



(51) International Patent Classification:

E21B 47/002 (2012.01) E21B 47/12 (2006.01)
E21B 47/04 (2006.01)

(21) International Application Number:

PCT/US2024/010227

(22) International Filing Date:

04 January 2024 (04.01.2024)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

18/403,243 03 January 2024 (03.01.2024) US

(71) Applicant: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US).

(72) Inventors: **ZOU, Zheguang**; 315 Jalan Ahmad Ibrahim, 639940 Singapore (SG). **DARBE, Robert P.**; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US). **BITTAR, Michael S.**; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US). **WU, Xiang**; 315 Jalan Ahmad Ibrahim, 639940 Singapore (SG). **YANG, Jie**; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US).

(74) Agent: **PEACOCK, Gregg**; 15201 Mason Road, Suite 1000-312, Cypress, Texas 77433 (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, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, 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, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, 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, ME, 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).

(54) Title: DOWNHOLE MEASURED DEPTH DETECTION FROM AZIMUTHAL BOREHOLE IMAGING

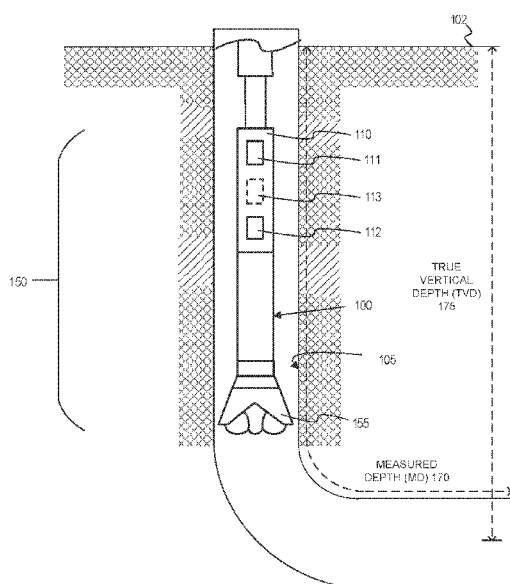


FIG. 1

(57) Abstract: Systems, methods, and apparatus, including computer programs encoded on computer-readable media, for detecting downhole measured depth of a borehole are disclosed. A downhole imaging tool of a drilling system may obtain azimuthal borehole images from at least a first sensor and a second sensor of the downhole imaging tool. Image cross-correlation is performed on the azimuthal borehole images. A time delay is determined based on the image cross-correlation on the azimuthal borehole images. A velocity of the downhole imaging tool is determined based on the time delay. A downhole measured depth of the downhole imaging tool within the borehole is determined based on the velocity. The downhole measured depth may be determined dynamically downhole by the downhole imaging tool without communications with surface equipment of the drilling system.

Published:

— *with international search report (Art. 21(3))*

DOWNHOLE MEASURED DEPTH DETECTION FROM AZIMUTHAL BOREHOLE IMAGING

TECHNICAL FIELD

[0001] The present invention relates generally to oil and gas systems and services, and more specifically to downhole measured depth detection from azimuthal borehole imaging.

BACKGROUND

[0002] The oil and gas services industry uses various types of downhole well devices or tools in well systems. For example, well systems may use well devices or tools to determine a measured depth of a borehole. Measured depth, which may be defined as the total length of the borehole measured along the actual well path, is a fundamental parameter used by drilling and wireline activities performed in the oil and gas services industry. Measured depth can mark the location of the well tool within the borehole, so that onboard sensors of the well tool know the location where measurements are made in the borehole. However, the information of measured depth is typically not available downhole at the tool level. Typically, measured depth is calculated at the ground surface based on rotation measurements during drilling (such as rotation measurements from drilling drawworks). The lack of accurate, real-time downhole depth information can limit advanced downhole calculation since logging and measurement data related to depth is typically distorted. Although downhole measured depth can be roughly estimated from the double integral of the tool's accelerometer data, the estimated measured depth is of low accuracy due to noise in the accelerometer data and significant drifting from the double integral calculations.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] **Figure 1** depicts a schematic diagrams of an example downhole azimuthal imaging tool of a drilling system that may be used for detecting a downhole measured depth, according to some implementations.

[0004] **Figure 2** depicts a conceptual diagram of an example technique performed by the downhole azimuthal imaging tool for determining a downhole measured depth, according to some implementations.

- [0005] **Figure 3** illustrates a technique for determining the time delay within two azimuthal borehole imaging measurements and the relationship to the measured depth offset, according to some implementations.
- 5 [0006] **Figure 4** illustrates a technique for extracting the time delay as a function of time based on image cross-correlation, according to some implementations.
- [0007] **Figure 5** illustrates an example image cross-correlation result for finding time delay between two azimuthal borehole images, according to some implementations.
- [0008] **Figure 6** illustrates the effect of time window size on the calculation of image cross-correlation, according to some implementations.
- 10 [0009] **Figure 7** illustrates an example image cross-correlation result when performing continuous image cross-correlation on azimuthal borehole images, according to some implementations.
- [0010] **Figure 8** shows the measured depth results plot based on image cross-correlation and a comparison with a reference measured depth value, according to some implementations.
- 15 [0011] **Figure 9** is a flowchart of example operations for determining a downhole measured depth using image cross-correlation and accelerometer measurements, according to some implementations.
- [0012] **Figure 10** is a flowchart of example operations for determining a downhole measured depth using image cross-correlation, according to some implementations.
- 20 [0013] **Figure 11** is a schematic diagram of a drilling rig system as an example of oil services systems that use surface and downhole equipment, according to some implementations.
- [0014] **Figure 12** depicts an example computer system that can be used in a downhole tool for determining a downhole measured depth using image cross-correlation.

DESCRIPTION

- 25 [0015] The description that follows includes example systems, methods, techniques, and program flows that describe aspects of the disclosure. However, it is understood that this

disclosure may be practiced without these specific details. For instance, this disclosure refers to certain well devices or tools in illustrative examples. Aspects of this disclosure can be instead applied to other types of well devices and tools. In other instances, well-known instruction instances, protocols, structures, and techniques have not been shown in detail to avoid confusion.

5 [0016] **Figure 1** depicts a schematic diagrams of an example downhole azimuthal imaging tool 110 of a drilling system that may be used for detecting a downhole measured depth, according to some implementations. In some implementations, the downhole azimuthal imaging tool 110 may be located in a drill string 100 of a drilling system (as further shown in Figure 11). For example, the downhole azimuthal imaging tool 110 may be located in the bottom hole
10 assembly (BHA) 150 of the drill string 100 that is lowered downhole from the surface 102 into a borehole 105. The BHA 150 may also include a drill bit 155. It is noted that the drill string 100 may include other parts and components (e.g., as shown in Figure 11) that are not shown for simplicity. In some implementations, the downhole azimuthal imaging tool 110 may include a first sensor 111 and a second sensor 112. It is noted, however, that the downhole azimuthal
15 imaging tool 110 may include any number of sensors. For example, the downhole azimuthal imaging tool 110 may include a third sensor 113.

[0017] In some implementations, the downhole azimuthal imaging tool 110 may be used to calculate accurate a downhole measured depth (MD) 170 from cross-correlation of high-resolution azimuthal borehole images. First, the azimuthal borehole images may be measured at
20 two or more locations using two or more sensors from the downhole azimuthal imaging tool 110 with high azimuthal resolution. For example, the downhole azimuthal imaging tool 110 may capture the azimuthal borehole images having high azimuthal resolution using at least the first sensor 111 and the second sensor 112 of the downhole azimuthal imaging tool 110. In some implementations, a high azimuthal resolution may be a resolution having greater than or equal to
25 32 bins. It is noted, however, that in other implementations the use of a different number of bits may be considered a high azimuthal resolution. By utilizing high azimuthal bins, the time window for cross-correlation can be greatly reduced (e.g., reduced to 1 sample), which results in more reliability and less sensitivity to image distortion. Second, a time delay (i.e., an offset between images) can be accurately obtained by cross-correlating the high-resolution azimuthal
30 borehole images with a short time window (as further described below in Figures 2-7), which can reduce the sensitivity of image distortion due to tool's velocity changes. Also, the time delay can

be estimated in the subsample scale, which may yield more accurate depth results. Third, the instantaneous velocity of the downhole azimuthal imaging tool 110 as a function of time can be calculated from the time delay. Finally, the relative downhole measured depth 170 can be determined from the velocity, as further below in Figures 2-7. For example, the downhole measured depth 170 may be integrated from the estimated velocity. This is different than traditional techniques that take the double integral of acceleration to find measured depth, which has been found to be noisy and sensitive to drifting. After determining the downhole measured depth 170, the true vertical depth (TVD) 175 can also be calculated.

[0018] In some implementations, high-resolution azimuthal borehole images may be acquired when the downhole azimuthal imaging tool 110 (i.e., in drilling status or active drilling) in order to obtain images from the sensors (such as sensors 111 and 112) in the full azimuthal directions. When the downhole azimuthal imaging tool 110 is not in drilling status (i.e., not rotating), the downhole measured depth 170 can be estimated using accelerometer data. In some implementations, when the downhole azimuthal imaging tool 110 obtains downhole measured depth 170 results from both high-resolution azimuthal borehole images and accelerometer measurements during a time period, the final result for the downhole measured depth 170 can be determined by combining the results from both high-resolution azimuthal borehole images and accelerometer measurements (e.g., such as by using a weighting ratio, as further described below with reference to Figures 2-9).

[0019] **Figure 2** depicts a conceptual diagram of an example technique performed by the downhole azimuthal imaging tool 110 for determining a downhole measured depth, according to some implementations. As shown in Figure 2, in some implementations, the downhole azimuthal imaging tool 110 may include a first sensor, which may be referred to as an upper sensor (SU) 211, and a second sensor, which may also be referred to as a lower sensor (SL) 212. The upper sensor 211 may include a first transmitter, which may also be referred to as an upper transmitter (TU) 221, and a first receiver, which may also be referred to as an upper receiver (RU) 231. The lower sensor 212 may include a second transmitter, which may also be referred to as a lower transmitter (TL) 222, and a second receiver, which may also be referred to as a lower receiver (RL) 232. It is noted, however, that in other implementations, the downhole azimuthal imaging tool 110 may have any number of transmitters and receivers. For example, in some implementations, the downhole azimuthal imaging tool 110 may include a third receiver,

which may also be referred to as a middle receiver 233. In some implementations, the middle receiver 233 may work in conjunction with either (or both) of the upper transmitter 221 and/or the lower transmitter 222 as a third sensor. In some implementations, the upper transmitters 221 and the lower transmitter 222 may be electromagnetic transmitters, and the upper receiver 231, the lower receiver 232, and optionally the middle receiver 233 may be electromagnetic receivers. The examples described above having both transmitters and receivers may be part of an active sensing system of the downhole azimuthal imaging tool 110 that uses both transmitters and receivers. It is noted, however, that in some implementations the downhole azimuthal imaging tool 100 may include a passive sensing system that uses only receivers. For example, a passive sensing system may listen or receive at least one of gamma ray measurements or noise measurements, among others. In some implementations, in a passive sensing system, the upper sensor 211 may include one or more upper receivers, and the lower sensor 212 may include one or more lower receivers.

[0020] In some implementations, the upper receiver 231, the lower receiver 232, and optionally the middle receiver 233 may be single receivers or may be rows of two or more receivers. For example, the downhole azimuthal imaging tool 110 may include three rows of receivers, and each row of receivers includes three receivers separated by 120 degrees to improve the azimuthal resolution and increase the speed of obtaining the azimuthal images. Thus, when drilling, the downhole azimuthal imaging tool 110 is rotating and can measure the attenuated electromagnetic waves from all directions of the borehole. It is noted, however, that the downhole azimuthal imaging tool 110 may include any number of rows of receivers and each row of receivers may include different number of individual receivers (or single receivers) and may be positioned in different orientations or spaced apart in varying degrees. The receivers (either individual or rows of receivers) can be spaced by a certain distance. For example, each row of receivers (or individual receiver) can be 20 inches apart. In this example, the upper measurements from the upper receiver 231 and the lower measurements from the lower receiver 232 are offset by a 40-inch distance. It is noted, however, that the spacing between each row of receivers (or individual receivers) can be any distance (e.g., such as 15 inches or 30 inches).

[0021] In Figure 2, the downhole azimuthal imaging tool 110 is shown at two different locations (depths) in the borehole during two different times (t_1 and t_2) during drilling. While drilling, the downhole azimuthal imaging tool 110 moves downward inside the borehole along

the well path. The upper sensor 211 and the lower sensor 212 are separated by a fixed distance, D in the axial (depth) direction. At a particular moment, such as a first time t_1 , the lower sensor 212 can detect a certain feature that can be recorded in a first azimuthal borehole image, $L(t)$.

Then, the downhole azimuthal imaging tool 110 continues the drilling operation downhole, and eventually the upper sensor 211 detects the same feature at a second time t_2 and the same feature can be recorded in a second azimuthal borehole image, $U(t)$. The time delay T between the lower sensor 212 and the upper sensor 211 seeing the same borehole feature can be calculated using the first time t_1 and the second time t_2 as follows: $T = t_2 - t_1$.

[0022] Example azimuthal borehole images that may be obtained from the upper receiver 231 of the upper sensor 211 and the lower receiver 232 of the lower sensor 212 are shown in **Figure 3**. As shown, the lower receiver 232 may detect a first azimuthal borehole image 301 having a borehole feature X during a first time, and the upper sensor 211 may detect a second azimuthal borehole image 302 having the same borehole feature X during a second time. Figure 3 also shows the time delay (or time offset) T between offset upper and lower sensors, which depends on the tool's traveling velocity. Within this time delay (T) period, the tool's measured depth may increase by distance D , which may be equal to the spacing between the upper sensor 211 and the lower sensor 212. When this spacing is relatively small, the downhole azimuthal imaging tool 110 can be viewed as traveling in uniform acceleration and the instantaneous velocity can be approximated to an average velocity. The averaged velocity for this time delay (T) period can be calculated by dividing D by T , as shown below in Equation 1.

$$[0023] \quad v_t \approx \bar{v} = \frac{D}{T} \quad (\text{Equation 1})$$

[0024] The downhole measured depth (Z_v) can be calculated by the integration of instantaneous velocity, as shown below in Equation 2.

$$[0025] \quad Z_v = \int v_t(t) dt = D \int \frac{1}{T(t)} dt \quad (\text{Equation 2})$$

[0026] The time delay may be calculated as a function of time, $T(t)$, from the two azimuthal borehole images, $L(t)$ (such as the first azimuthal borehole image 301 or lower image) and $U(t)$ (such as the first azimuthal borehole image 302 or upper image). As described, to automatically extract the time delay, image cross-correlation can be implemented.

[0027] The time delay as a function of time can be extracted based on image cross-correlation, as illustrated in the technique shown in **Figure 4**. To determine the time delay for a certain marker or feature, while the downhole azimuthal imaging tool 110 performs image cross-correlation, a time window with a certain window size is used to capture the marker or feature in the first azimuthal borehole image 301 and extract that portion of data as a template. Then, a time window of the same size (as used in the first azimuthal borehole image) is used to slide through the second azimuthal borehole image 302 to try to detect the same marker or feature. In the example shown in Figure 4, if there is a distinguishable feature, X , shown in both azimuthal borehole images 301 and 302, the downhole azimuthal imaging tool 110 can use a time window to extract the feature in the first azimuthal borehole image 301 (or lower image $L(t)$) as a template and use a time window of the same (or approximately the same) size to search the appearance of the feature, X , on the second azimuthal borehole image 302 (or upper image $U(t)$). This process can be performed using image cross-correlation. Equation 3 below shows the definition of cross-correlation function. In Equation 3, $f(t)$ is a function associated with the first azimuthal borehole image 301, $g(t)$ is a function associated with the second azimuthal borehole image 302, τ is the displacement or offset, and $R(\tau)$ is the cross-correlation results (or outputs).

$$[0028] \quad R(\tau) = f(t) * g(t) = \int_{-\infty}^{\infty} f(t) \cdot g(\tau - t) dt \quad (\text{Equation 3})$$

[0029] In some implementations, zero-normalized cross-correlation may be used for the cross-correlation of the azimuthal borehole images (such as the images 301 and 302) for two-dimensional image data. Equation 4 below shows the definition of the zero-normalized cross-correlation function. In some implementations, the zero-normalized cross-correlation can outperform other methods, especially when the two sensor images are both raw data and not calibrated. In Equation 4, $f(t)$ is a function associated with the first azimuthal borehole image 301, $g(t)$ is a function associated with the second azimuthal borehole image 302, τ is the displacement or offset, n is the number of pixels (or depth samples), u_f is the average of f , σ_f is the standard deviation of f , u_g is the average of g , σ_g is the standard deviation of g , and $R(\tau)$ is the zero-normalized cross-correlation results (or outputs).

$$[0030] \quad R(\tau) = \frac{1}{n} \sum_t \frac{(f(t) - u_f) \cdot (g(\tau - t) - u_g)}{\sigma_f \sigma_g} \quad (\text{Equation 4})$$

[0031] In both the cross-correlation technique and zero-normalized cross-correlation technique, when sliding through the second azimuthal borehole image 302 ($U(t)$) using the template from the first azimuthal borehole image 301 ($L(t)$), the cross-correlation is low when the borehole features does not match the template (i.e., the feature X from the first image does not match any features in the second image), and the correlation is high when the borehole features matches the template (the feature X from the first image matches a features in the second image). The time delay (T) is the temporal location of the maximum correlation, i.e., the maximum cross-correlation results $R(\tau)$, as represented by Equation 5 below.

$$[0032] \quad T = \arg \max_{\tau \in R} R(\tau) \quad (\text{Equation 5})$$

10 [0033] To find the time-delay as a function of time, $T(t)$, a batch loop can be executed to loop through all features in the first azimuthal borehole image 301 ($L(t)$) and correlate with the features in the second azimuthal borehole image 302 ($U(t)$), as described above. Therefore, instantaneous velocity as a function of time can be calculated from time delay, and relative measured depth can be integrated from velocity.

15 [0034] In some implementations, the image cross-correlation technique uses images obtained from the sensors that are measured in the full azimuthal directions, or in other words, the downhole azimuthal imaging tool 110 should be rotating (i.e., in drilling status or active drilling). When the downhole azimuthal imaging tool 110 is not in drilling status (or active drilling), the measured depth (Z_a) can be estimated from the double integral of the accelerometer data $a(t)$, which is shown below in Equation 6.

$$[0035] \quad Z_a = \iint a(t) dt^2 \quad (\text{Equation 6})$$

[0036] In some implementations, the final measured depth result (Z) can be combined from image cross-correlation measured depth result and the acceleration measured depth result, such as by using a weighting technique and weighting ratio shown in Equation 7.

$$25 \quad [0037] \quad Z = \alpha Z_v + (1 - \alpha) Z_a \quad (\text{Equation 7})$$

[0038] In Equation 7, a weighting ratio, α , is introduced to dynamically control the weights between image cross-correlation measured depth and the accelerometer measured depth. A high weight may be used when the high-resolution azimuthal images are available (e.g., when the

downhole azimuthal imaging tool 110 is rotating during active drilling), and a low weight may be used when the downhole azimuthal imaging tool 110 is not rotating (e.g., not drilling, tripping in, tripping out). In some implementations, when both the cross-correlation measured depth and the accelerometer measured depth results are available during a time period, a weight may be given to both the cross-correlation measured depth results and the accelerometer measured depth results with, for example, a higher weight for the cross-correlation measured depth results. In some implementations, the weight function can be calculated based on the status of drilling, so it is a function of measurement data. For example, the weight can be estimated from downhole accelerometer (a) and Rotation Per Minute (RPM) measurements. In this example, the weight function can be represented as $\alpha(a, RPM)$. In some implementations, the image quality or image resolution may also be considered when assigning a weight to the cross-correlation measured depth results. For example, a higher weight may be assigned for the cross-correlation measured depth results when the images are high-resolution images, and a lower weight may be assigned for the cross-correlation measured depth results when the images are not high-resolution images.

[0039] As described in Figure 1, although examples described herein use two sensors for capturing azimuthal borehole images, three or more sensors can be used to perform the image cross-correlation techniques described herein. It is noted that results estimated from three or more sensors may further reduce the estimation error of time delay and improve the accuracy of calculated downhole measured depth. It is further noted that azimuthal measurements that may be used for techniques described herein may include, but not limited to, one or more of density, gamma ray, or acoustics, which are all suitable for downhole measured depth detection.

[0040] **Figure 5** illustrates an example image cross-correlation result for finding time delay between two azimuthal borehole images, according to some implementations. The azimuthal borehole images may include the first azimuthal borehole image 301 (or lower image $L(t)$) and the second azimuthal borehole image 302 (or upper image $U(t)$). As shown both images have the same feature X, but there is a noticeable time delay when the feature is detected in the corresponding image. The cross-correlation result and time delay plot 500 shows the cross-correlation output (or result) as a function of time. In the example shown in plot 500, the time offset calculated by cross-correlation is 52 samples.

[0041] **Figure 6** illustrates the effect of time window size on the calculation of image cross-correlation, according to some implementations. As shown, different correlation windows sizes

can be used for image cross-correlation on the azimuthal borehole images. In Figure 6, from left to right, the time window sizes 601 are 10 pixels, 5 pixels, and 1 pixel, respectively. The image cross-correlation results and time delay plots 600 show that all three time window sizes 601 can identify the similar time offset, e.g., offset index = 52 (in the example shown), suggesting that for high-resolution azimuthal borehole images, the time window sizes 601 used for finding time delay can be reduced to as small as 1 pixel. A small correlation window can lead to better performance (less delay, less computational complexity, and less sensitivity to distortion). Also, time delay estimated by cross-correlating high-resolution azimuthal borehole images with short time windows can reduce the sensitivity of image distortion due to the tool's velocity change.

10 [0042] **Figure 7** illustrates an example image cross-correlation result when performing continuous image cross-correlation on azimuthal borehole images, according to some implementations. The azimuthal borehole images may include the first azimuthal borehole image 301 (or lower image $L(t)$) and the second azimuthal borehole image 302 (or upper image $U(t)$). Plot 700 shows the output 2-d cross-correlation matrix, as a function of time delay and time, $C(T, t)$. Plot 701 shows the extracted time delay, by finding the peak in Plot 700 as a function of time $T(t)$. The results show that the cross-correlation can find the time delay as a function of time. This time delay can be further used to estimate velocity, as described previously. **Figure 8** shows the measured depth results plot 800 based on image cross-correlation and a comparison with a reference measured depth value. The estimated measured depth result determined by image cross-correlation is plotted in gray, and the reference measured depth is plotted using the dashed line. As shown, the estimated measured depth result determined by image cross-correlation is consistent with the reference measured depth value.

[0043] **Figure 9** is a flowchart 900 of example operations for determining a downhole measured depth using image cross-correlation and accelerometer measurements, according to some implementations. In some implementations, the tool is disposed into the borehole with the BHA (block 901). The downhole azimuthal imaging tool 110 obtains lower (L) and upper (U) azimuthal borehole images from two or more sensors at two or more locations (block 902). For example, the first azimuthal borehole image (or lower L image) and the second azimuthal borehole image (or upper U image) are obtained from two or more sensors at two or more locations with high azimuthal resolution (e.g., 32 bins or 64 bins). It is noted, however, that more than two images can be obtained, and two images are used in this example for simplicity.

The L and U images are cross-correlated along the time axis (block 904), and the output is a 2-d correlation matrix, with one axis being time, and the other axis being time offset. Then, the time delay is extracted from the 2-d correlation matrix, by finding the time offset of the maximum value for each time axis (block 906). Next, the velocity is calculated from time delay, by
5 integrating over time (block 908). Finally, the downhole measured depth is calculated from the velocity, by integrating over time (block 910).

[0044] Furthermore, in some implementations, concurrently with the cross-correlation measurements, the downhole azimuthal imaging tool 110 can measure acceleration and rotation (such as RPM) (block 952). The drilling status is estimated from the acceleration and rotation
10 measurements (block 954). A weighting ratio is automatically assigned based on the estimated drilling status (block 956). The velocity is calculated from the acceleration by integration, and if the image-based estimated velocity is available (e.g., drilling status), the velocity can be corrected (block 958). Finally, the measured depth is calculated from the acceleration measurements (block 960). Once the image cross-correlation measured depth and acceleration-
15 based measured depth are calculated, the results are combining based on the weighting ratio (block 970). The final measured depth results are calculated by combining the image cross-correlation measured depth and acceleration-based measured depth results using the weighting ratio (block 980).

[0045] The downhole depth calculated from image cross-correlation technique can enable
20 advanced downhole calculations, which has the potential to improve or expand various drilling and wireline services. For example, the downhole image cross-correlation technique can be used to determine a measured depth in the tool level for downhole automatic dip picking. The downhole automatic dip picking process can have less time delay, less uplink data, and more accuracy in dip results, compared to automatic dip picking performed at the surface. The
25 accurate downhole depth information can reduce the cost (or health, safety and environment risks) related to depth uncertainty. Furthermore, as the oil and gas services industry moves towards drilling automation, the accurate detection of the downhole measured depth can be critical to drilling automation initiatives. Tasks that are performed by human on the ground today can be performed automatically downhole in tools by algorithms. For example, automated
30 formation evaluation and geosteering can be done downhole immediately once the data (e.g., such as the measured depth data) are collected. The benefits of such downhole automation may

include more accuracy (accessible to full raw data), less time delay (no transmission lag), and less uplink data (e.g., such as by sending results and decision only). The measured depth data can also be used for autonomous steering of the downhole tools, including the drilling tools, without having to communicate with the surface equipment.

5 [0046] **Figure 10** is a flowchart 1000 of example operations for determining a downhole measured depth using image cross-correlation, according to some implementations. The operations may include obtaining, at a downhole imaging tool of a drilling system, azimuthal borehole images from at least a first sensor and a second sensor of the downhole imaging tool (block 1010). The operations may include performing image cross-correlation on the azimuthal borehole images (block 1020). The operations may include determining a time delay based on the image cross-correlation on the azimuthal borehole images (block 1030). The operations may include determining a velocity of the downhole imaging tool based on the time delay (block 1040). The operations may include determining a downhole measured depth of the downhole imaging tool within the borehole based on the velocity (block 1050).

15 [0047] **Figure 11** is a schematic diagram of a drilling rig system as an example of oil services systems that use surface and downhole equipment, according to some implementations. For example, in Figure 11 it can be seen how a system 1164 may also form a portion of a drilling rig 1102 located at the surface 1104 of a well. It is noted that while drilling system 1164 may be illustrated as land-based, the present techniques may also be applicable in offshore applications. Drilling of oil and gas wells is commonly carried out using a string of drill pipes connected together so as to form a drilling string 1108 that may be lowered through a rotary table 1110 into a borehole 1112. Here a drilling platform 1186 may be equipped with a derrick 1188 that supports a hoist. A computer system 1190 may be communicatively coupled to any sensors and control devices attached to surface equipment or to the downhole equipment (e.g., downhole well devices and downhole well tools) of the system 1164. One or more of the downhole well devices or well tools may include the downhole imaging tool 110 that may be used for detecting a downhole measured depth, as shown in Figure 1 and described above in Figures 1-10.

[0048] The drilling rig 1102 may provide support for the drill string 1108. The drill string 1108 may operate to penetrate the rotary table 1110 for drilling the borehole 1112 through subsurface formations 1114. The drill string 1108 may include a Kelly 1116, drill pipe 1118, and a bottom hole assembly 1120, perhaps located at the lower portion of the drill pipe 1118.

[0049] The bottom hole assembly 1120 may include drill collars 1122, one or more downhole tools (including the downhole imaging tool 110), and a drill bit 1126. The drill bit 1126 may operate to create a borehole 1112 by penetrating the surface 1104 and subsurface formations 1114. The one or more additional downhole tools may comprise any of a number of different types of tools including MWD tools, LWD tools, and others.

[0050] During drilling operations, the drill string 1108 (perhaps including the Kelly 1116, the drill pipe 1118, and the bottom hole assembly 1120) may be rotated by the rotary table 1110. In addition to, or alternatively, the bottom hole assembly 1120 may also be rotated by a motor (e.g., a mud motor) that may be located downhole. The drill collars 1122 may be used to add weight to the drill bit 1126. The drill collars 1122 may also operate to stiffen the bottom hole assembly 1120, allowing the bottom hole assembly 1120 to transfer the added weight to the drill bit 1126, and in turn, to assist the drill bit 1126 in penetrating the surface 1104 and subsurface formations 1114.

[0051] Drilling operations may utilize various surface equipment, such as a mud pump 1132 or other types of surface equipment. The surface equipment may be outfitted with one or more sensors and one or more control devices. During drilling operations, the mud pump 1132 may pump drilling fluid (sometimes known by those of ordinary skill in the art as “drilling mud”) from a mud pit 1134 through a hose 1136 into the drill pipe 1118 and down to the drill bit 1126. In some implementations, one or more sensors may monitor one or more metrics of the pump drilling fluid (such as flow rate), and one or more control devices may control one or more operations of the mud pump 1132 (such as opening and closing one or more valves or other mechanisms). The drilling fluid may flow out from the drill bit 1126 and be returned to the surface 1104 through an annular area 1140 between the drill pipe 1118 and the sides of the borehole 1112. The drilling fluid may then be returned to the mud pit 1134, where such fluid may be filtered. In some embodiments, the drilling fluid may be used to cool the drill bit 1126, as well as to provide lubrication for the drill bit 1126 during drilling operations. Additionally, the drilling fluid may be used to remove subsurface formation 1114 cuttings created by operating the drill bit 1126. It may be the images of these cuttings that many implementations operate to acquire and process.

[0052] Although some example well systems are shown in Figures 1 and 11, it is noted, however, that the downhole imaging tool 110 described in Figures 1-11 can be used in any type

of well system in the oil and gas industry. For example, the well systems may be any type of drilling well systems, completion well systems, and producing well systems.

[0053] **Figure 12** depicts an example computer system that can be used in a downhole tool for determining a downhole measured depth using image cross-correlation. The computer system 1200 may be an example of a downhole computer system that may be used downhole during the operation of the well system. For example, the computer system 1200 may be a microcomputer, microcontroller or types of computers and processing devices that may be used downhole in well systems. In some implementations, the computer system 1200 may be used downhole by the downhole azimuthal imaging tool 110 described in Figures 1-11 and other downhole well devices and tools. The computer system 1200 may include one or more processors 1201 (possibly including multiple cores, multiple nodes, and/or implementing multi-threading, etc.). The computer system 1200 may include memory 1207. The memory 1207 may be system memory or any type or implementation of machine or computer readable media having instructions that are executable by the one or more processors 1201 to implement the operations described in Figures 1-11. The memory 1207 may be system memory or any type or implementation of machine or computer readable and writable media having the ability to receive, process and/or store data from sensors and devices (including those described in Figures 1-11). The computer system 1200 also may include a bus 1203 and a network interface 1205. The computer system 1200 also may include a communications module 1208 that may control wired and wireless communications, such as receiving sensor data from downhole sensors, communicating with other downhole devices or tools, and communicating with surface equipment. The computer system 1200 also may include at least an image cross-correlation unit 1211 and a downhole depth computation unit 1213, among other processing units or modules that are used during the operation of the downhole well device or tool. For example, the image cross-correlation unit 1211 may perform the image cross-correlation operations described in Figures 1-10 during the operation of the well system. The downhole depth computation unit 1213 may work in conjunction with the image cross-correlation unit 1211 to determine the downhole measured depth, as described above in Figures 1-10. The functionality described herein may be implemented with an application-specific integrated circuit, in logic implemented in the processor(s) 1201, in a co-processor on a peripheral device or card, etc. Further, implementations may include fewer or additional components not illustrated in Figure 12. The processor(s) 1201 and the network interface 1205 may be coupled to the bus 1203. Although

illustrated as being coupled to the bus 1203, the memory 1207 may be coupled to the processor(s) 1201.

[0054] As will be appreciated, aspects of the disclosure may be embodied as a system, method or program code/instructions stored in one or more machine-readable media.

5 Accordingly, aspects may take the form of hardware, software (including firmware, resident software, micro-code, etc.), or a combination of software and hardware aspects that may all generally be referred to herein as a “circuit,” “module” or “system.” The functionality presented as individual modules/units in the example illustrations can be organized differently in accordance with any one of platform (operating system and/or hardware), application ecosystem,
10 interfaces, programmer preferences, programming language, administrator preferences, etc.

[0055] Any combination of one or more machine-readable medium(s) may be utilized. The machine-readable medium may be a machine-readable signal medium or a machine-readable storage medium. A machine-readable storage medium may be, for example, but not limited to, a system, apparatus, or device, that employs any one of or combination of electronic, magnetic,
15 optical, electromagnetic, infrared, or semiconductor technology to store program code. More specific examples (a non-exhaustive list) of the machine-readable storage medium would include the following: a portable computer diskette, a hard disk, a random-access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a portable compact disc read-only memory (CD-ROM), an optical storage device, a
20 magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a machine-readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device. A machine-readable storage medium is not a machine-readable signal medium.

[0056] A machine-readable signal medium may include a propagated data signal with
25 machine-readable program code embodied therein, for example, in baseband or as part of a carrier wave. Such a propagated signal may take any of a variety of forms, including, but not limited to, electro-magnetic, optical, or any suitable combination thereof. A machine-readable signal medium may be any machine-readable medium that is not a machine-readable storage medium and that can communicate, propagate, or transport a program for use by or in connection
30 with an instruction execution system, apparatus, or device.

[0057] Program code embodied on a machine-readable medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0058] Computer program code for carrying out operations for aspects of the disclosure may be written in any combination of one or more programming languages, including an object oriented programming language such as the Java® programming language, C++ or the like; a dynamic programming language such as Python; a scripting language such as Perl programming language or PowerShell script language; and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The program code may execute entirely on a stand-alone machine, may execute in a distributed manner across multiple machines, and may execute on one machine while providing results and or accepting input on another machine.

[0059] The program code/instructions may also be stored in a machine-readable medium that can direct a machine to function in a particular manner, such that the instructions stored in the machine-readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0060] While the aspects of the disclosure are described with reference to various implementations and exploitations, it will be understood that these aspects are illustrative and that the scope of the claims is not limited to them. In general, techniques for detecting downhole measured depth as described herein may be implemented with facilities consistent with any hardware system or hardware systems. Many variations, modifications, additions, and improvements are possible.

[0061] Plural instances may be provided for components, operations or structures described herein as a single instance. Finally, boundaries between various components, operations, and data stores are somewhat arbitrary, and particular operations are illustrated in the context of specific illustrative configurations. Other allocations of functionality are envisioned and may fall within the scope of the disclosure. In general, structures and functionality presented as separate components in the example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be

implemented as separate components. These and other variations, modifications, additions, and improvements may fall within the scope of the disclosure.

[0062] As used herein, the term “or” is inclusive unless otherwise explicitly noted. Thus, the phrase “at least one of A, B, or C” is satisfied by any element from the set {A, B, C} or any combination thereof, including multiples of any element.

[0063] Example Embodiments

[0064] Example Embodiments can include the following:

[0065] Embodiments #1: A method for detecting downhole measured depth of a borehole, comprising: obtaining, at a downhole imaging tool of a drilling system, azimuthal borehole images from at least a first sensor and a second sensor of the downhole imaging tool; performing image cross-correlation on the azimuthal borehole images; determining a time delay based on the image cross-correlation on the azimuthal borehole images; and determining a velocity of the downhole imaging tool based on the time delay.

[0066] Embodiments #2: The method of Embodiments #1, further comprising determining a downhole measured depth of the downhole imaging tool within the borehole based on the velocity.

[0067] Embodiments #3: The method of Embodiments #1, wherein the azimuthal borehole images include a first azimuthal borehole image obtained from the first sensor and a second azimuthal borehole image obtained from the second sensor, and determining the time delay based on the image cross-correlation on the azimuthal borehole images comprising: extracting a borehole feature in the first azimuthal borehole image using a time window; performing the image cross-correlation on the second azimuthal borehole image using the extracted borehole feature in the time window as a template for detecting at least a portion of the borehole feature in the second azimuthal borehole image; and determining the time delay based on a time offset between a first time instant the borehole feature was detected in the first azimuthal borehole image and a second time instant at least the portion of the borehole feature was detected in the second azimuthal borehole image.

[0068] Embodiments #4: The method of Embodiments #1, wherein determining the time delay based on the image cross-correlation on the azimuthal borehole images includes

determining the time delay by performing a batch loop for the image cross-correlation of a plurality of borehole features in the azimuthal borehole images.

5 [0069] Embodiments #5: The method of Embodiments #1, wherein obtaining the azimuthal borehole images and performing the image cross-correlation on the azimuthal borehole images are performed while the drilling system is performing drilling operations.

[0070] Embodiments #6: The method of Embodiments #2, further comprising: determining a second downhole measured depth based on accelerometer measurements; and determining a final downhole measured depth based on the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the
10 accelerometer measurements.

[0071] Embodiments #7: The method of Embodiments #6, wherein the final downhole measured depth is determined dynamically downhole by the downhole imaging tool without communications with surface equipment of the drilling system.

15 [0072] Embodiments #8: The method of Embodiments #6, further comprising: determining a weighting ratio for the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements; and determining the final downhole measured depth by combining the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements based on the weighting ratio.

20 [0073] Embodiments #9: The method of Embodiments #8, wherein the weighting ratio is determined based on at least one of rotation per minute (RPM) measurements, accelerometer measurements, and image resolution.

[0074] Embodiments #10: The method of Embodiments #1, wherein the image cross-correlation is a zero-normalized cross-correlation.

25 [0075] Embodiments #11: A downhole imaging tool for detecting downhole measured depth, comprising: at least a first sensor and a second sensor; one or more processors; and a computer-readable storage medium having instructions stored thereon that are executable by the one or more processors to cause the downhole imaging tool to: obtain azimuthal borehole images from at least the first sensor and the second sensor; perform image cross-correlation on the

azimuthal borehole images; determine a time delay based on the image cross-correlation on the azimuthal borehole images; and determine a velocity of the downhole imaging tool based on the time delay.

5 [0076] Embodiments #12: The downhole imaging tool of Embodiments #11, further comprising instructions that cause the downhole imaging tool to determine a downhole measured depth of the downhole imaging tool within the borehole based on the velocity.

10 [0077] Embodiments #13: The downhole imaging tool of Embodiments #11, wherein the azimuthal borehole images include a first azimuthal borehole image obtained from the first sensor and a second azimuthal borehole image obtained from the second sensor, and the instructions that cause the downhole imaging tool to determine the time delay based on the image cross-correlation further comprise instructions to cause the downhole imaging tool to:
extract a borehole feature in the first azimuthal borehole image using a time window; perform the image cross-correlation on the second azimuthal borehole image using the extracted borehole feature in the time window as a template for detecting at least a portion of the borehole feature in
15 the second azimuthal borehole image; and determine the time delay based on a time offset between a first time instant the borehole feature was detected in the first azimuthal borehole image and a second time instant at least the portion of the borehole feature was detected in the second azimuthal borehole image.

20 [0078] Embodiments #14: The downhole imaging tool of Embodiments #12, further comprising instructions that cause the downhole imaging tool to: determine a second downhole measured depth based on accelerometer measurements; and determine a final downhole measured depth based on the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements.

25 [0079] Embodiments #15: The downhole imaging tool of Embodiments #14, further comprising instructions that cause the downhole imaging tool to: determine a weighting ratio for the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements; and determine the final downhole measured depth by combining the downhole measured depth determined from the

image cross-correlation and the second downhole measured depth determined from the accelerometer measurements based on the weighting ratio.

[0080] Embodiments #16: The downhole imaging tool of Embodiments #11, wherein: the first sensor includes a first transmitter and a first receiver, and the second sensor includes a second transmitter and a second receiver, wherein the first receiver and the second receiver are separated by a distance in a depth direction of the borehole; or the first sensor includes a first transmitter and a first row of a first plurality of receivers, and the second sensor includes a second transmitter and a second row of a second plurality of receivers, wherein the first row of the first plurality of receivers and the second row of the second plurality of receivers are separated by the distance in the depth direction of the borehole; or the first sensor includes one or more receivers and the second sensor includes one or more receivers, wherein the one or more receivers of the first sensor and the one or more receivers of the second sensor are separated by the distance in the depth direction of the borehole.

[0081] Embodiments #17: A non-transitory computer-readable storage medium having instructions stored thereon that are executable by one or more processors of a downhole imaging tool, the instructions comprising: instructions for obtaining, at the downhole imaging tool, azimuthal borehole images from at least a first sensor and a second sensor of the downhole imaging tool; instructions for performing image cross-correlation on the azimuthal borehole images; instructions for determining a time delay based on the image cross-correlation on the azimuthal borehole images; instructions for determining a velocity of the downhole imaging tool based on the time delay; and instructions for determining a downhole measured depth of the downhole imaging tool within the borehole based on the velocity.

[0082] Embodiments #18: The non-transitory computer-readable storage medium of Embodiments #17, wherein the azimuthal borehole images include a first azimuthal borehole image obtained from the first sensor and a second azimuthal borehole image obtained from the second sensor, and the instructions further include: instructions for extracting a borehole feature in the first azimuthal borehole image using a time window; instructions for performing the image cross-correlation on the second azimuthal borehole image using the extracted borehole feature in the time window as a template for detecting at least a portion of the borehole feature in the second azimuthal borehole image; and instructions for determining the time delay based on a time offset between a first time instant the borehole feature was detected in the first azimuthal

borehole image and a second time instant at least the portion of the borehole feature was detected in the second azimuthal borehole image.

[0083] Embodiments #19: The non-transitory computer-readable storage medium of Embodiments #17, wherein the instructions further include: instructions for determining a second
5 downhole measured depth based on accelerometer measurements; and instructions for determining a final downhole measured depth based on the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements.

[0084] Embodiments #20: The non-transitory computer-readable storage medium of
10 Embodiments #19, wherein the instructions further include: instructions for determining a weighting ratio for the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements; and instructions for determining the final downhole measured depth by combining the downhole measured depth determined from the image cross-correlation and the second downhole measured
15 depth determined from the accelerometer measurements based on the weighting ratio.

WHAT IS CLAIMED IS:

1. A method for detecting downhole measured depth of a borehole, comprising:
obtaining, at a downhole imaging tool of a drilling system, azimuthal borehole images
from at least a first sensor and a second sensor of the downhole imaging tool;
5 performing image cross-correlation on the azimuthal borehole images;
determining a time delay based on the image cross-correlation on the azimuthal borehole
images; and
determining a velocity of the downhole imaging tool based on the time delay.
- 10 2. The method of claim 1, further comprising:
determining a downhole measured depth of the downhole imaging tool within the
borehole based on the velocity.
3. The method of claim 1, wherein the azimuthal borehole images include a first azimuthal
15 borehole image obtained from the first sensor and a second azimuthal borehole image obtained
from the second sensor, and determining the time delay based on the image cross-correlation on
the azimuthal borehole images comprising:
extracting a borehole feature in the first azimuthal borehole image using a time window;
performing the image cross-correlation on the second azimuthal borehole image using the
20 extracted borehole feature in the time window as a template for detecting at least a
portion of the borehole feature in the second azimuthal borehole image; and
determining the time delay based on a time offset between a first time instant the
borehole feature was detected in the first azimuthal borehole image and a second
time instant at least the portion of the borehole feature was detected in the second
25 azimuthal borehole image.
4. The method of claim 1, wherein determining the time delay based on the image cross-
correlation on the azimuthal borehole images includes determining the time delay by performing
a batch loop for the image cross-correlation of a plurality of borehole features in the azimuthal
30 borehole images.

5. The method of claim 1, wherein obtaining the azimuthal borehole images and performing the image cross-correlation on the azimuthal borehole images are performed while the drilling system is performing drilling operations.
- 5 6. The method of claim 2, further comprising:
determining a second downhole measured depth based on accelerometer measurements;
and
determining a final downhole measured depth based on the downhole measured depth
determined from the image cross-correlation and the second downhole measured
10 depth determined from the accelerometer measurements.
7. The method of claim 6, wherein the final downhole measured depth is determined
dynamically downhole by the downhole imaging tool without communications with surface
equipment of the drilling system.
- 15 8. The method of claim 6, further comprising:
determining a weighting ratio for the downhole measured depth determined from the
image cross-correlation and the second downhole measured depth determined
from the accelerometer measurements; and
20 determining the final downhole measured depth by combining the downhole measured
depth determined from the image cross-correlation and the second downhole
measured depth determined from the accelerometer measurements based on the
weighting ratio.
- 25 9. The method of claim 8, wherein the weighting ratio is determined based on at least one of
rotation per minute (RPM) measurements, accelerometer measurements, and image resolution.
10. The method of claim 1, wherein the image cross-correlation is a zero-normalized cross-
correlation.
- 30 11. A downhole imaging tool for detecting downhole measured depth, comprising:
at least a first sensor and a second sensor;
one or more processors; and

- a computer-readable storage medium having instructions stored thereon that are executable by the one or more processors to cause the downhole imaging tool to: obtain azimuthal borehole images from at least the first sensor and the second sensor;
- 5 perform image cross-correlation on the azimuthal borehole images; determine a time delay based on the image cross-correlation on the azimuthal borehole images; and determine a velocity of the downhole imaging tool based on the time delay.
- 10 12. The downhole imaging tool of claim 11, further comprising instructions that cause the downhole imaging tool to: determine a downhole measured depth of the downhole imaging tool within the borehole based on the velocity.
- 15 13. The downhole imaging tool of claim 11, wherein the azimuthal borehole images include a first azimuthal borehole image obtained from the first sensor and a second azimuthal borehole image obtained from the second sensor, and the instructions that cause the downhole imaging tool to determine the time delay based on the image cross-correlation further comprise instructions to cause the downhole imaging tool to:
- 20 extract a borehole feature in the first azimuthal borehole image using a time window; perform the image cross-correlation on the second azimuthal borehole image using the extracted borehole feature in the time window as a template for detecting at least a portion of the borehole feature in the second azimuthal borehole image; and determine the time delay based on a time offset between a first time instant the borehole
- 25 feature was detected in the first azimuthal borehole image and a second time instant at least the portion of the borehole feature was detected in the second azimuthal borehole image.
14. The downhole imaging tool of claim 12, further comprising instructions that cause the
- 30 downhole imaging tool to: determine a second downhole measured depth based on accelerometer measurements; and

determine a final downhole measured depth based on the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements.

- 5 15. The downhole imaging tool of claim 14, further comprising instructions that cause the downhole imaging tool to:

determine a weighting ratio for the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements; and

- 10 determine the final downhole measured depth by combining the downhole measured depth determined from the image cross-correlation and the second downhole measured depth determined from the accelerometer measurements based on the weighting ratio.

- 15 16. The downhole imaging tool of claim 11, wherein:

the first sensor includes a first transmitter and a first receiver, and the second sensor includes a second transmitter and a second receiver, wherein the first receiver and the second receiver are separated by a distance in a depth direction of the borehole; or

- 20 the first sensor includes a first transmitter and a first row of a first plurality of receivers, and the second sensor includes a second transmitter and a second row of a second plurality of receivers, wherein the first row of the first plurality of receivers and the second row of the second plurality of receivers are separated by the distance in the depth direction of the borehole; or

- 25 the first sensor includes one or more receivers and the second sensor includes one or more receivers, wherein the one or more receivers of the first sensor and the one or more receivers of the second sensor are separated by the distance in the depth direction of the borehole.

- 30 17. A non-transitory computer-readable storage medium having instructions stored thereon that are executable by one or more processors of a downhole imaging tool, the instructions comprising:

instructions for obtaining, at the downhole imaging tool, azimuthal borehole images from
at least a first sensor and a second sensor of the downhole imaging tool;
instructions for performing image cross-correlation on the azimuthal borehole images;
instructions for determining a time delay based on the image cross-correlation on the
5 azimuthal borehole images;
instructions for determining a velocity of the downhole imaging tool based on the time
delay; and
instructions for determining a downhole measured depth of the downhole imaging tool
within the borehole based on the velocity.

10

18. The non-transitory computer-readable storage medium of claim 17, wherein the
azimuthal borehole images include a first azimuthal borehole image obtained from the first
sensor and a second azimuthal borehole image obtained from the second sensor, and the
instructions further include:

15

instructions for extracting a borehole feature in the first azimuthal borehole image using a
time window;
instructions for performing the image cross-correlation on the second azimuthal borehole
image using the extracted borehole feature in the time window as a template for
detecting at least a portion of the borehole feature in the second azimuthal
20 borehole image; and
instructions for determining the time delay based on a time offset between a first time
instant the borehole feature was detected in the first azimuthal borehole image and
a second time instant at least the portion of the borehole feature was detected in
the second azimuthal borehole image.

25

19. The non-transitory computer-readable storage medium of claim 17, wherein the
instructions further include:

30

instructions for determining a second downhole measured depth based on accelerometer
measurements; and
instructions for determining a final downhole measured depth based on the downhole
measured depth determined from the image cross-correlation and the second
downhole measured depth determined from the accelerometer measurements.

20. The non-transitory computer-readable storage medium of claim 19, wherein the instructions further include:

instructions for determining a weighting ratio for the downhole measured depth
determined from the image cross-correlation and the second downhole measured
5 depth determined from the accelerometer measurements; and
instructions for determining the final downhole measured depth by combining the
downhole measured depth determined from the image cross-correlation and the
second downhole measured depth determined from the accelerometer
measurements based on the weighting ratio.

10

1/12

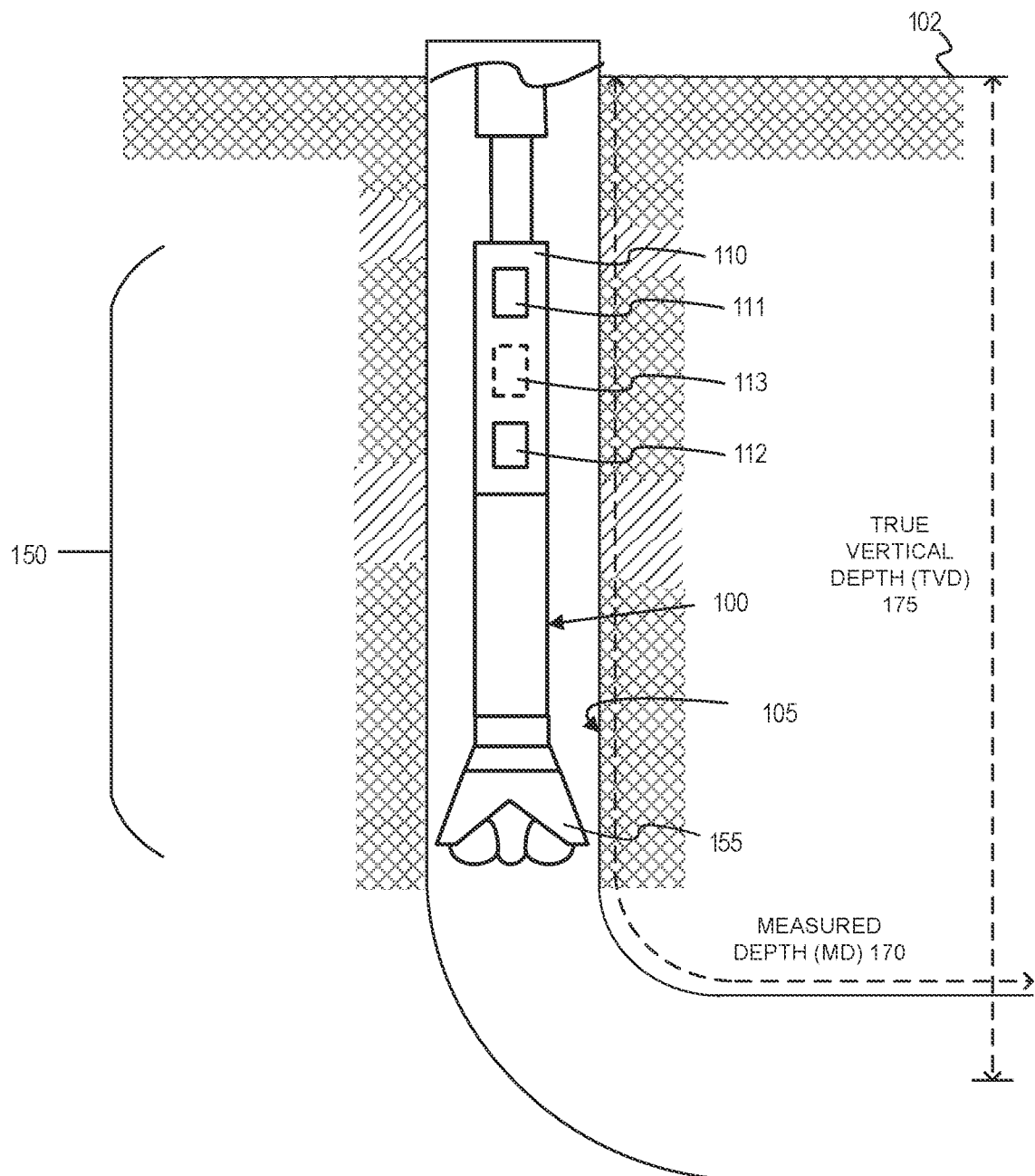


FIG. 1

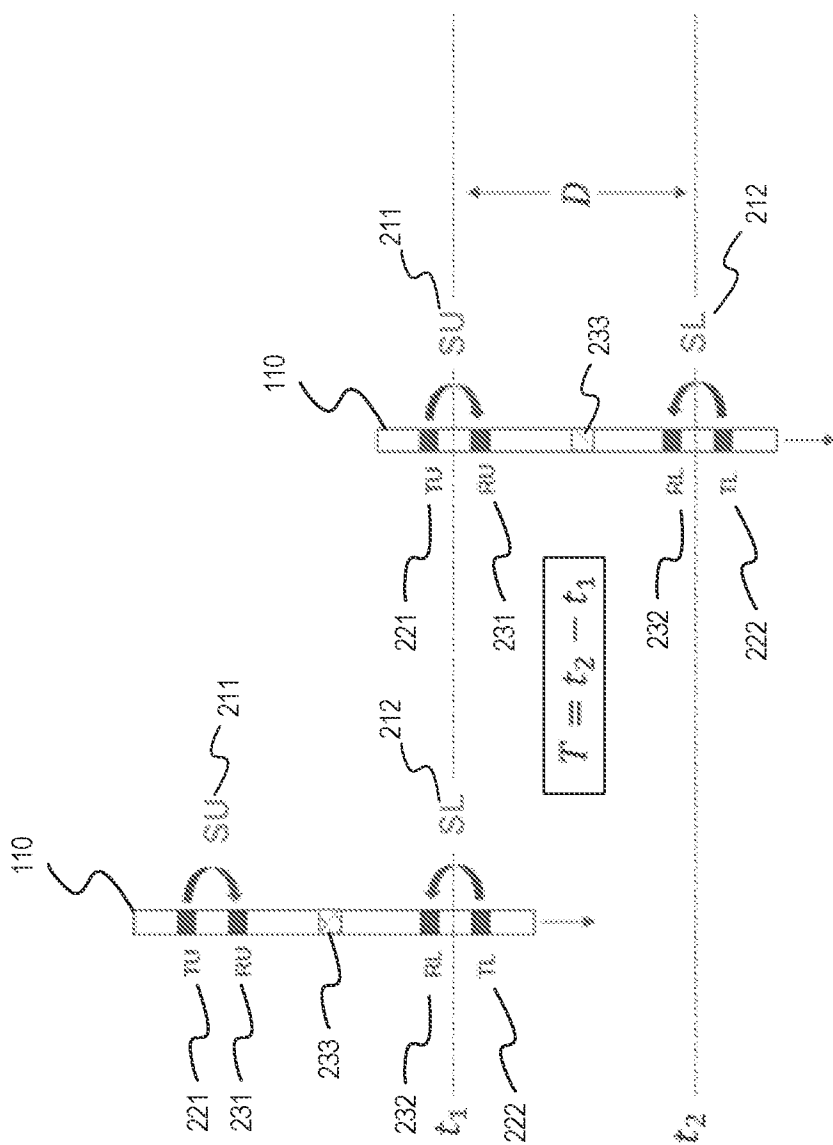


FIG. 2

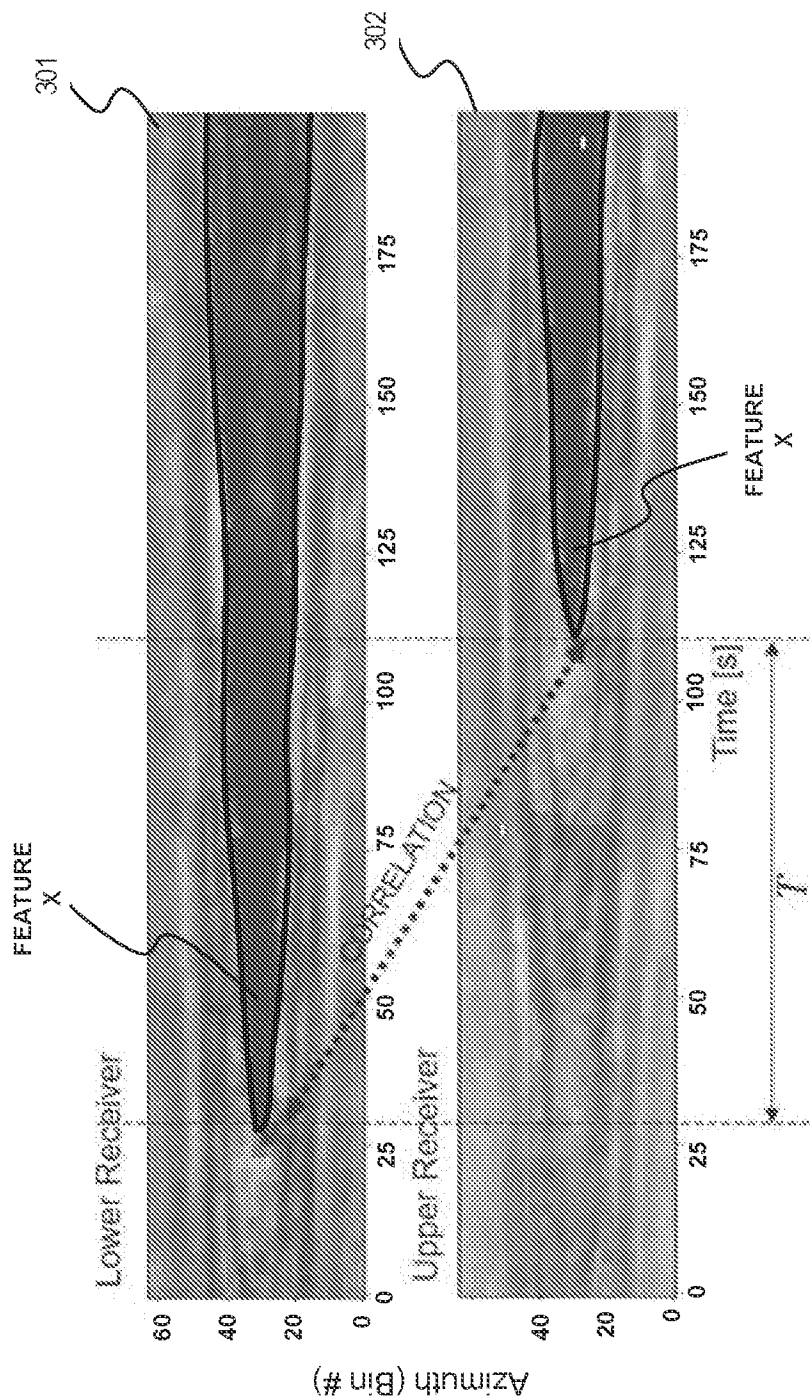


FIG. 3

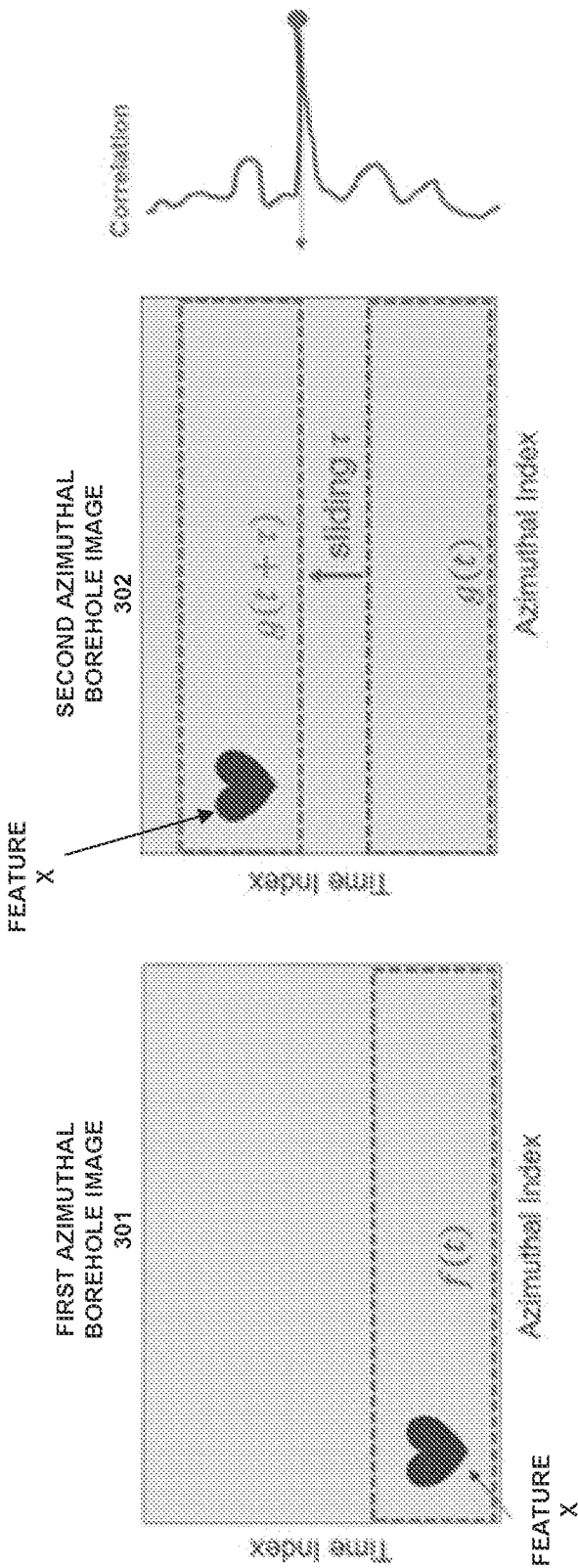


FIG. 4

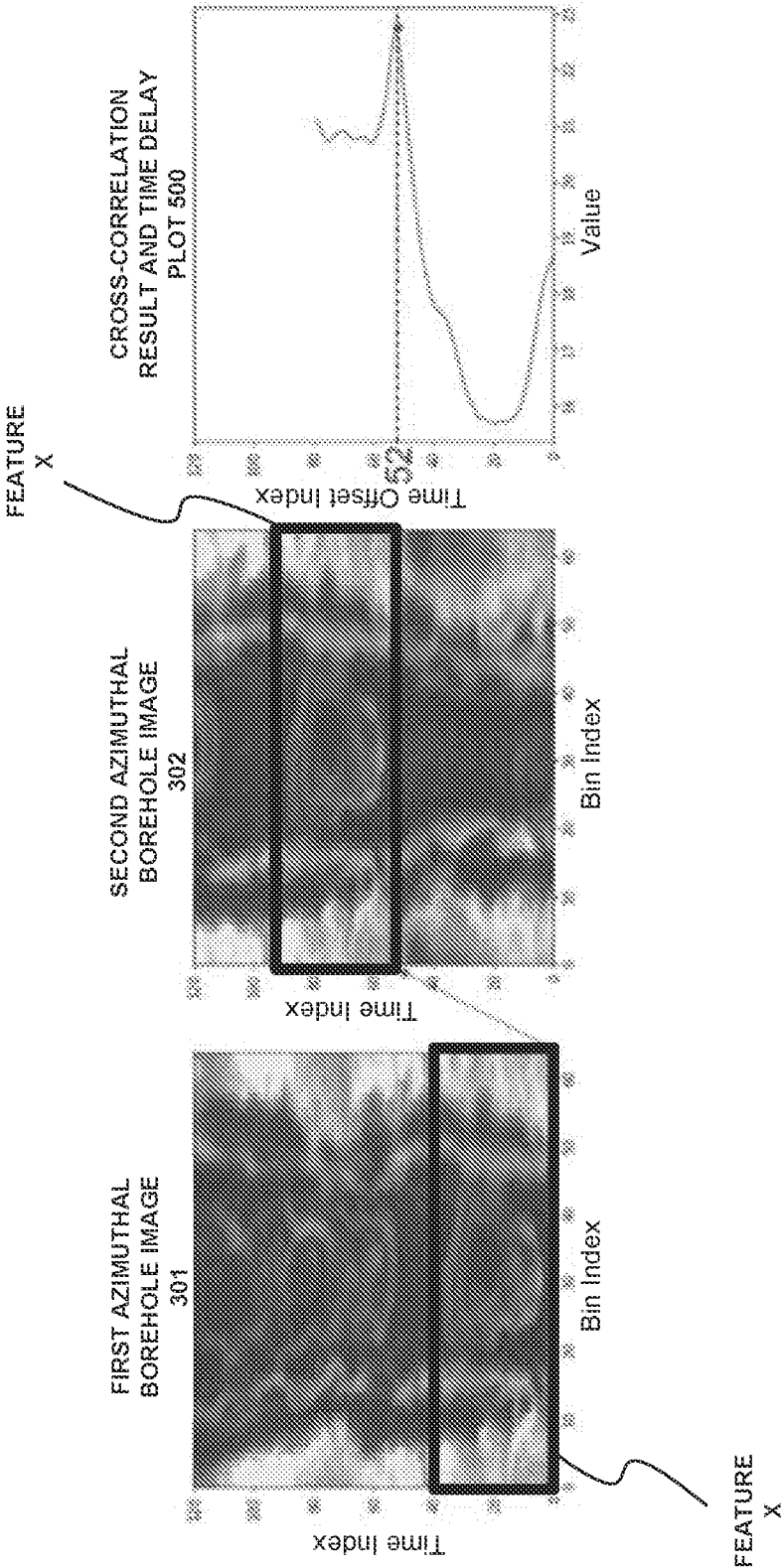


FIG. 5

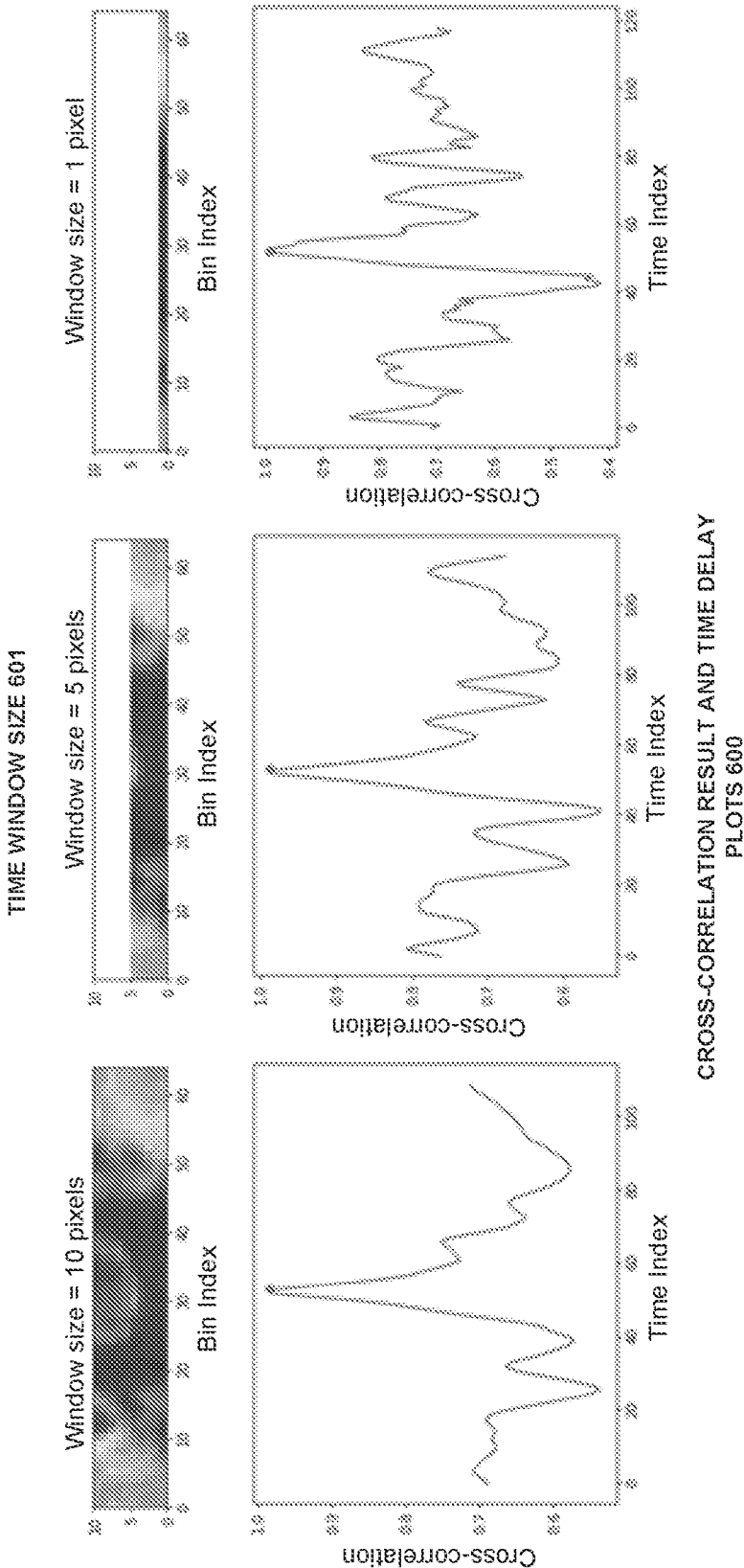


FIG. 6

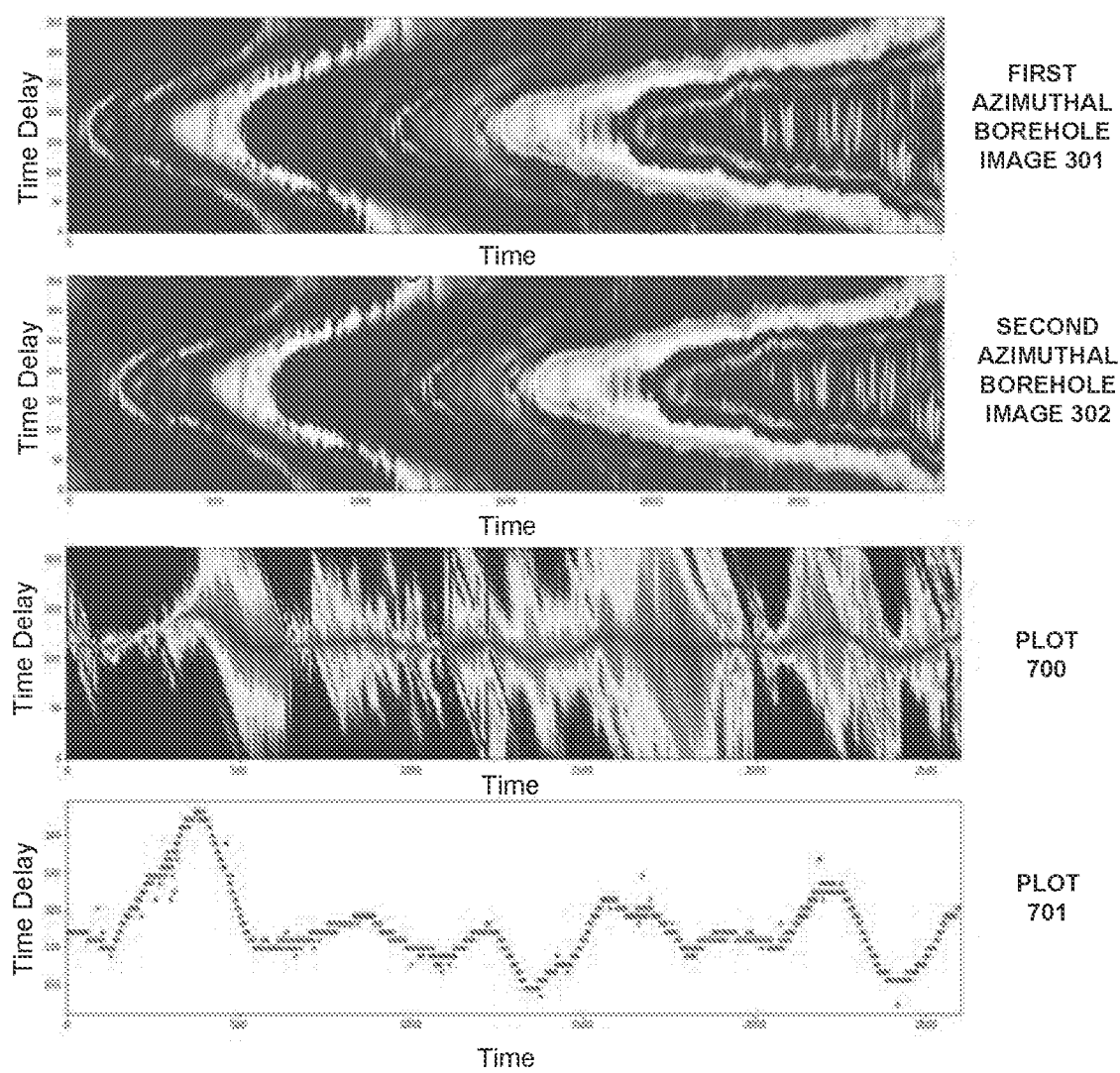


FIG. 7

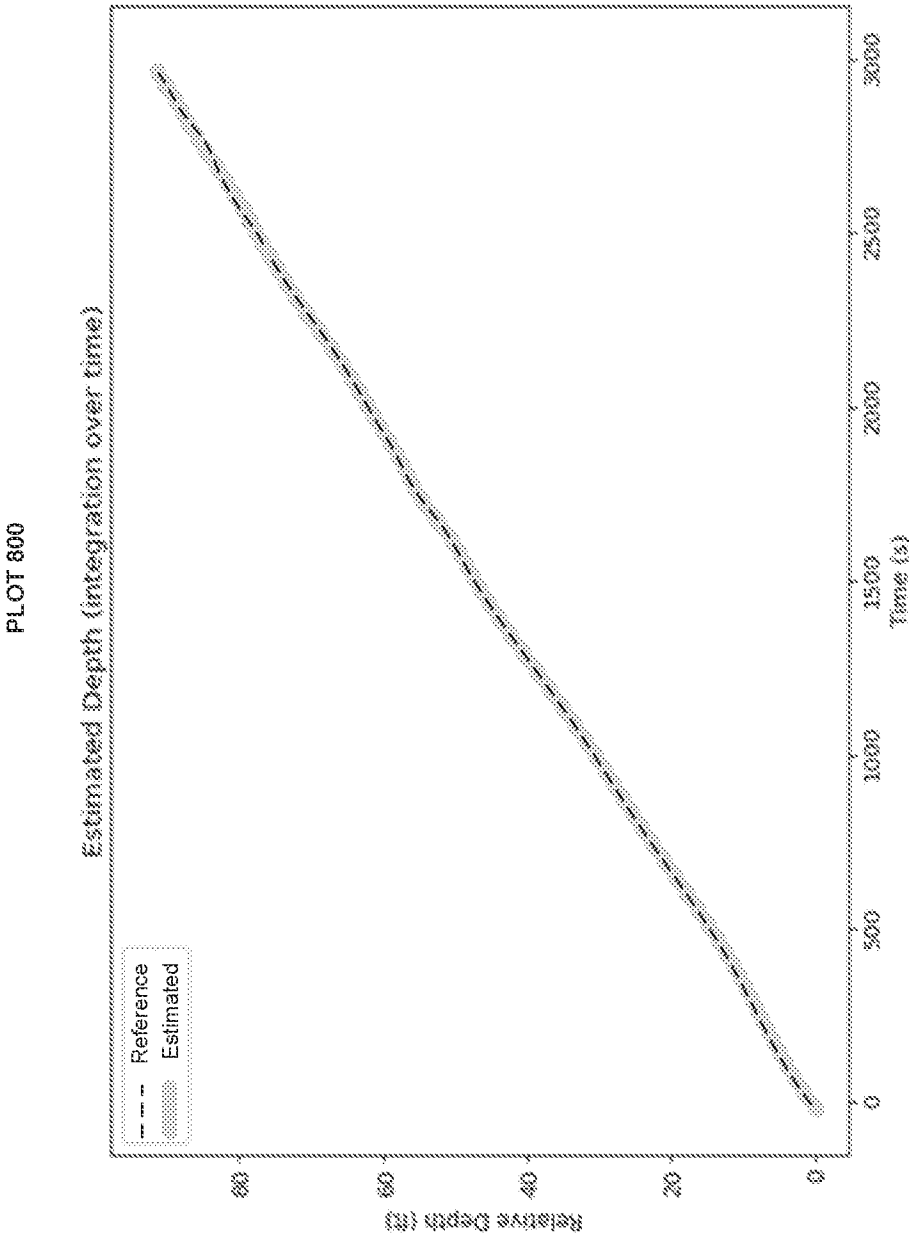


FIG. 8

9/12

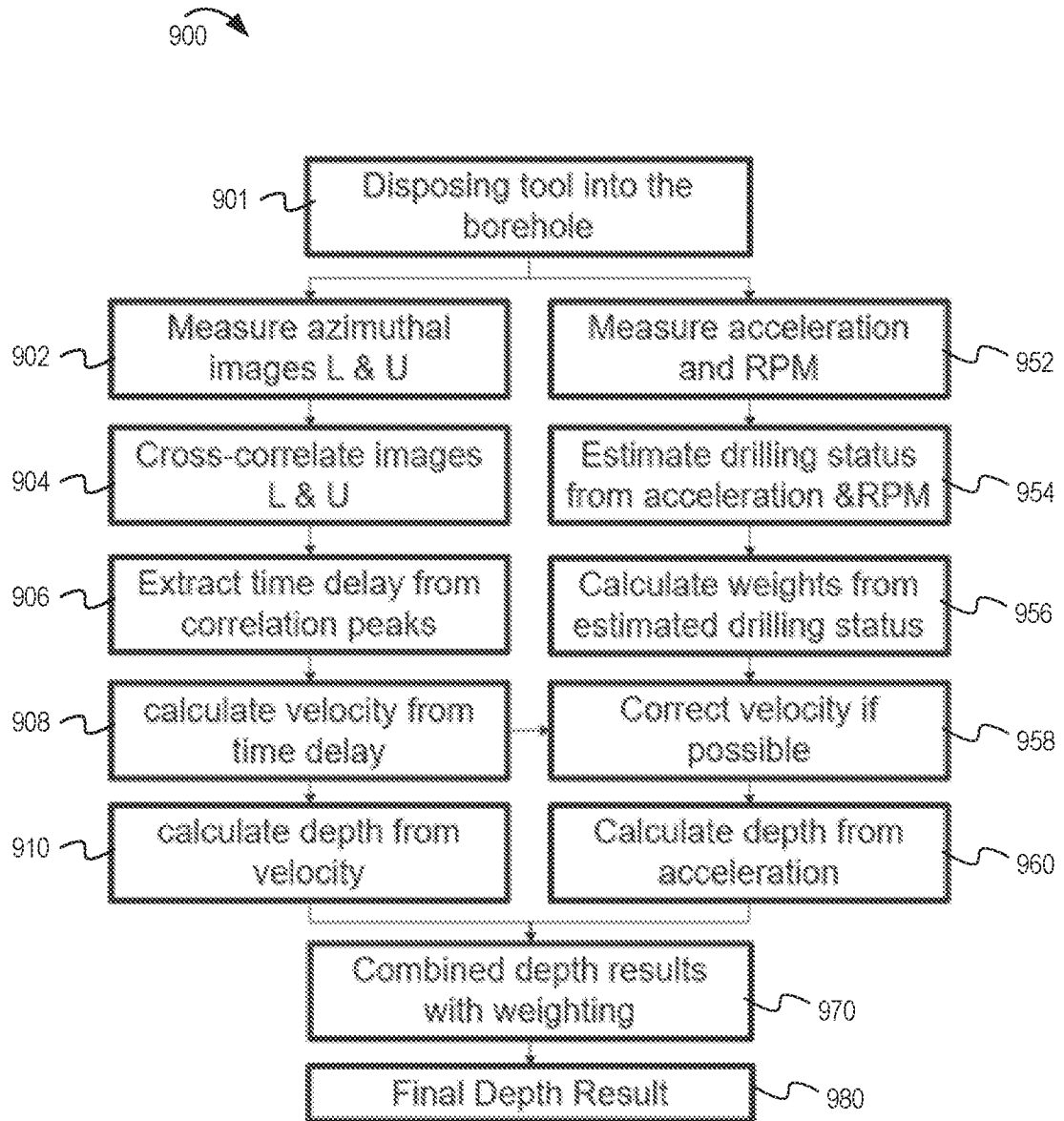


FIG. 9

10/12

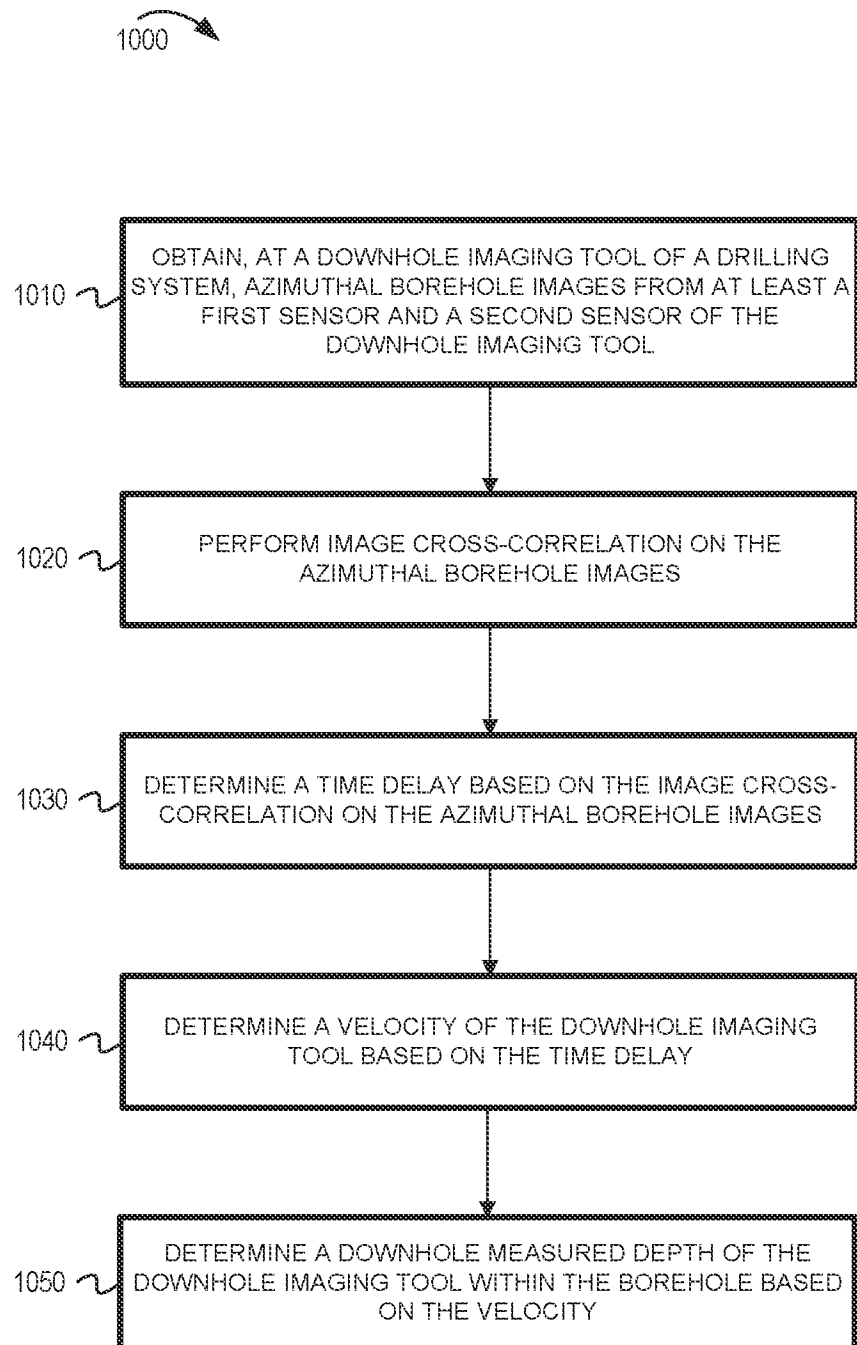


FIG. 10

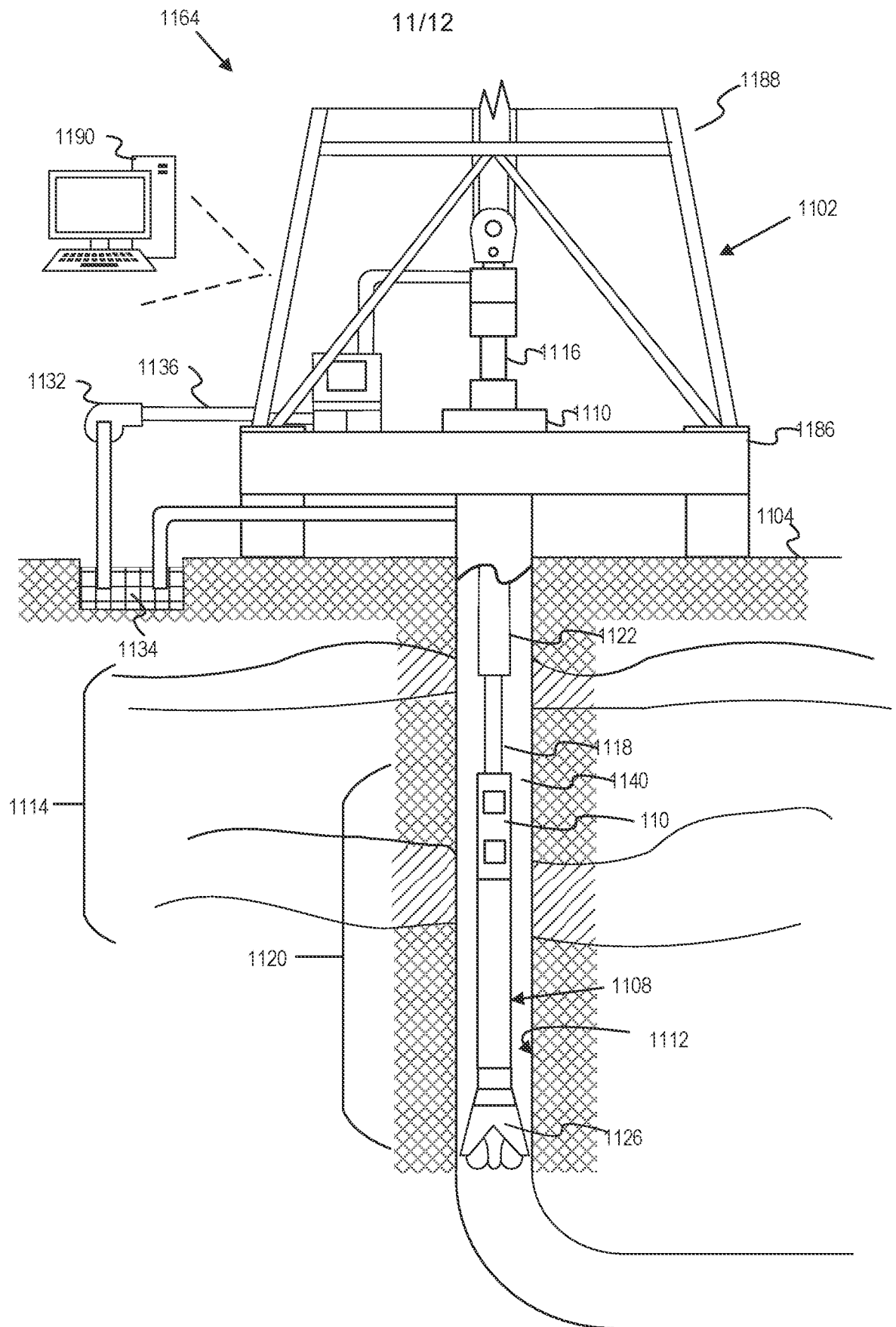


FIG. 11

12/12

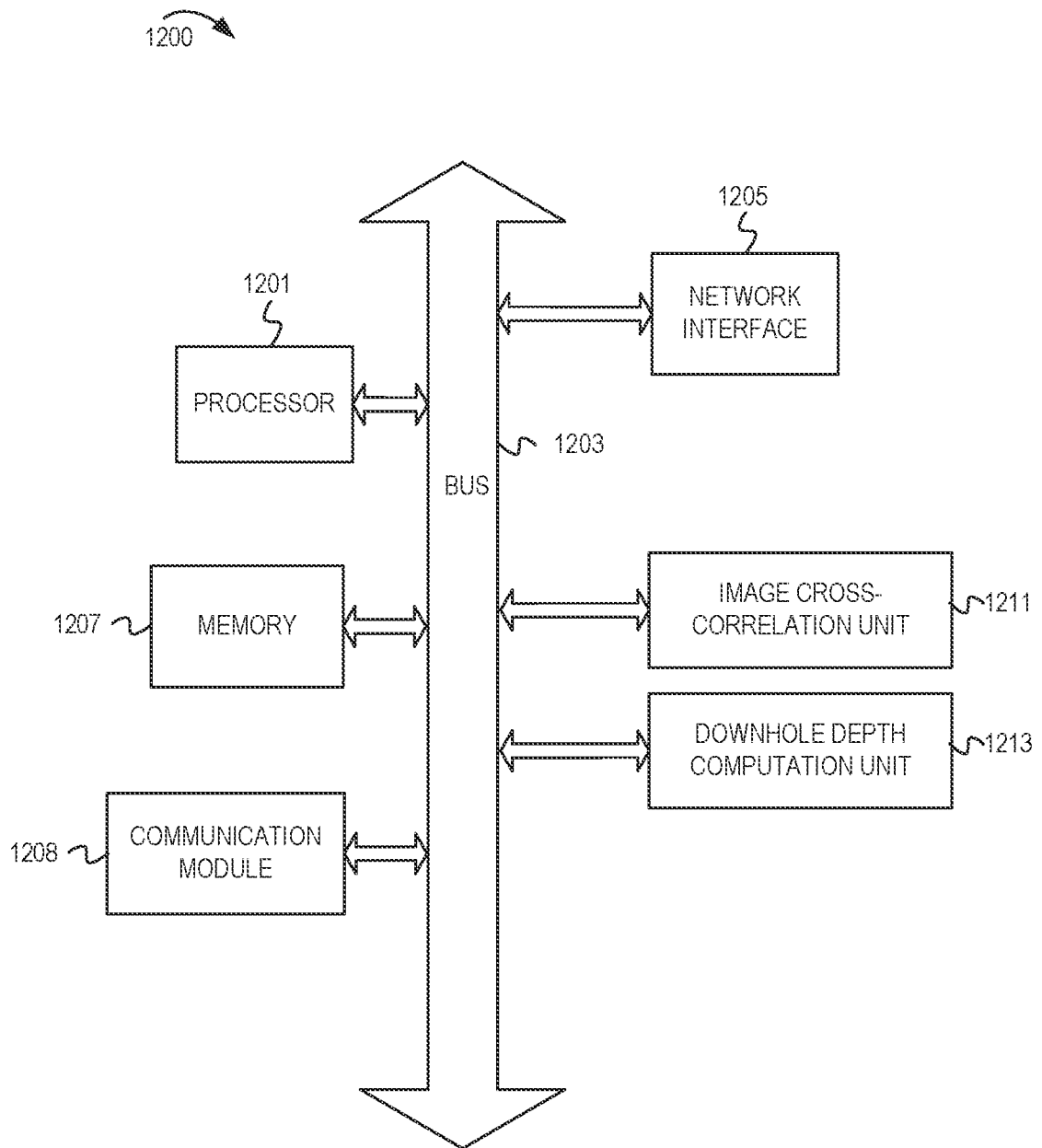


FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/010227

A. CLASSIFICATION OF SUBJECT MATTER E21B 47/002(2012.01)i; E21B 47/04(2006.01)i; E21B 47/12(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 47/002(2012.01); E21B 43/16(2006.01); E21B 47/09(2006.01); E21B 47/12(2006.01); E21B 47/16(2006.01); E21B 49/00(2006.01); E21B 7/04(2006.01); G01P 3/68(2006.01); G01V 3/00(2006.01); G01V 3/18(2006.01) 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: borehole, drilling, depth, imaging tool, azimuthal, image, time, delay, cross-correlation, velocity		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2021-0088546 A1 (E.V. OFFSHORE LIMITED) 25 March 2021 (2021-03-25) paragraphs [0027], [0061], [0069], [0144], claims 1, 3, and figures 1a-4	1,2,4,5,10-12,16,17 3,6-9,13-15,18-20
Y	US 2012-0217008 A1 (MOOS et al.) 30 August 2012 (2012-08-30) paragraphs [0022]-[0023], [0045], [0065], claim 1 and figures 3-5	1,2,4,5,10-12,16,17
Y	US 2015-0361789 A1 (HALLIBURTON ENERGY SERVICES, INC.) 17 December 2015 (2015-12-17) paragraphs [0040]-[0041] and figure 5A	16
A	WO 2023-235357 A1 (SCHLUMBERGER TECHNOLOGY CORPORATION et al.) 07 December 2023 (2023-12-07) paragraphs [0010]-[0014], claim 1, and figures 1, 2	1-20
☒ 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 “D” document cited by the applicant in the international application “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 25 September 2024		Date of mailing of the international search report 26 September 2024
Name and mailing address of the ISA/KR Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea Facsimile No. +82-42-481-8578		Authorized officer PARK, Tae Wook Telephone No. +82-42-481-3405

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/010227

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2010-083761 A1 (SCHLUMBERGER CANADA LIMITED et al.) 29 July 2010 (2010-07-29) abstract and claims 1, 4, 14	1-20

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2024/010227

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
US	2021-0088546	A1	25 March 2021	CA	3091872	A1	29 August 2019
				EP	3755880	A1	30 December 2020
				US	11649715	B2	16 May 2023
				WO	2019-162642	A1	29 August 2019
US	2012-0217008	A1	30 August 2012	CA	2695593	A1	12 February 2009
				CA	2695593	C	26 February 2013
				CA	2727542	A1	17 December 2009
				CA	2727542	C	13 August 2013
				EP	2179134	A2	28 April 2010
				EP	2179134	B1	10 January 2018
				EP	2276910	A1	26 January 2011
				GB	2473561	A	16 March 2011
				GB	2473561	B	18 July 2012
				MX	2010001327	A	17 March 2010
				MX	355385	B	17 April 2018
				NO	20101743	L	20 December 2010
				RU	2010107877	A	20 September 2011
				RU	2496003	C2	20 October 2013
				US	2008-0078242	A1	03 April 2008
				US	2008-0307875	A1	18 December 2008
				US	2009-0065252	A1	12 March 2009
				US	2009-0084176	A1	02 April 2009
				US	7548817	B2	16 June 2009
				US	7966874	B2	28 June 2011
				US	8015868	B2	13 September 2011
				US	8190369	B2	29 May 2012
				US	9238942	B2	19 January 2016
				WO	2008-040030	A2	03 April 2008
				WO	2008-040030	A3	03 April 2008
				WO	2009-021010	A2	12 February 2009
				WO	2009-021010	A3	03 June 2011
				WO	2009-117236	A1	24 September 2009
				WO	2009-152337	A2	17 December 2009
				WO	2009-152337	A3	25 February 2010
US	2015-0361789	A1	17 December 2015	EP	3033485	A1	22 June 2016
				MX	2016006441	A	19 July 2016
				US	10119394	B2	06 November 2018
				WO	2015-099765	A1	02 July 2015
WO	2023-235357	A1	07 December 2023	None			
WO	2010-083761	A1	29 July 2010	US	2010-0182313	A1	22 July 2010
				US	8228758	B2	24 July 2012