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Inventor(s)	Wang; Ruijia et al.

Single-well reflected horizontal shear wave imaging with mixed types of transmitters and receivers

Abstract

A borehole sonic logging tool and method for imaging. The borehole sonic logging tool may comprise a transmitter configured to transmit a sonic waveform into a formation, wherein the transmitter is a dipole, and a receiver configured to record a reflected wave as waveform data, wherein the receiver is a quadrupole. A method may comprise disposing a downhole tool into a borehole, selecting a frequency range for the transmitter to a horizontally-polarized shear formation body wave, broadcasting the sonic waveform as the horizontally-polarized shear formation body wave into the formation penetrated by the borehole with the transmitter, recording a reflected wave on the receiver as waveform data, wherein the reflected wave is the horizontally-polarized shear formation body wave reflected from a reflector, and processing the waveform data with an information handling system.

Inventors:	**Wang; Ruijia (Singapore, SG), Hornby; Brian (Fulshear, TX)**
Applicant:	**Halliburton Energy Services, Inc.** (Houston, TX)
Family ID:	**1000008748644**
Assignee:	**Halliburton Energy Services, Inc. (Houston, TX)**
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Primary Examiner: Turner; Shelby A

Assistant Examiner: Sun; Xiuqin

Attorney, Agent or Firm: C. Tumey Law Group PLLC

Background/Summary

BACKGROUND

(1) In order to obtain hydrocarbons such as oil and gas, boreholes are drilled through hydrocarbon-bearing subsurface formations. Logging tests are subsequently made to determine the properties of formations surrounding the borehole. In wireline logging, a drilling apparatus that forms the borehole is removed so that testing equipment can be lowered into the borehole for testing. In measurement-while-drilling techniques, the testing equipment is conveyed down the borehole along with the drilling equipment. These tests may include resistivity testing equipment, gamma radiation testing equipment, seismic imaging equipment, etc. Seismic imaging using borehole acoustic measurements may obtain an image of the formation structural changes away from the borehole.

(2) Traditional methods for reflection sonic imaging of formation structural changes away from the borehole use the same type of transmitter and receiver for reflected horizontal shear wave imaging. Such methods sometimes suffer due to the strong borehole modes. This may bury and/or “wash out” desired reflected signals in the borehole mode signal.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) These drawings illustrate certain aspects of some examples of the present disclosure, and should not be used to limit or define the disclosure.

(2) FIG. **1** illustrate an example of a borehole sonic logging system;

(3) FIG. **2** illustrates an example of a drilling system;

(4) FIG. **3** illustrate an example of a borehole sonic logging tool disposed in a borehole;

(5) FIG. **4**A is a workflow for utilizing a quadrupole transmitter;

(6) FIG. **4**B is a workflow for utilizing a dipole transmitter;

(7) FIG. **5**A illustrates a dipole transmitter and/or receiver;

(8) FIG. **5**B illustrates a quadrupole transmitter and/or receiver;

(9) FIG. **6** is a graph of a dipole radiation and/or reception pattern;
(10) FIG. **7** is a graph of a quadrupole radiation and/or reception pattern;
(11) FIG. **8** is a graph of a dipole-quadrupole radiation and/or reception pattern for formation horizontal-polarized shear (SH) waves;
(12) FIG. **9** is a graph of a dipole-quadrupole radiation and/or reception pattern for formation vertical-polarized shear (SV) waves;
(13) FIG. **10** is a graph of recorded data from a dipole-quadrupole combination showing raw waveforms with both borehole guided waves and reflected waves;
(14) FIG. **11** is a graph of recorded data from a dipole-quadrupole combination showing shear reflections after wave separation; and
(15) FIGS. **12**A and **12**B illustrate an example of a sonic tool with the capability for firing dipole signals and receiving quadrupole signals.
(16) FIG. **13** displays a workflow for dipole-quadrupole processing.

DETAILED DESCRIPTION

(17) This disclosure may generally relate to systems and methods for measuring reflected waves from a reflector and borehole guide waves with a hybrid receiver and/or transmitter combination. Implementing a hybrid transmitter and/or receiver combination may decrease the influence of borehole guided waves. In examples, a hybrid transmitter and/or receiver combination may be a combination of a dipole transmitter and a quadrupole receiver.
(18) FIG. **1** illustrates a cross-sectional view of a borehole sonic logging system **100**. As illustrated, borehole sonic logging system **100** may comprise a borehole sonic logging tool **102** attached to a vehicle **104**. In examples, it should be noted that borehole sonic logging tool **102** may not be attached to a vehicle **104**. Borehole sonic logging tool **102** may be supported by rig **106** at surface **108**. Borehole sonic logging tool **102** may be tethered to vehicle **104** through conveyance **110**. Conveyance **110** may be disposed around one or more sheave wheels **112** to vehicle **104**. Conveyance **110** may include any suitable means for providing mechanical conveyance for borehole sonic logging tool **102**, including, but not limited to, wireline, slickline, coiled tubing, pipe, drill pipe, downhole tractor, or the like. In some embodiments, conveyance **110** may provide mechanical suspension, as well as electrical connectivity, for borehole sonic logging tool **102**. Conveyance **110** may comprise, in some instances, a plurality of electrical conductors extending from vehicle **104**. Conveyance **110** may comprise an inner core of seven electrical conductors covered by an insulating wrap. An inner and outer steel armor sheath may be wrapped in a helix in opposite directions around the conductors. The electrical conductors may be used for communicating power and telemetry between vehicle **104** and borehole sonic logging tool **102**. Information from borehole sonic logging tool **102** may be gathered and/or processed by information handling system **114**. For example, signals recorded by borehole sonic logging tool **102** may be stored on memory and then processed by borehole sonic logging tool **102**. The processing may be performed real-time during data acquisition or after recovery of borehole sonic logging tool **102**. Processing may alternatively occur downhole or may occur both downhole and at surface. In some embodiments, signals recorded by borehole sonic logging tool **102** may be conducted to information handling system **114** by way of conveyance **110**. Information handling system **114** may process the signals, and the information contained therein may be displayed for an operator to observe and stored for future processing and reference. Information handling system **114** may also contain an apparatus for supplying control signals and power to borehole sonic logging tool **102**.
(19) Systems and methods of the present disclosure may be implemented, at least in part, with information handling system **114**. Information handling system **114** may include any instrumentality or aggregate of instrumentalities operable to compute, estimate, classify, process, transmit, receive, retrieve, originate, switch, store, display, manifest, detect, record, reproduce, handle, or utilize any form of information, intelligence, or data for business, scientific, control, or

other purposes. For example, an information handling system **114** may be a processing unit **116**, a network storage device, or any other suitable device and may vary in size, shape, performance, functionality, and price. Information handling system **114** may include random access memory (RAM), one or more processing resources such as a central processing unit (CPU) or hardware or software control logic, ROM, and/or other types of nonvolatile memory. Additional components of the information handling system **114** may include one or more disk drives, one or more network ports for communication with external devices as well as various input and output (I/O) devices, such as a input device **118** (e.g., keyboard, mouse, etc.) and a video display **120**. Information handling system **114** may also include one or more buses operable to transmit communications between the various hardware components.

(20) Alternatively, systems and methods of the present disclosure may be implemented, at least in part, with non-transitory computer-readable media **122**. Non-transitory computer-readable media **122** may include any instrumentality or aggregation of instrumentalities that may retain data and/or instructions for a period of time. Non-transitory computer-readable media **122** may include, for example, storage media such as a direct access storage device (e.g., a hard disk drive or floppy disk drive), a sequential access storage device (e.g., a tape disk drive), compact disk, CD-ROM, DVD, RAM, ROM, electrically erasable programmable read-only memory (EEPROM), and/or flash memory; as well as communications media such wires, optical fibers, microwaves, radio waves, and other electromagnetic and/or optical carriers; and/or any combination of the foregoing.

(21) As illustrated, borehole sonic logging tool **102** may be disposed in borehole **124** by way of conveyance **110**. Borehole **124** may extend from a wellhead **134** into a formation **132** from surface **108**. Generally, borehole **124** may include horizontal, vertical, slanted, curved, and other types of borehole geometries and orientations. Borehole **124** may be cased or uncased. In examples, borehole **124** may comprise a metallic material, such as tubular **136**. By way of example, the tubular **136** may be a casing, liner, tubing, or other elongated steel tubular disposed in borehole **124**. As illustrated, borehole **124** may extend through formation **132**. Borehole **124** may extend generally vertically into the formation **132**. However, borehole **124** may extend at an angle through formation **132**, such as horizontal and slanted boreholes. For example, although borehole **124** is illustrated as a vertical or low inclination angle well, high inclination angle or horizontal placement of the well and equipment may be possible. It should further be noted that while borehole **124** is generally depicted as a land-based operation, those skilled in the art may recognize that the principles described herein are equally applicable to subsea operations that employ floating or sea-based platforms and rigs, without departing from the scope of the disclosure.

(22) In examples, rig **106** includes a load cell (not shown) which may determine the amount of pull on conveyance **110** at surface **108** of borehole **124**. While not shown, a safety valve may control the hydraulic pressure that drives drum **126** on vehicle **104** which may reel up and/or release conveyance **110** which may move borehole sonic logging tool **102** up and/or down borehole **124**. The safety valve may be adjusted to a pressure such that drum **126** may only impart a small amount of tension to conveyance **110** over and above the tension necessary to retrieve conveyance **110** and/or borehole sonic logging tool **102** from borehole **124**. The safety valve is typically set a few hundred pounds above the amount of desired safe pull on conveyance **110** such that once that limit is exceeded; further pull on conveyance **110** may be prevented.

(23) In examples, borehole sonic logging tool **102** may operate with additional equipment (not illustrated) on surface **108** and/or disposed in a separate borehole sonic logging system (not illustrated) to record measurements and/or values from formation **132**. Borehole sonic logging tool **102** may comprise a transmitter **128**. Transmitter **128** may be connected to information handling system **114**, which may further control the operation of transmitter **128**. Transmitter **128** may include any suitable transmitter for generating sound waves that travel into formation **132**, including, but not limited to, piezoelectric transmitters. Transmitter **128** may be a monopole source or a multi-pole source (e.g., a dipole source). Combinations of different types of transmitters may

also be used. During operations, transmitter **128** may broadcast sound waves (e.g., sonic waveforms) from borehole sonic logging tool **102** that travel into formation **132**. The sound waves may be emitted at any suitable frequency range. For example, a broad band response could be from about 0.2 KHz to about 20 KHz, and a narrow band response could be from about 1 KHZ to about 6 KHz. It should be understood that the present technique should not be limited to these frequency ranges. Rather, the sounds waves may be emitted at any suitable frequency for a particular application.

(24) Borehole sonic logging tool **102** may also include a receiver **130**. As illustrated, there may be a plurality of receivers **130** disposed on borehole sonic logging tool **102**. Receiver **130** may include any suitable receiver for receiving sound waves, including, but not limited to, piezoelectric receivers. For example, the receiver **130** may be a monopole receiver or multi-pole receiver (e.g., a dipole receiver). In examples, a monopole receiver **130** may be used to record compressional-wave (P-wave) signals, while the multi-pole receiver **130** may be used to record shear-wave (S-wave) signals. Receiver **130** may measure and/or record sound waves broadcast from transmitter **128** as received signals. The sound waves received at receiver **130** may include both direct waves that traveled along the borehole **124** and refract through formation **132** as well as waves that traveled through formation **132** and reflect off of near-borehole bedding and propagate back to the borehole. The reflected waves may include, but are not limited to, compressional (P) waves and shear(S) waves. By way of example, the received signal may be recorded as an acoustic amplitude as a function of time. Information handling system **114** may control the operation of receiver **130**. The measured sound waves may be transferred to information handling system **114** for further processing. In examples, there may be any suitable number of transmitters **128** and/or receivers **130**, which may be controlled by information handling system **114**. Information and/or measurements may be processed further by information handling system **114** to determine properties of borehole **124**, fluids, and/or formation **132**. By way of example, the sound waves may be processed to generate a reflection image of formation structures, which may be used for dip analysis as discussed in more detail below.

(25) FIG. **2** illustrates an example in which borehole sonic logging tool **102** may be included in a drilling system **200**. As illustrated, borehole **124** may extend from wellhead **134** into formation **132** from surface **108**. A drilling platform **206** may support a derrick **208** having a traveling block **210** for raising and lowering drill string **212**. Drill string **212** may include, but is not limited to, drill pipe and coiled tubing, as generally known to those skilled in the art. A kelly **214** may support drill string **212** as it may be lowered through a rotary table **216**. A drill bit **218** may be attached to the distal end of drill string **212** and may be driven either by a downhole motor and/or via rotation of drill string **212** from surface **108**. Without limitation, drill bit **218** may include, roller cone bits, PDC bits, natural diamond bits, any hole openers, reamers, coring bits, and the like. As drill bit **218** rotates, it may create and extend borehole **124** that penetrates various subterranean formations **204**. A pump **220** may circulate drilling fluid through a feed pipe **222** to kelly **214**, downhole through interior of drill string **212**, through orifices in drill bit **218**, back to surface **108** via annulus **224** surrounding drill string **212**, and into a retention pit **226**.

(26) With continued reference to FIG. **2**, drill string **212** may begin at wellhead **134** and may traverse borehole **124**. Drill bit **218** may be attached to a distal end of drill string **212** and may be driven, for example, either by a downhole motor and/or via rotation of drill string **212** from surface **108**. Drill bit **218** may be a part of bottom hole assembly **228** at distal end of drill string **212**. Bottom hole assembly **228** may further comprise borehole sonic logging tool **102**. Borehole sonic logging tool **102** may be disposed on the outside and/or within bottom hole assembly **228**. Borehole sonic logging tool **102** may comprise a plurality of transmitters **128** and/or receivers **130**. Borehole sonic logging tool **102** and/or the plurality of transmitters **128** and receivers **130** may operate and/or function as described above. As will be appreciated by those of ordinary skill in the art, bottom hole assembly **228** may be a measurement-while drilling (MWD) and/or logging-while-

drilling (LWD) system.

(27) Without limitation, bottom hole assembly **228**, transmitter **128**, and/or receiver **130** may be connected to and/or controlled by information handling system **114**, which may be disposed on surface **108**. Without limitation, information handling system **114** may be disposed down hole in bottom hole assembly **228**. Processing of information recorded may occur down hole and/or on surface **108**. Processing occurring downhole may be transmitted to surface **108** to be recorded, observed, and/or further analyzed. Additionally, information recorded on information handling system **114** that may be disposed down hole may be stored until bottom hole assembly **228** may be brought to surface **108**. In examples, information handling system **114** may communicate with bottom hole assembly **228** through a communication line (not illustrated) disposed in (or on) drill string **212**. In examples, wireless communication may be used to transmit information back and forth between information handling system **114** and bottom hole assembly **228**. Information handling system **114** may transmit information to bottom hole assembly **228** and may receive, as well as process, information recorded by bottom hole assembly **228**. In examples, a downhole information handling system (not illustrated) may include, without limitation, a microprocessor or other suitable circuitry, for estimating, receiving and processing signals from bottom hole assembly **228**. Downhole information handling system (not illustrated) may further include additional components, such as memory, input/output devices, interfaces, and the like. In examples, while not illustrated, bottom hole assembly **228** may include one or more additional components, such as analog-to-digital converter, filter and amplifier, among others, that may be used to process the measurements of bottom hole assembly **228** before they may be transmitted to surface **108**. Alternatively, raw measurements from bottom hole assembly **228** may be transmitted to surface **108**.

(28) Any suitable technique may be used for transmitting signals from bottom hole assembly **228** to surface **108**, including, but not limited to, wired pipe telemetry, mud-pulse telemetry, acoustic telemetry, and electromagnetic telemetry. While not illustrated, bottom hole assembly **228** may include a telemetry subassembly that may transmit telemetry data to surface **108**. Without limitation, an electromagnetic source in the telemetry subassembly may be operable to generate pressure pulses in the drilling fluid that propagate along the fluid stream to surface **108**. At surface **108**, pressure transducers (not shown) may convert the pressure signal into electrical signals for a digitizer (not illustrated). The digitizer may supply a digital form of the telemetry signals to information handling system **114** via a communication link **230**, which may be a wired or wireless link. The telemetry data may be analyzed and processed by information handling system **114**.

(29) As illustrated, communication link **230** (which may be wired or wireless, for example) may be provided which may transmit data from bottom hole assembly **228** to an information handling system **114** at surface **108**. Information handling system **114** may include a processing unit **116**, a video display **120**, an input device **118** (e.g., keyboard, mouse, etc.), and/or non-transitory computer-readable media **122** (e.g., optical disks, magnetic disks) that may store code representative of the methods described herein. In addition to, or in place of processing at surface **108**, processing may occur downhole.

(30) FIG. **3** illustrates an example of shear wave imaging with borehole sonic logging tool **102**. As illustrated, borehole sonic logging tool **102** may be disposed in a borehole **124**, which may be filled with fluid **300**. In examples, transmitter **128** may emit sonic waveforms **302** into borehole **124**. In examples, at least one sonic waveform **302** may travel into formation **132** and may be reflected as a reflected signal **306** by a reflector **304** in formation **132**. Without limitation, reflector **304** may be a formation boundary, a fault, a cave, or a fracture. In examples, reflected signals **306** may travel back to borehole **124** and may be captured by receivers **130** in borehole **124**. Simultaneously, sonic waveforms **302** signals which may become trapped in borehole **124** as borehole guide waves **308** may propagate along the axis of borehole **124** and may be captured by receivers **130**. In examples, borehole guide waves **308** may “wash out” reflected signals **306**, which may reflect from reflector

304 away from borehole **124**. For example, borehole guide waves **308** may prevent reflected signals **306** from being recorded or may be recorded over reflected signals **306**.

(31) Reflected signals **306** may be captured utilizing the same type of transmitter **128** and receiver **130**. For example, both transmitter **128** and receiver **130** may be a monopole or a dipole. As illustrated in FIG. **3**, both borehole guide waves **308** and reflected signals **306** may be recorded by receiver **130**. Generally, a filtering procedure may be remove borehole guided waves **308**, which may be considered noise when imaging with reflected waves **306**.

(32) However, for detecting reflected signals **306** that travel at least one wavelength from a reflector **304**, receiver **130** and transmitter **128** may not need to be the same type of device. For example, in single-well imaging techniques a transmitter **128** may emit sonic waveform **302** as a formation body wave. A formation body wave may be transmitted and received by type of transmitter **128** and/or receiver **130**. Additionally, formation body waves that may be transmitted or received by different types of transmitters **128** or receivers **130** may also be formation body waves. Therefore, using mixed (e.g., different) types of transmitters **128** and receivers **138** (e.g., monopole, dipole, etc.) may be a feasible solution for far-detection of reflected signals **306**.

(33) During measurement operations, utilizing mixed-types of transmitters **128** and receivers **130** may suppress borehole guide waves **308**. For example, if transmitter **128** and receiver **130** are of different types, no signal will be recorded. However, because of tool eccentricity or other factors, coupled wave field with other azimuthal types might be generated, and receiver **130** may capture at least a portion of coupled wave fields.

(34) During measurement operations which may use horizontal-polarized shear waves, all types of transmitters **128**, except a monopole transmitter, may generate any formation body wave into formation **132**, with continued reference to FIG. **3**. For example, a dipole transmitter may generate horizontally-polarized shear formation body waves with a radiation pattern of a numerical “8.” Likewise, a quadrupole source may generate horizontally-polarized shear formation body waves in formation **132** with a radiation pattern of ‘quatrefoil’ in a pattern of a numerical “8.” During measurement operations, there may be different methods for operating a dipole transmitter or a quadrupole transmitter.

(35) FIG. **4**A illustrates workflow **400** for operating a quadrupole source during measurement operations. Workflow **400** may begin with step **402**, where an operator may select a frequency range where a quadrupole source may effectively emit horizontally-polarized shear formation body waves and a dipole receiver may effective receive the reflected horizontally-polarized shear formation body waves. For example, an optimal frequency range may be determined by using forward modeling to examine the dipole and monopole excitation/reception amplitude curves to determine the optimal frequency range where a quadrupole source has sufficient energy in that range and the dipole receiver can effectively receive the desired signal in that frequency range. In addition-suitable field test data would help establish comparable frequency bands for quadrupole and dipole emission and reception. In step **404**, an operator may use one or more quadrupole sources to emit sonic waveforms **302** (e.g., referring to FIG. **3**) with the selected frequency range into a formation **132** (e.g., referring to FIG. **3**). In examples, the operator may control transmitter **128** and receiver **130** (e.g., referring to FIG. **3**) with an information handling system **114** (e.g., referring to FIG. **1**). In step **406**, an operator may use one or more dipole receivers to capture reflected signals **306** or borehole guide waves **308**. In step **408**, the operator may process horizontally-polarized shear formation body waves to image formation **132**. For example, processing may be performed on information handling system **114** and may remove borehole guide waves **308** from recorded data.

(36) FIG. **4**B illustrates workflow **410** for operating a dipole source during measurement operations. Workflow **410** may begin with step **412**, where an operator may select a frequency range where a dipole source may effectively emit horizontally-polarized shear formation body waves and a quadrupole receiver may effective receive the reflected horizontally-polarized shear

formation body waves. For example, an optimal frequency range may be determined by using forward modeling to examine the dipole and monopole excitation/reception amplitude curves to determine the optimal frequency range where a dipole source has sufficient energy in that range and the quadrupole receiver can effectively receive the desired signal in that frequency range. In addition-suitable field test data would help establish comparable frequency bands for quadrupole and dipole emission and reception. In step **414**, an operator may use one or more dipole sources to emit sonic waveforms **302** (e.g., referring to FIG. **3**) with the selected frequency range into a formation **132** (e.g., referring to FIG. **3**). In examples, the operator may control transmitter **128** and receiver **130** (e.g., referring to FIG. **3**) with an information handling system **114** (e.g., referring to FIG. **1**). In step **416**, an operator may use one or more quadrupole receivers to capture reflected signals **306** or borehole guide waves **308**. In step **418**, the operator may process horizontally-polarized shear formation body waves to image formation **132**. For example, processing may be performed on information handling system **114** and may remove borehole guide waves **308** from recorded data. Measurements from the methods described above may increase azimuth resolution.

(37) During operations, azimuth resolution in a dipole-dipole system may be degraded. It should be noted that herein 'dipole-dipole', the first word represents the transmitter type, while the second world represents the receiver type. FIGS. **5**A and **5**B shows the sketch map for a dipole (FIG. **5**A) and a quadrupole (FIG. **5**B), represented by a combination of a number of point sources. For example, a dipole may be represented by two point sources with opposite phase, a positive phase dipole **500** and a negative phase dipole **502**. During measurement operations, the dipole may emit horizontally-polarized shear formation body waves in any direction except the two azimuths where positive phase dipole **500** and negative phase dipole **502** are disposed. A quadrupole, as illustrated in FIG. **5**B, may be represented by four point sources with different phases, two positive phase dipoles **500** and two negative phase dipoles **502**. During measurement operations, the quadrupole may generate horizontally-polarized shear formation body waves to any azimuth except the azimuths each positive phase dipole **500** and negative phase dipole **502** are disposed. It should be noted that a dipole receiver and a quadrupole receiver may be represented by a number of point receivers and may only sense reflected signals **306** and/or borehole guide waves **308** (e.g., referring to FIG. **3**) in any azimuth except the azimuth were the point receivers may be. The fields for transmission and receiver may be illustrated as a pattern in a three hundred and sixty degree path.

(38) For example, FIGS. **6** and **7** illustrates a theoretical radiation/receiving pattern of horizontally-polarized shear formation body waves for a dipole source and a receiver, as illustrated in FIG. **6**. FIG. **7** illustrates a theoretical radiation/receiving pattern for a quadrupole source/receiver, in a fluid-filled borehole **124** (e.g., referring to FIG. **1**). FIG. **6** shows that the dipole radiation pattern shows a shape of the number 8, with target azimuth at 0-degree and 180-degree. FIG. **7** shows that the quadrupole radiation pattern shows a shape of 'quatrefoil' with target azimuth at 0-, 90-, 180-, and 270-degree. Comparing FIG. **6** with FIG. **7**, dipole lobe **600** may be wider than quadrupole lobe **700**. The wider lobe for dipole lobe **600** may reduce resolution in determining an azimuth of horizontally-polarized shear formation body waves. Additionally, there may be two dipole lobes **600** in FIG. **6**, which may allow for two areas to estimate the azimuth of horizontally-polarized shear formation body waves, as each dipole lobe **600** may have a 180-degree uncertainty in the radiation and receiving patterns. As illustrated in FIG. **7**, the quadrupole pattern and four quadrupole lobes **700** may be narrower than the dipole pattern and dipole lobes **600** in FIG. **6**. Therefore, quadrupole lobes **700** may have a higher azimuthal resolution. Quadrupole lobes **700** may provide four solutions for horizontally-polarized shear azimuth estimates as each quadrupole lobe **700** may have a 90-degree uncertainty in the radiation and receiving patterns. During measurement operations, utilizing the same type of source and/or receivers for measuring horizontally-polarized shear formation body waves, it may be inevitable that dipole-dipole data might provide azimuth angle with relatively low azimuth-resolution, while a quadrupole-quadrupole data might provide four possible angles for reflected signals **306** from reflector **304**

(e.g., referring to FIG. **3**) which might confuse an operator. As a contrast, using mixed types of transmitters and/or receives, for example, dipole-quadrupole, or quadrupole-dipole, an operator may take advantage of the two different types of sources and receivers, and provide an optimized reflector azimuth estimate.
(39) For example, FIG. **8** illustrates a combined pattern of horizontally-polarized shear (SH) formation body waves if a dipole-quadrupole combination is utilized, with a conventional dipole-dipole pattern including dipole lobes **600** and/or dipole-quadrupole lobes. It should be noted that dipole-quadrupole lobes include side lobes **800** and main lobes **810**. Note that for the dipole-quadrupole combination, the quadrupole receiver, whose target azimuth is consistent with the dipole source, is utilized here. The target azimuth is the angle when the transducer radiation/reception reaches its maximum value. For example, dipole lobes **600** have radiation and/or receiver patterns with target azimuths of 0-degree and 180-degree. Quadrupole reception include four side lobes **800** and two main lobes **810**. The azimuth of reflectors **304** (e.g., referring to FIG. **3**) is determined from the maximum amplitude of reflected signals (e.g., referring to FIG. **3**), i.e., the maximum at the main lobes. In examples, side lobes **800** may receive signals at a low level, which may have little influence on azimuth estimation based on the maximum value of main lobes of **810**. Furthermore, 90-degree uncertainty with quadrupole lobes **700** may be removed with a dipole source emitting lobes **600** by choosing the two quadrupole lobes of 0-degree and 180-degree line up with the dipole radiation lobes, as the other two quadrupole lobes of 90-degree and 270-degree is highly suppressed by the dipole radiation lobes. It should also be noted that the width of dipole lobes may be reduced as compared to that of a dipole-dipole pattern (e.g., referring to FIG. **6**), which may be due to the use of a quadrupole receiver and quadrupole lobes **700**. Combining radiation patterns for dipole lobes **600** and/or quadrupole lobes **700** may increase sensitivity and measurement area.
(40) As illustrated in FIG. **9**, a radiation pattern of a combined dipole lobes **600** and quadrupole lobes **700** may produce a combined lobe **900** for vertical-polarized shear (SV) formation body waves. The primary radiation azimuths of the SV waves for dipole lobes **600** and quadrupole lobes **700** may be different and by combining dipole lobes **600** and quadrupole lobes **700** in a dipole-quadrupole scheme, the radiation/receiver pattern may decrease the maximum value of captured reflected SV waves. Thus, the interferences of SV waves on SH wave extractions will be decreased by the transmitter and receiver combination, especially at the target azimuth of SH waves (0- and 180-degree in FIG. **8**). It suggests that the dipole-quadrupole combination may have an advantage over the dipole-dipole combination in estimating an azimuth of reflector **304** (e.g., referring to FIG. **3**). It should be noted that a quadruple-dipole combination has the same radiation and/or receiver pattern as a dipole-quadrupole combination, by reciprocity.
(41) FIG. **10** illustrates an example of the dipole-quadrupole reflected signals acquired by borehole sonic logging tool **102** (e.g., referring to FIG. **1**). The graph illustrates that shear horizontal waves may be captured with a combination of a dipole source and a quadrupole receiver. FIG. **10** illustrates that full waves trains are acquired by the dipole-quadrupole acoustic system, where both dipole waves, coupled quadrupole waves and reflected waves are included. FIG. **11** shows the reflected shear waves separated from the waveforms in FIG. **10** by a median-filter. As illustrated, reflected shear waves are clearly captured by receiver **130** (e.g., referring to FIG. **1**) which may be a dipole-quadrupole hybrid. In examples, additional processing steps may enhance the signal-to-noise ratio (SNR) of reflected signals **306** (e.g., referring to FIG. **3**). For example, optimize the operation frequency, stacking and filtering the final signal for better SNR, or the practitioner may slow down the logging speed to decrease the road noise level. Processing techniques for a dipole-quadrupole hybrid borehole sonic logging tool **102** may produce dipole-quadrupole signals for imaging reflectors **304** (e.g., referring to FIG. **3**) near borehole **124** (e.g., referring to FIG. **3**).
(42) FIG. **12**A illustrates an example of a borehole sonic logging tool **102** with the capability for firing dipole signals and receiving quadrupole signals. In examples, borehole sonic logging tool

102 may include cross dipole transmitter (e.g., an X-dipole **1200** and a Y-dipole transmitter **1202**). Borehole sonic logging tool **102** may include at least one side array receiver **1204**. FIG. **12**B illustrates side array receiver **1204**. In examples, side array receiver **1204** may include any number of individual receivers (A-H). Combining waveforms at A, C, E and G, may produce quadrupole waveforms referring to receiver A. Combining waveforms at B, D, F and H, may produce quadrupole waveforms referring to receiver B.

(43) FIG. **13** shows an example workflow **1300** for dipole-quadrupole processing. It should be noted that a similar workflow **1300** may be applied for quadrupole-dipole processing. In examples. Workflow **1300** may begin with step **1302**. In step **1302** an operator may input a data set of sixteen components, which may include recorded data for both X and Y dipole sources firings, namely XA, XB, XC, XD, XE, XF, XG, XH, YA, YB, YC, YD, YE, YF, YG, YH recordings from a sonic logging tool **102** (e.g., referring to FIGS. **12**A and **12**B) and input the recorded data into an information handling system **114** (e.g., referring to FIG. **1**). The operator may then decompose the **16**C (e.g., sixteen component) data to **4**C (four component) data of XA.sub.Q, XB.sub.Q, YA.sub.Q, and YB.sub.Q (it should be noted that the first letter represents the dipole source, and the second letter represents the quadrupole receiver) on information handling system **114**. In step **1306** an operator may remove borehole guided waves **308** and separate the up going and down going reflected signals **306** arriving from reflectors **304**. In step **1308** the operator may select a target azimuth of θ. The target azimuth is the angle where the transducer radiation/reception lobe reaches its maximum value. In step **1310** the operator may rotate the dipole source to face θ, and measure X.sub.θA.sub.Q, X.sub.θB.sub.Q, Y.sub.θA.sub.Q, and Y.sub.θB.sub.Q. In step **1312** the operator may rotate the quadrupole receiver to face θ, and measure X.sub.θA.sub.Qθ, X.sub.θB.sub.Qθ, Y.sub.θA.sub.Qθ, and Y.sub.θB.sub.Qθ. As so, the two quadrupole lobes **700** are lined up with the two dipole radiation lobes (e.g., radiation lobes **600** on FIG. **9**). In step **1314** the operator may select an azimuth to maximize the reflected shear horizontal signals in X.sub.θB.sub.Qθ or Y.sub.θA.sub.Qθ. It should be noted that X.sub.θB.sub.Qθ and Y.sub.θA.sub.Qθ may be identified as inline components for measuring formation body shear horizontal waves. In step **1316** the operator may migrate X.sub.θB.sub.Qθ or Y.sub.θA.sub.Qθ signals to image a reflector **304**. In step **1318** the operator may output the estimated azimuth and the image from both the up going and down going reflected signals **306** from reflectors **304**.

(44) Improvements over current devices and methods may be found in utilizing dipole transmitters and an array of quadrupole receivers to emit and capture shear horizontal waves for reflection imaging. By providing an alternative imaging solution to for shear horizontal imaging with dipole sources and receivers. As discussed above, methods may be provide a simpler imaging flow with less need to attenuated standard borehole guided waves.

(45) This method and system may include any of the various features of the compositions, methods, and system disclosed herein, including one or more of the following statements.

(46) Statement 1. A borehole sonic logging tool for imaging may comprise a transmitter configured to transmit a sonic waveform into a formation, wherein the transmitter is a dipole, and a receiver configured to record a reflected wave as waveform data, wherein the receiver is a quadrupole.

(47) Statement 2. The borehole sonic logging tool of statement 1, wherein the borehole sonic logging tool is disposed on a conveyance.

(48) Statement 3. The borehole sonic logging tool of statements 1 or 2, wherein the borehole sonic logging tool is disposed on a bottom hole assembly.

(49) Statement 4. The borehole sonic logging tool of statements 1-3, further comprising one or more receivers, wherein the one or more receivers are each quadrupoles.

(50) Statement 5. The borehole sonic logging tool of statements 1-4, wherein the transmitter is the quadrupole.

(51) Statement 6. The borehole sonic logging tool of statement 5, wherein the receiver is the dipole.

(52) Statement 7. The borehole sonic logging tool of statement 6, further comprising one or more

receivers, wherein the one or more receivers are each dipoles.
(53) Statement 8. The borehole sonic logging tool of statements 1-4 and 5, further comprising an information handling system configured to at least partially process the waveform data.
(54) Statement 9. A method for measuring a horizontal-polarized shear wave may comprise disposing a downhole tool into a borehole, wherein the downhole tool may comprise a transmitter configured to transmit a sonic waveform into a formation, wherein the transmitter is a dipole; and a receiver configured to record a response from a borehole, wherein the receiver is a quadrupole; selecting a frequency range for the transmitter to a horizontally-polarized shear formation body wave; broadcasting the sonic waveform as the horizontally-polarized shear formation body wave into the formation penetrated by the borehole with the transmitter; recording a reflected wave on the receiver as waveform data, wherein the reflected wave is the horizontally-polarized shear formation body wave reflected from a reflector; and processing the waveform data with an information handling system.
(55) Statement 10. The method of statement 9, wherein the transmitter is the quadrupole.
(56) Statement 11. The method of statement 10, wherein the receiver is the dipole.
(57) Statement 12. The method of statement 9, further comprising recording a borehole guide wave.
(58) Statement 13. The method of statement 12, further comprising removing the borehole guide wave during the processing the waveform data.
(59) Statement 14. A method for processing a dipole-quadrupole signal may comprise inputting a sixteen component data set into an information handling system; decomposing the sixteen component data set to a four component data set with the information handling system; removing borehole guide waves from the four component data set with the information handling system; separating reflected waves as up going signals and down going signals; selecting a target azimuth of θ; rotating a dipole transmitter to face θ; rotating a quadrupole receiver to face θ; selecting a second azimuth to record horizontally-polarized shear waves; imaging a reflector from a formation; and displaying an image of the reflector.
(60) Statement 15. The method of statement 14, wherein the sixteen component data set comprises variables XA, XB, XC, XD, XE, XF, XG, XH, YA, YB, YC, YD, YE, YF, YG, and YH.
(61) Statement 16. The method of statements 14 or 15, wherein the four component data set comprises variables XA.sub.Q, XB.sub.Q, YA.sub.Q, and YB.sub.Q.
(62) Statement 17. The method of statements 14-16, wherein the rotating the dipole transmitter to face θ measures variable X.sub.θA.sub.Q, X.sub.θB.sub.Q, Y.sub.θA.sub.Q, and Y.sub.θB.sub.Q.
(63) Statement 18. The method of statements 14-17, wherein the rotating the quadrupole receiver to face θ measures X.sub.θA.sub.Qθ, X.sub.θB.sub.Qθ, Y.sub.θA.sub.Qθ, and Y.sub.θB.sub.Qθ.
(64) Statement 19. The method of statements 14-18, wherein the horizontally-polarized shear waves are measured in X.sub.θB.sub.Qθ or Y.sub.θA.sub.Qθ directions.
(65) Statement 20. The method of statements 14-19, wherein the imaging the reflector from the formation is at least partially from measurements in X.sub.θB.sub.Qθ or Y.sub.θA.sub.Qθ directions.
(66) The preceding description provides various examples of the systems and methods of use disclosed herein which may contain different method steps and alternative combinations of components. It should be understood that, although individual examples may be discussed herein, the present disclosure covers all combinations of the disclosed examples, including, without limitation, the different component combinations, method step combinations, and properties of the system. It should be understood that the compositions and methods are described in terms of “comprising,” “containing,” or “including” various components or steps, the compositions and methods can also “consist essentially of” or “consist of” the various components and steps. Moreover, the indefinite articles “a” or “an,” as used in the claims, are defined herein to mean one or more than one of the element that it introduces.

(67) For the sake of brevity, only certain ranges are explicitly disclosed herein. However, ranges from any lower limit may be combined with any upper limit to recite a range not explicitly recited, as well as, ranges from any lower limit may be combined with any other lower limit to recite a range not explicitly recited, in the same way, ranges from any upper limit may be combined with any other upper limit to recite a range not explicitly recited. Additionally, whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any included range falling within the range are specifically disclosed. In particular, every range of values (of the form, “from about a to about b,” or, equivalently, “from approximately a to b,” or, equivalently, “from approximately a-b”) disclosed herein is to be understood to set forth every number and range encompassed within the broader range of values even if not explicitly recited. Thus, every point or individual value may serve as its own lower or upper limit combined with any other point or individual value or any other lower or upper limit, to recite a range not explicitly recited.
(68) Therefore, the present examples are well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular examples disclosed above are illustrative only, and may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Although individual examples are discussed, the disclosure covers all combinations of all of the examples. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. It is therefore evident that the particular illustrative examples disclosed above may be altered or modified and all such variations are considered within the scope and spirit of those examples. If there is any conflict in the usages of a word or term in this specification and one or more patent(s) or other documents that may be incorporated herein by reference, the definitions that are consistent with this specification should be adopted.

Claims

1. A borehole sonic logging tool for imaging comprising: a hybrid transmitter and receiver combination comprising: a plurality of dipole transmitters to transmit a plurality of dipole sonic waveform into a formation; and a plurality of receivers to receive sonic waveforms from the formation, wherein the plurality of receivers are arranged in an azimuthal array around the logging tool and configured to detect reflected waves from a dipole transmission from the plurality of dipole transmitters; and an information handling system in communication with the hybrid transmitter and receiver combination, wherein the information handling system; selects a frequency range for the plurality of dipole transmitters to transmit a horizontally-polarized shear formation body wave using a forward model; combines detected reflected waves from a first subset of the plurality of receivers in the azimuthal array to produce a first quadrupole waveform, and combines received detected waves from a second subset of the plurality of receivers in the azimuthal array to produce a second quadrupole waveform; determines at least part of a target azimuth; rotates the hybrid transmitter and receiver towards the target azimuth; receives waveform data with the hybrid transmitter and receiver combination from a reflection interface of the horizontally-polarized shear formation body wave within the formation; separates from the waveform data one or more reflected signals from one or more borehole signals; enhances the signal-to-noise ratio of the one or more reflected signals; filters the one or more reflected signals with a median filter; and processes the reflected signals to form an image.
2. The borehole sonic logging tool of claim 1, wherein the borehole sonic logging tool is disposed on a conveyance.
3. The borehole sonic logging tool of claim 1, wherein the borehole sonic logging tool is disposed on a bottom hole assembly.

4. The borehole sonic logging tool of claim 1, wherein the information handling further determines an optimal frequency range with forward modeling.
5. The borehole sonic logging tool of claim 4, wherein the at least one of the plurality of receivers records a borehole guide wave.
6. The borehole sonic logging tool of claim 5, wherein the information handling system removes the borehole guide wave during the determining an optimal frequency range with forward modeling.
7. A method comprising: disposing a downhole tool into a borehole, wherein the downhole tool comprises: a hybrid transmitter and receiver combination comprising: a plurality of dipole transmitters to transmit a sonic waveform into a formation; and a plurality of receivers to receive sonic waveforms from the formation, wherein the plurality of receivers are arranged in an azimuthal array around the logging tool and configured to detect reflected waves from a dipole transmission from the plurality of dipole transmitters; and selecting a frequency range for the transmitter to a horizontally-polarized shear formation body wave; determining at least part of a target azimuth; rotating the hybrid transmitter and receiver combination towards the target azimuth; broadcasting the sonic waveform as the horizontally-polarized shear formation body wave into the formation penetrated by the borehole with the transmitter; recording reflected waves on the plurality of receivers as waveform data; and combining the recorded waveform data from a first subset of the plurality of receivers in the azimuthal array to produce a first quadrupole waveform, and combining the recorded waveform data from a second subset of the plurality of receivers in the azimuthal array to produce a second quadrupole waveform.
8. The method of claim 7, further comprising recording a borehole guide wave.
9. The method of claim 8, further comprising removing the borehole guide wave during the processing the waveform data.
10. The method of claim 7, further comprising enhancing the signal-to-noise ratio of reflected signals during the processing the waveform data.
11. The method of claim 7, further comprising filtering the reflected wave with a median filter during the processing the waveform data.
12. The method of claim 7, further comprising determining an optimal frequency range using forward modeling.