develops “ripples” (red curve) resulting from interference of the scattered light. Such signals can be processed in a manner analogous to processing seismic signals, using sophisticated programs and computationally fast machines.

DETAILED DESCRIPTION OF THE DISCLOSURE

The disclosure provides a novel method of well ranging using DAS sensors. DAS transforms nearly any fiber-optic cable into a distributed array of acoustic sensors.

To record data requires a specialized Coherent Optical Time Domain Reflectometer (C-OTDR) unit referred to as an “Interrogator Unit” or “IU”, which is connected to the fiber used for measurement.

Currently, an entire (~4 km) cable can be sampled at a rate of up to 20 kHz. At this rate, the IU injects laser pulses into the fiber, and as the fiber is strained by external acoustic disturbances, the IU processes and records the changes in the back-scattered light. Processing divides the fiber into a distributed array of acoustic sensors, which results in data that is comparable to conventional seismic data recorded on geophones.

An optical pulse is launched into the fiber and minute portions of the light traveling outward are (Rayleigh) scattered backwards in a distributed manner such that this scattered light returning may be measured temporally with a...
fast receiver to produce a record or trace of distributed loss of the fiber out to distances of 10's of Km.

DAS systems currently use single-mode fiber, as opposed to the multimode fiber typically used for DTS, but the type of fiber does not affect deployment, and multiple fibers are easily deployed in a single capillary tube.

A DAS fiber optic cable is deployed in the Reference Well to determine relative distance and direction from Active Well, which is e.g., being actively drilled. Neither dedicated installation of fiber nor any optimization of the cable construction or connectors is needed, and we used wireline to deploy the DAS cable, although other methods can be used.

Unlike the fiber cables used in the communication industry, fiber optics designed for oil and gas wells utilize specialized glass chemistry, coatings and construction to withstand downhole conditions. DAS fiber optic cable suitable for use herein is available from a number of suppliers, including OFS (Norcross Ga.), Halliburton (Houston Tex.), Schlumberger (Houston Tex.); BMP Enterprises (Belleville Tex.) and the like.

The DAS cable is connected at the surface to a C-OTDR, which receives, records and processes the signals. OTDR instruments are available from many manufacturers, including Anritsu America (Richardson Tex.), PIMON (Munich Germany); AFI Global (Duncan S.C.). Further, most of the companies selling the DAS fiber optic cable for downhole use also sell the OTDR units and have dedicated software thereon for the signal analysis algorithms unique to this industry.

Drilling noise and any other acoustic emissions generated in the Active Well (e.g. drilling, perforations, hydraulic fracturing, etc.) are recorded and processed by the OTDR using the DAS fiber in the Reference Well and based on that information, the drilling of the Active Well can be steered toward the Reference Well if intersection is desired, or steered to be parallel thereto, for example in SAGD wells, or otherwise steered for the well configuration that is needed.

For a given acoustic source emission location in the Active Well, a unique signal pattern will be generated and recorded by the DAS system in the Reference Well. A variety of pattern recognition, signal processing, and event location techniques may then be used to determine the range between the Reference and Active wells to high precision.

To date, we have tested the above concept using — and found that the system is accurate up to — inches. Recordings were made while tools were run in hole, during drilling, perforing and fracking and the technology proved sufficiently reliable and sensitive to detect these in-well activities and use that information to determine distance and direction from the reference well hosting the DAS cable.

The present invention is exemplified with respect to an Active Well that was drilled for test purposes. However, this is exemplary only, and the invention can be broadly applied to control any desired well configuration. The following examples are intended to be illustrative only, and not unduly limit the scope of the appended claims.

Test 1

For the testing of the system described herein, we will deploy DAS cable into a Reference Well using wirelines. 2000 meters of cable is deployed into a local well, and signals recorded using a C-OTDR. An Active well is initiated 50 m from the original Reference wellpad, with a pathway intended to intersect the Reference well. Signals received by the DAS cable in the reference well are inter-
interpreted. Our preliminary results are expected to show complete accuracy, such that the wells intersect as planned.

[0091] Using OTDR technology, it is possible to determine an amount of backscattered light arriving from any point along the fiber optic cable. Although the duration of the light pulse determines the lower limit on the spatial resolution, the resulting signal can be used to extract information at any larger interval. This can be accomplished by dividing the backscattered light signal into a series of bins in time. The data within each bin is summed to give information about the average strain on the length of fiber between the endpoints of the bin. These bins can be made arbitrarily large to sample longer sections of the fiber.

[0092] The bins may be equally sized and continuously spread over the entire length of the fiber with the end of one bin becoming the start of the next, but if desired, the size and position of each bin, in addition to the spacing between consecutive bins, can be tailored to yield the optimum desired spatial sampling resolution and sensitivity.

[0093] Thus, by time-gating the received backscattered signal, each fiber optic cable can be treated as a plurality of discrete, distributed acoustic “sensors” (DAS), with each sensor corresponding to a section of cable. The time-gating can be controlled to produce sections/sensors that are as long or as short as desired. For example, one portion of the cable can sense at high resolution, using relatively short sections of cable having lengths \( L_1 \), while another portion of cable can sense at a lower resolution, using relatively longer sections of cable having lengths \( L_2 \). In some embodiments, higher-resolution section length \( L_1 \) preferably falls within the range 0.1 to 10 m and lower-resolution section length \( L_2 \) preferably falls within the range 10 to 1000+ m.

[0094] One of the challenges is processing a large volume of the data collected at high speeds. For 10 km of fiber, 1 m intervals at 10 kHz sampling, the minimum data rate is 100 MSamples/s. A number of fast signal processing techniques have been developed to analyze the acoustic spectrum of the signal along the entire length of fiber and identify flow characteristics along the wellbore. In addition using coherent phase array processing techniques, the propagation of the acoustic energy along the wellbore can be analyzed in space-frequency domain (k-w) to determine the speed of sound and, thereby, measure distance, etc.

[0095] One example of a suitable DAS technology is a system called Blue Rose. This system exploits the physical phenomenon of Rayleigh optical scattering, which occurs naturally in optical fibers used traditionally for OTDR techniques. Blue Rose detects backscattered light and uses the signal to give information about acoustic events caused by activities near the cable. The sensor is a single strand of single-mode optical fiber with an elastomeric, polymeric, metallic, ceramic, or composite coating that is buried in the ground at a depth of approximately nine inches. Alternatively, coherent OTDR (C-OTDR) processes can be used to obtain similar acoustic information from an optical system, as disclosed in US Application No. 20090114386.

[0096] In other embodiments, an optical system such as that described in U.S. application Ser. No. 2008277568 can be used. That system uses pulsed pairs of light signals that have different frequencies and are separated in time. If used, such a system allows processing of the signal to be carried out more easily and with a greater signal-to-noise ratio than is the case if radiation of a single frequency backscattered from different positions along the length of optical fiber is used to generate a signal at a photodetector by interferometry.

[0097] The present disclosure also relates to a computing apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes of signal processing, or it may comprise a general-purpose computer selectively activated or reconfigured for signal processing. Such computer programs may be stored in a computer readable storage medium, preferably non-transitory, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, and magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs,EEPROMs, magnetic or optical cards, or any type of media suitable for storing electronic instructions, each coupled to a computer system bus.

[0098] In one embodiment, the computer system or apparatus may include graphical user interface (GUI) components such as a graphics display and a keyboard which can include a pointing device (e.g., a mouse, trackball, or the like, not shown) to enable interactive operation. The GUI components may be used both to display data and processed data and to allow the user to select among options for implementing aspects of the method or for adding information about reservoir inputs or parameters to the computer programs. The computer system may store the results of the system and methods described above on disk storage, for later use and further interpretation and analysis. Additionally, the computer system may include on or more processors for running said spreadsheet and simulation programs.

[0099] As yet another option, the computer program can provide a display of the two wells, their existing placement as well as the planned trajectory. Using this display, the drilling operator can control the trajectory to compensate for any unplanned deviations.

[0100] Hardware for implementing the inventive methods may include massively parallel and distributed Linux clusters, which utilize both CPU and GPU architectures. Alternatively, the hardware may use a LINUX OS, XML universal interface run with supercomputing facilities provided by Linux Network, including the next-generation Clusterworks Advanced cluster management system. Another system is the Microsoft Windows 7 Enterprise or Ultimate Edition (64-bit, SP1) with Dual-quad core or hex-core processor, 64 GB RAM memory with Fast rotational speed hard disk (10,000-15,000 rpm) or solid state drive (300 GB) with NVIDIA Quadro K5000 graphics card and high resolution monitor. Slower systems could also be used.

[0101] The term “many-core” as used herein denotes a computer architectural design whose cores include CPUs and GPUs. Generally, the term “cores” has been applied to measure how many iCPUs are on a giving computer chip. However, graphic cores are now being used to offset the work of CPUs. Essentially, many-core processors use both computer and graphic processing units as cores.

[0102] The following references are incorporated by reference in their entirety for all purposes.

[0103] U.S. Provisional Application Ser. No. 62/305,758 filed Mar. 9, 2016, entitled “LOW FREQUENCY DISTRIBUTED ACOUSTIC SENSING,”
The method of claim 1, wherein said determining step is performed by a program stored in a computer.

11) The method of claim 10, wherein said display is a 3D display and said map is a 3D map.

12) The method of claim 1, including the further step of printing, displaying or saving to a non-transitory machine-readable storage medium the recorded or processed signals (or both).

13) A paper or plastic printout or a 3D display of the recorded or processed signals of the method of claim 1.

14) A 3D display of the map of the method of claim 11.

15) A non-transitory machine-readable storage medium containing or having saved thereto the recorded or processed signals (or both) of the method of claim 1.

16) A non-transitory machine-readable storage medium, which when executed by at least one processor of a computer, performs the determining step of the method of claim 1.

17) The method according to claim 1, wherein an active drill bit provides said acoustic signal.

18) A method of drilling a preplanned wellbore pathway, comprising:
   a) providing a distributed acoustic sensing (DAS) fiber optic cable in a reference well, said DAS cable operably connected to a Coherent Optical Time Domain Reflectometer (C-OTDR);
   b) generating a light signal in said DAS cable;
   c) generating an acoustic signal in an active well being drilled to follow a preplanned wellbore pathway;
   d) receiving a perturbed light signal in said DAS cable;
   e) recording said received signal using said OTDR;
   f) processing said recorded signal to determine a distance and direction between said test well and said reference well based on said processed signal;
   g) controlling a drilling trajectory of a drill bit in said active well based on said direction and said direction so that said drill bit follows said preplanned wellbore pathway.

19) The method of claim 10, wherein said OTDR is a coherent-OTDR (C-OTDR).

20) A method of drilling a preplanned wellbore pathway, comprising:
   a) providing a distributed acoustic sensing (DAS) fiber optic cable in a reference well, said DAS cable operably connected to a Coherent Optical Time Domain Reflectometer (C-OTDR);
   b) generating an intermittent laser light signal in said DAS cable;
   c) generating an acoustic signal in an active well being drilled to follow a preplanned wellbore pathway;
   d) receiving a backscatter signal in said DAS cable, wherein said laser light signal is perturbed by said acoustic signal to produce said backscatter signal;
   e) recording said backscatter signal using said C-OTDR;
   f) processing said recorded signal to determine a distance and direction between said active well and said reference well;
   g) displaying a map of said active well, said reference well, and said preplanned wellbore pathway;
   h) controlling a trajectory of a drill bit in said active well based on said map so that said drill bit and active well follows said preplanned wellbore pathway.

21) The method of claim 12, wherein said C-OTDR is a high coherence C-OTDR.
22) The method of claim 12, wherein first and second DAS cables are provided in first and second reference wells, providing two processed signals used for triangulation.

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