

United States Patent

[11] 3,622,971

[72]	Inventor	Jan J. Arps Dallas, Tex.
[21]	Appl. No.	837,700
[22]	Filed	June 30, 1969
[45]	Patented	Nov. 23, 1971
[73]	Assignee	Arps Corporation Dallas, Tex.

[56]

References Cited

UNITED STATES PATENTS

2,486,529	11/1949	Jackson	33/205
3,014,282	12/1961	Wist	33/205
3,252,225	5/1966	Hixson	33/205
3,253,341	5/1966	Bergan	33/205
3,431,654	5/1969	Alder	33/205

Primary Examiner—Rodney D. Bennett, Jr.

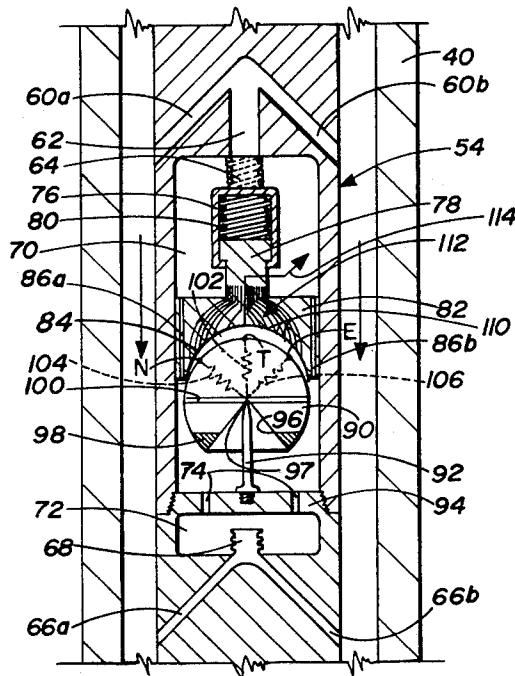
Assistant Examiner—H. A. Birmiel

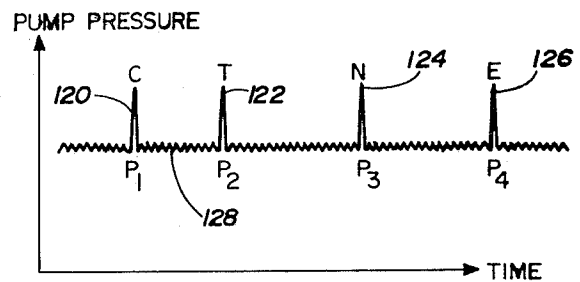
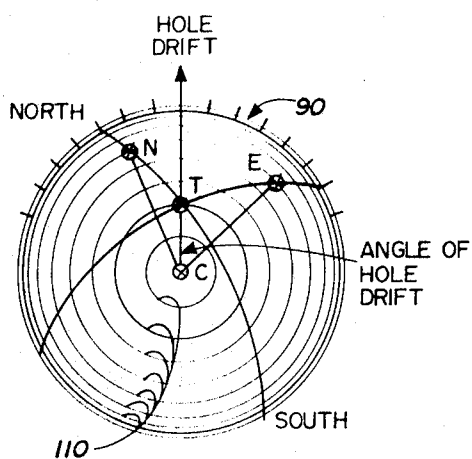
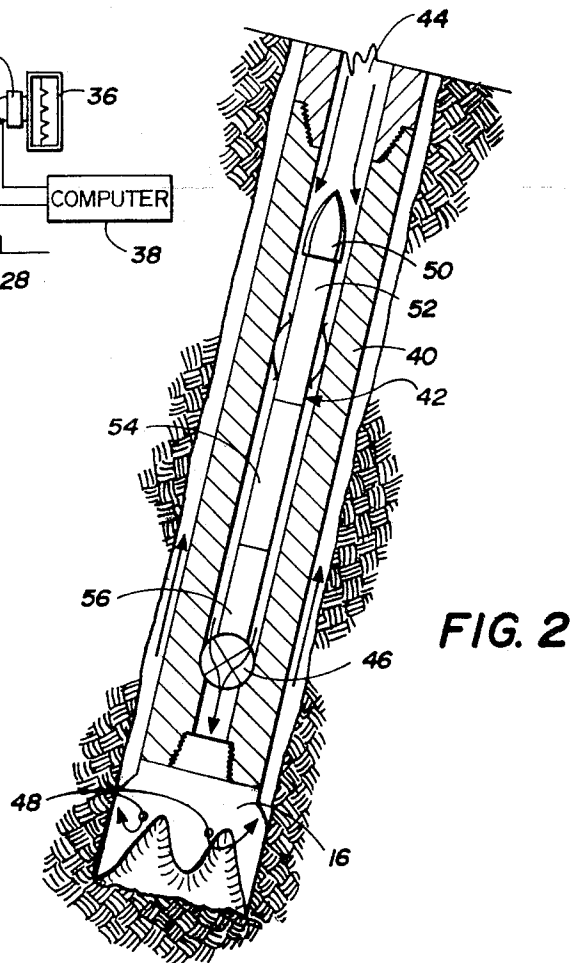
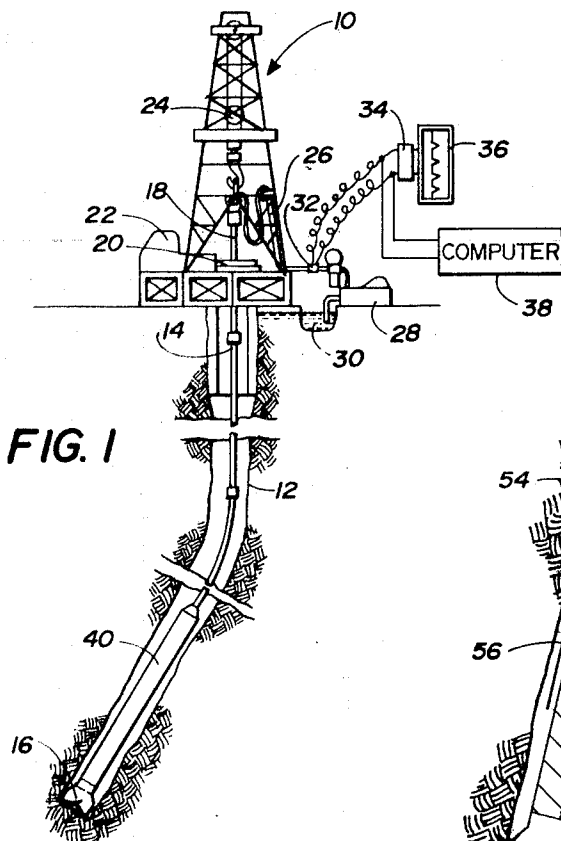
Attorney—Richards, Harris & Hubbard

**[54] METHOD AND APPARATUS FOR SURVEYING
THE DIRECTION AND INCLINATION OF A
BOREHOLE**
24 Claims, 12 Drawing Figs.

[52]	U.S. Cl.	340/18, 33/205
[51]	Int. Cl.	324/48, G01v 1/40
[50]	Field of Search	33/205; 324/48; 340/18

ABSTRACT: A magnetic reference member is maintained in a stationary position within a drill during drilling operations. The reference member is released in response to temporary cessation of the drilling operations and then seeks a predetermined reference orientation. In response to resumption of drilling operations, the reference member is again clamped in a stationary position and the relative position of the drill with respect to the reference member is detected and transmitted uphole during the drilling operations.





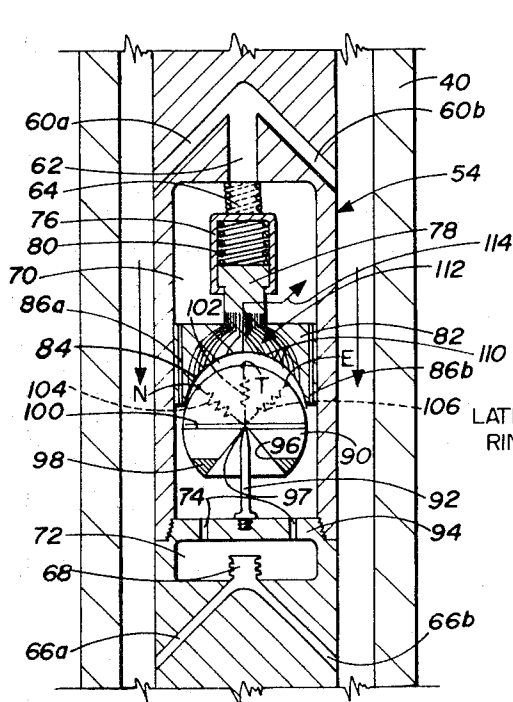


FIG. 3

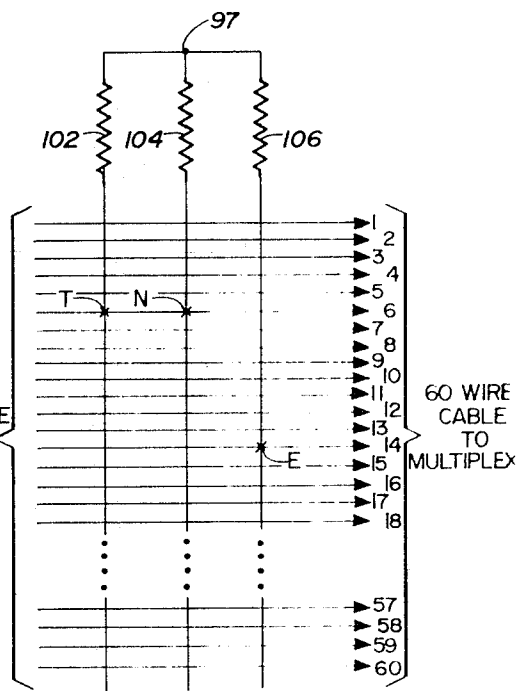


FIG. 6

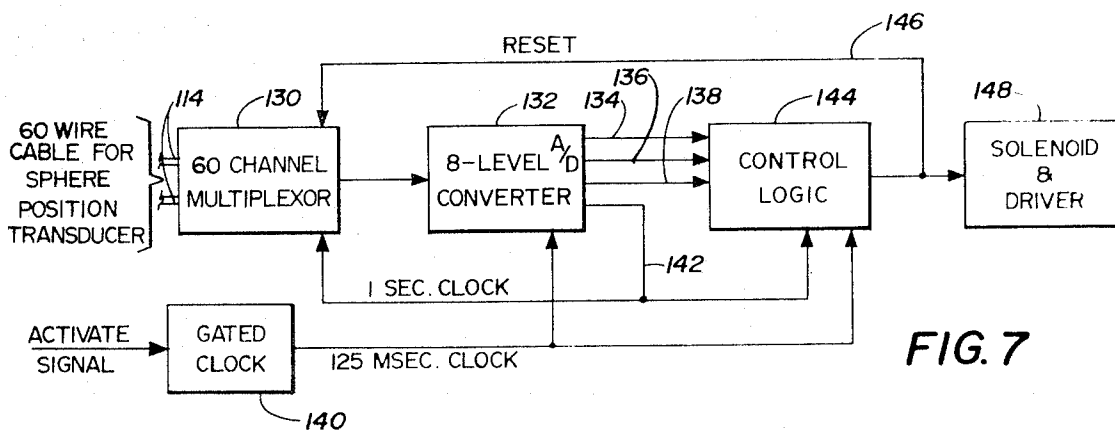


FIG. 7

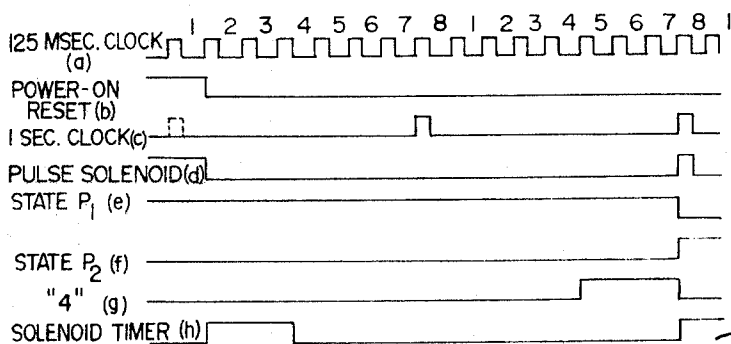


FIG. 8

INVENTOR:
JAN J. ARPS

Richards, Harris & Hubbard
ATTORNEYS

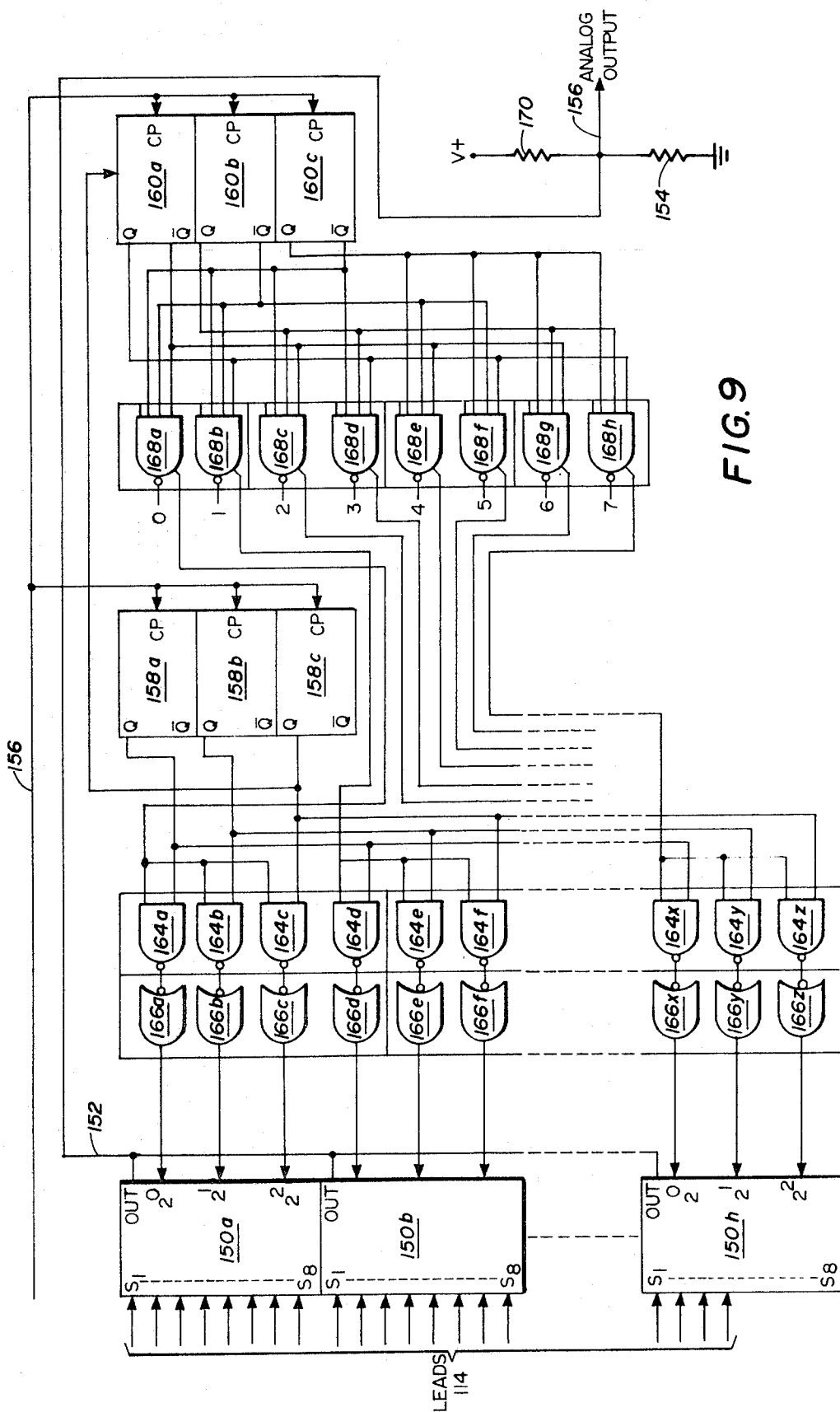
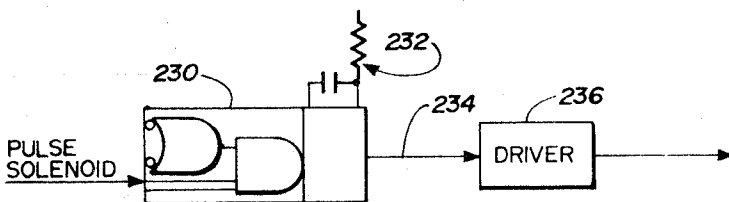
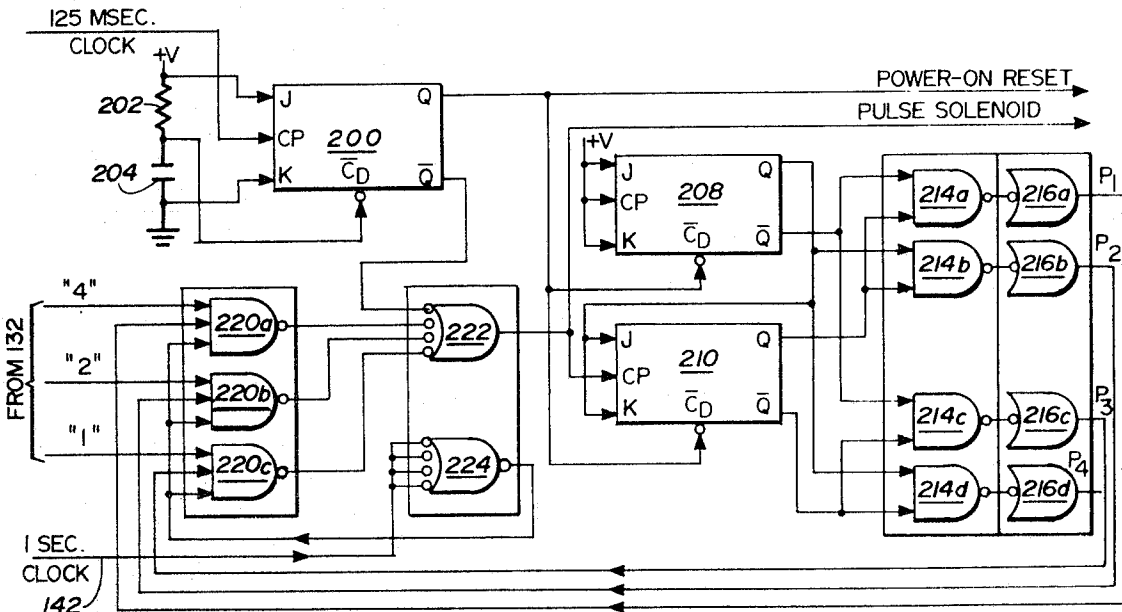
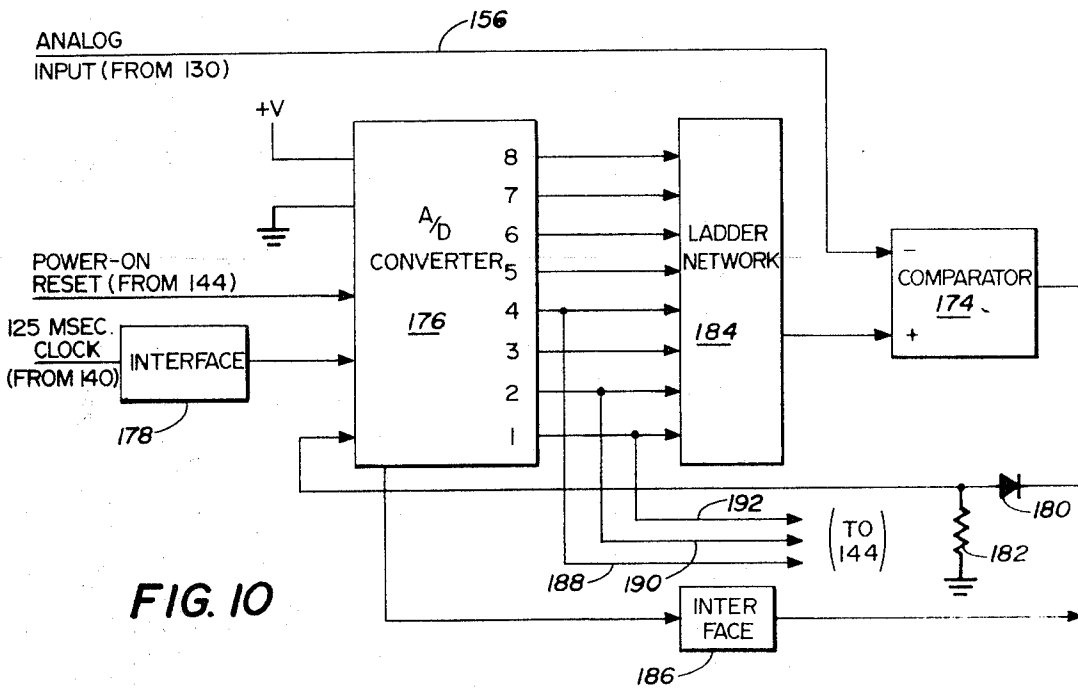


FIG. 9



INVENTOR
JAN J. ARPS

Richards, Harris & Hubbard
ATTORNEYS

METHOD AND APPARATUS FOR SURVEYING THE DIRECTION AND INCLINATION OF A BOREHOLE

FIELD OF THE INVENTION

This invention relates to the surveying of boreholes, and more particularly to the automatic intermittent surveying of the inclination and direction of a borehole during normal drilling operations.

THE PRIOR ART

It is important for a number of reasons to determine the inclination and direction of well bores while they are being drilled. For instance, during the drilling of a vertical borehole, it is desirable to measure the inclination of the borehole with respect to vertical in order to allow adjustments to be made in the drilling apparatus to prevent an excessively crooked borehole. Additionally, in deeper offshore oil well drilling areas wherein fixed platforms are extremely expensive, it is thus economical to build a central platform and to complete a number of development wells from the central platform by means of directional drilling. In such directional drilling, it is important to maintain the borehole at or near the desired direction and angle.

A number of techniques have been heretofore developed for intermittently providing indications of the inclination and direction of a borehole. For instance, the McLaughlin et al. U.S. Pat. No. 1,987,696 and the Trotter et al. U.S. Pat. No. 2,508,899, among others, disclose freely movable spherical magnetic members disposed adjacent the drill bit, with structure provided for clamping the magnetic member at a selected time so that the entire drill string may be removed from the borehole to enable detection of the relative position of the magnetic member and the drill bit. This periodic interruption of drilling operations for measurement of the angle and direction of the drift of the borehole is time consuming and economically undesirable. Other conventional surveying techniques are also objectionable in that they involve interrupting the drilling operation, running a surveying instrument on a wire or cable down the drill string, taking a reading and then retrieving the instrument. Such interruptions may require up to 35 percent of the total drilling time.

SUMMARY OF THE INVENTION

In accordance with the present invention, a reference member is maintained in a stationary position within a drill during the drilling operations. The reference member is released in response to cessation of the drilling operations and then seeks a predetermined reference orientation. The reference member is clamped in a stationary position in response to resumption of drilling operations, and then the relative position of the drill with respect to the reference member is automatically detected during drilling operations and telemetered uphole.

In accordance with a more specific aspect of the invention, a generally spherical magnetic reference member is disposed within a chamber in the region of a drill bit. Structure responsive to mudflow in the drill system is provided to clamp the reference member in a stationary position during drilling operations, and to release the reference member for free movement during cessation of drilling operations. The relative positions of the reference member and the drill bit are detected during drilling operations and indications of the relative positions are telemetered uphole by variances in mud pressure.

In accordance with another aspect of the invention, a spherical reference member is freely mounted within a drill. Structure is provided for selectively clamping the reference member and for contacting contact points disposed on the reference member. A multiplexor sequentially senses the position of the contact points. An analog-to-digital converter is responsive to the multiplexor to generate digital signals representative of the position of the contact points. A control logic circuit is operable in response to the converter for con-

trolling a mudflow valve in the drill to telemeter pressure pulses uphole.

THE DRAWINGS

For a more complete understanding of the present invention and for other objects and advantages thereof, reference is now made to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a somewhat diagrammatic illustration of a typical directional drilling system;

FIG. 2 is a partially sectioned view of the drilling system shown in FIG. 1 illustrating the present invention;

FIG. 3 is a sectional view of a portion of the invention shown in FIG. 2;

FIG. 4 is a diagrammatic illustration of the geometry of the compass sphere and latitude rings of the invention;

FIG. 5 is an illustration of pump pressure telemetry according to the invention;

FIG. 6 is a schematic diagram of the electrical connections between one position of the compass sphere and the sensing device of the invention;

FIG. 7 is a block diagram of the position-sensing circuitry of the invention;

FIG. 8a-h are sample timing waveforms for the operation of portions of the system shown in FIG. 7;

FIG. 9 is a schematic diagram of the 60-channel multiplexor of the invention;

FIG. 10 is a block diagram of the eight-level analog-to-digital converter of the invention;

FIG. 11 is a block diagram of the control logic circuitry shown in FIG. 7; and

FIG. 12 is a block diagram of the solenoid driver shown in FIG. 7.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. 1, a conventional oil derrick generally designated by numeral 10 is disposed over a borehole 12. A drill string 14 extends through the borehole 12 and terminates at a conventional drill bit 16 at the bottom of the borehole. The upper end of the drill pipe is attached to and supported by a kelly 18 which is rotated by a rotary table 20 operated by draw works 22 in the conventional manner. The traveling block 24 supports a conventional swivel and hook attached to the drill string 14. A drilling fluid conduit 26 receives drilling fluid from a pump 28 which discharges drilling fluid from a supply sump 30 into the drill string 14 in the conventional manner.

A pressure change detecting device 32 is connected in the drilling fluid conduit 26 for generation of electrical signals representative of pressure changes in the drilling fluid supply. These electrical signals are fed through an amplifier 34 to a conventional recorder 36. Additionally, the signals are fed to a computer system 38. The apparatus thus described, and particularly the detecting device 32, amplifier 34 and recorder 36, may be of the type described in U.S. Pat. No. 2,930,137 issued on Mar. 29, 1962, to J. J. Arps, or any other conventional type of system.

A nonmagnetic drill collar structure 40 is connected above the drill bit 16 to detect the direction of inclination of the drill string 14 according to the invention. The drill collar 40 is constructed from nonmagnetic material, such as K-Monel, to allow the use of magnetic members within the collar.

FIG. 2 is a partially sectioned view of the drill bit 16 and the drill collar 40 and illustrates a surveying instrument 42 centrally located within an annular mudflow opening 44 through the drill string 14. The mudflow through the aperture 44 thus flows downwardly through the annular space between the instrument 42 and the drill collar 40. The mud then flows through a pulsation valve 46 and passes outwardly from the drill bit 16 through bit nozzles 48 in the conventional manner. The mudflow then travels upwardly through the annular space between the drill collar 40 and the borehole wall. The pulsa-

tion valve 46 is adapted when closed to throttle or restrict the downward flow of the drilling mud through the drill string and thus create a pressure change signal in the mud which is sensed by the device 32. This pulsation valve may be of any conventional type, or of the type disclosed in the previously identified U.S. Pat. No. 2,930,137.

The surveying instrument 42 of the invention includes a spinner cap 50, preferably constructed from a suitable material such as hard rubber, and equipped with spiral vanes which cause the cap to rotate due to the downward mudflow. The rotating shaft, not shown, of the mud-driven spinner cap 50 is connected through a stuffing box to a constant voltage electric generator 52 which provides electrical power for the instrument 42. Alternatively, a battery may be utilized for a voltage supply. The inclination-surveying apparatus of the invention is contained within an intermediate section 54. The lowermost section 56 of the assembly contains electronic instrumentation and switching mechanisms which periodically actuate the valve 46 in a manner to be subsequently described in greater detail.

FIG. 3 illustrates in detail a cross section of the intermediate section 54. Upstream mud pressure inlet channels 60a-b provide communication between the annular mudflow opening 44 and an aperture 62 which opens into a spring-loaded bellows 64. Differences in fluid pressure within the inlet channels 60a-b cause bellows 64 to constrict or expand vertically. Downstream mud pressure inlet channels 66a-b communicate directly with a second bellows 68 which also expands or constricts vertically in accordance with the fluid pressure within the inlets 66a-b. A chamber 70 is formed between bellows 64 and 68, with a smaller secondary chamber 72 communicating with chamber 70 by apertures 74. Chambers 70 and 72 are filled with a suitable high-viscosity oil or glycerin which provides damping action to the position-sensing mechanism within the chamber 70.

Bellows 64 is connected at its lower end to a gripping device 76 which slidably receives the enlarged end of a shaft member 78. A spring 80 is disposed within the gripping device 76 and provides a constant downward bias on the enlarged end of the shaft 78. Spring 80 is provided to prevent the pressure within the chamber 70 from becoming excessive and thereby possibly damaging the sensing structure therein. The shaft 78 is integrally connected to a constraining member 82 which includes a semispherical concave surface 84 in the lower end thereof. Apertures 86a-b enable the damping liquid to circulate freely through the constraining member 82. The constraining member 82 is dimensioned to move freely axially within the chamber 70, but also such that the member 82 is maintained in an aligned position with respect to the axis of the drill collar and the borehole.

A compass sphere 90 is pivotally mounted on a pivot member 92 which is rigidly connected to the flange 94 which divides chamber 70 and chamber 72. The compass sphere 90 is constructed from relatively light, nonmagnetic material and includes a cone-shaped opening 96 cut into the bottom portion thereof, so that the pivot member 92 may be connected to the center of the compass sphere 90. A low-friction bearing 97 is provided between the pivot member 92 and the compass sphere 90, the bearing 97 also serving as an electric contact between the sphere 90 and the pivot member 92. An annular ballasting or weighted portion 98 is provided on the compass sphere to bring the center of gravity of the compass sphere below the low-friction bearing 97. A bar magnet 100 is disposed within the compass sphere 90 and thus tends to maintain the compass sphere 90 in a horizontal position and oriented toward magnetic north. The cone-shaped opening 96 allows a substantial amount of freedom of movement of the sphere 90.

The compass sphere 90 is further provided with three spaced-apart electrical contact points T, N and E on its outer periphery. Contact points T, N and E preferably comprise small circles of electrically conducting material such as copper or the like. Contact point T is disposed at the exact top

center of the compass sphere 90, contact point N is removed 30° from the contact point T in the direction towards the north pole of the magnet 100, and contact point E is removed 30° in an easterly direction from the top of the sphere. Contact points T, N and E are electrically connected through resistors 102, 104 and 106. The terminals of each of the resistances 102, 104 and 106 are commonly tied to the electrically conductive bearing 97. A predetermined voltage is applied to the pivot member 92 to provide voltage to each of the resistors 102, 104 and 106.

The magnitudes of each of the resistors 102-106 are different, and in the preferred embodiment, resistance 102 is 50,000 ohms, resistance 104 is 100,000 ohms and resistance 106 is 200,000 ohms. It will, of course, be understood that various other magnitudes may be utilized for the resistors to provide various required operating characteristics for the system. The relative magnitudes of the resistors enables the electronic circuitry in unit 52 to detect the relative position of the compass sphere 90.

The concave surface 84 of the constraining member 82 is provided with a plurality of concentric metallic latitude rings 110. As will be later described, in the preferred embodiment 60 rings are concentrically disposed on member 82. Each of the rings 110 are individually connected to one of a plurality of electric wires 112, each of the wires 112 being brought together in a bundle 114 which is connected to the scanning circuitry in the electronic unit 52. Each metallic part in the assembly shown in FIG. 3 is made from a nonmagnetic material, except the magnet 100 which comprises a strong permanently magnetized material.

In operation of the device shown in FIGS. 1-3, when mud is flowing through the annular opening 44 during normal drilling, a higher pressure is provided opposite the upstream inlet channels 60a-b than adjacent the downhole inlet channels 66a-b. The pressure differential thus causes the top bellows 64 to be downwardly extended and the bottom bellows 68 to be downwardly constricted. The downward movement of the top bellows 64 moves the constraining member 82 downwardly to clamp the compass sphere 90 firmly against the bearing 97.

When the constraining member 82 clamps the compass sphere 90 in a stationary position, the three electrical contact points T, N and E on sphere 90 make electrical contact with certain of the concentric latitude rings 110 on the member 82. The electrical scanning circuitry in unit 52 senses the position of the compass sphere 90 by determining which of the concentric rings 110 contacts the electrical contacts of the sphere 90. The electronic unit 52 then modulates the pressure pulsation valve 46. The modulation, or temporary partial closure, of the valve 46 causes momentary pressure spikes in the mud stream which may be detected at the surface to denote the angle and the direction of slope of the drill string in a manner to be subsequently described.

Whenever a new joint of drill pipe is to be added to the drill string, the driller stops the rotary table and lifts the drill string until the string can be secured by "slips" in the rotary table. The driller then stops the mud pumps and the mud circulation, unscrews the "kelly" from the top part of the drill string and moves the kelly aside. A new joint of drill string is then picked up and screwed on. The drill string is then lowered by means of "elevators," the kelly picked up, remounted and screwed on and circulation of the mud and rotation of the drill string is resumed.

While the new joint of drill pipe is being added, the absence of mudflow through the annular opening 44 causes the above-described pressure differential between the inlet channels 60a-b and 66a-b to disappear. The spring-loaded bellows 64 is then moved upwardly and the gripping device 76 moves the shaft 78 and the constraining member 82 upwardly to release the clamping action on the compass sphere 90.

When the compass sphere 90 is released from constraint by the constraining member 82, the drill pipe is in a stationary condition. The compass sphere 90 will thus seek a position

whereby the compass bar 100 is in a horizontal position and is pointed to the magnetic north, such that the contact point T on the compass sphere 90 is in a vertical position. The liquid within the chamber 70 is such that it retains a suitable high viscosity even under the relatively high temperatures of a borehole environment, and thus quick damping is provided to the oscillatory motions of the compass sphere 90 in seeking its stabilized position.

As long as there is no mud circulation, the compass sphere 90 remains in its unrestrained condition. After the new joint of drill pipe has been added, and while the kelly is remounted and screwed on, the compass sphere 90 will seek its final position which effectively measures the angle and direction of the drift of the borehole. The compass seeks its final position in less time than is required to mount the kelly assembly and screw the assembly into the last joint of drill pipe added. When mud circulation is again resumed, the pressure differential exerted between the inlet chambers 60a-b and 66a-b causes the constraining member 82 to again clamp the compass sphere 90 to preserve an accurate reading of the angle and direction of the borehole drift.

Resumption of the mudflow also reactivates the entire electronic unit 52 by rotating the spinner cap 50 to provide electric power for the instrumentation and telemetry operation of the device. The intelligence contained in the position of the compass sphere 90 is then detected by the concentric latitude rings 110, and the resulting information is translated into a series of electrical pulses which activate pressure pulsation valve 46 in a time sequence representative of the position of sphere 90.

FIG. 4 is a somewhat diagrammatic view of the top portion of the compass sphere 90 within a slanted borehole taken along the axis of the borehole, along with indications of the positions of the concentric latitude rings 110 upon sphere 90 when member 82 restrains the sphere 90. The point C thus represents the center of the concave surface 84 of the member 82, while the points T, N and E represent the electrical contact points on the sphere 90. The angular distance between point C and the contact point T represents the angle of the drift of the borehole. Also, the angular distance between C and N represents a point in the magnetic meridian 30° northward from the vertical, while the distance between point C and point E represents a point 30° eastward from the vertical.

In FIG. 4, the latitude rings 110 disposed over the sphere 90 are shown at intervals of approximately 10°, but it will be understood that in actual practice the contact rings will have a much closer spacing of about 1°. In a preferred embodiment, 60 latitude rings are utilized. The diameters of the electrical contact points T, N and E are generally equal to the width between the latitude rings 110 so that the same contact point can never contact more than one latitude ring.

FIG. 6 schematically illustrates the connection of the terminals of resistor 102, 104 and 106 within the sphere 90 to a supply of positive voltage fed through the pivot member 92 to bearing 97. The other terminal of resistor 102 is connected to point T, which in the example illustrated is shown as contacting the sixth latitude ring from the center of the member 82. The other terminal of resistor 104 is connected to point N, which in the example shown is also clamped on the sixth latitude ring. The terminal of resistor 106 is connected to point E, and in the present example is shown clamped upon the 14th latitude ring from the center of member 82.

The particular latitude rings 110 which are in contact with points T, N and E are sensed by the electrical scanning circuitry of the invention, in a manner to be subsequently described, which generates signals representative of the relative position of the compass sphere 90. In the preferred method, the scanning device initiates operation with the center point C which represents zero angle of drift. In a step-wise manner, the scanning device periodically scans successive latitude rings 110 until a short circuit is detected between ground, the appropriate latitude ring 110, one of the contact

points T, N or E, one of the resistances 102-106 and the bearing 97. Whenever such a short circuit is detected, the system measures the total resistivity of the circuit to distinguish between the three contact points T, N and E. The difference in resistivity is caused by the difference in magnitude of the resistors 102, 104 and 106. The information obtained from the magnitude of the resistances controls the sequence in which the information is telemetered to the surface. The signals generated by the scanning device operate the valve 46 in order to cause pressure pulses through the drilling mud which are sensed uphole.

The preferred technique for telemetering information uphole is illustrated in FIG. 5. A telemetering cycle is initiated by the generation of a pressure pulse 120 which is received uphole and recorded on the recording chart as shown in FIG. 5. The downhole device then scans successively at 1-second intervals, and in 1° steps, the latitude rings 110 of the device until the scanning device senses a short circuit with a total resistivity approximating the resistor 102. When this resistivity is sensed, the particular latitude ring in contact with point T has been sensed and the pressure pulsation valve 46 is actuated to send the pressure pulse 122 uphole for recording on the recorder chart.

The scanning device then instantaneously returns to its zero position and is reset to detect a total resistance in a short circuit equal generally to resistance 104. Once the latitude ring is sensed which is in contact with contact point N, a pressure spike 124 is generated and is recorded uphole on the recorder chart. The sensing device then again returns to its starting position at zero latitude and initiates scanning for a short circuit having a resistivity approximating the value of the resistor 106 to determine the position of the contact point E. Upon the determining of the particular latitude ring 110 contacting point E, the pressure pulse 126 is generated and received uphole. The normal fluctuations of valve 46 are illustrated by the pulses 128.

After reception of a full cycle of pressure pulses in the manner shown in FIG. 5, it may often be desirable to initiate several repeated scanning cycles so that good average measurements may be obtained.

The pressure spikes in a scanning cycle always arrive at the surface in a sequence representing the latitudes of points T, N and E. Since the angular distances between points T, N and E are known to be 30° each, and since the three time intervals determined by the pressure spikes represent the latitudes measured for points T, N and E, the problem of determining the angle of the drift and the direction of the drift of the borehole is now fully defined.

It will of course be understood that FIG. 6 illustrates schematically only one possible particular position of the compass sphere 90, and that other angles of inclination and directions of deviation will cause the contact points T, N and E to contact different latitude rings.

As an example of the operation of the present device, assume that the time interval between pressure spikes 120 and 122 in FIG. 5 is 19 seconds, the time interval between spikes 122 and 124 is 47 seconds and the time interval between pressure spikes 124 and 126 is 42 seconds. Since the spacing between the latitude rings 110 is 1°, and one latitude ring is sensed each second by the scanning device, the angle of the hole drift is the angular distance between point C and contact point T and is thus 19°.

Also, the angular distance between points C and N are equal to 47°, while the angular distance between points N and T is equal to 30°. Considering the triangle CNT, it may be shown by utilization of conventional spherical trigonometric functions as defined on page 347 of C.R.C. Standard Mathematical Tables, 1954 ed., that:

$$s = \frac{\angle CT + \angle CN + \angle NT}{2} = \frac{19 + 47 + 30}{2} = 48^\circ \quad (1)$$

wherein s = the semiperimeter of the triangle CNT, and CT, CN and NT represent the latitude readings;

$$r = \pm \sqrt{\frac{\sin(48-19) \sin(48-47) \sin(48-30)}{\sin 48}} = \pm 0.0595 \quad (2)$$

wherein r = distance in spherical coordinates

$$\tan \frac{NTC}{2} = \tan \frac{180-x}{2} = \frac{\pm 0.0595}{\sin(48-47)} = \pm 3.4097 \quad (3)$$

wherein x = direction of hole drift

$$x = 32.7^\circ \text{ or } 327.3^\circ \quad (4)$$

Therefore, the direction of hole drift equals 32.7° or 327.3° .

It will be seen that the above measurement results in two possible solutions for the direction of hole drift. In order to resolve this ambiguity, the triangle CTE is considered utilizing the spherical trigonometric functions defined above:

$$s = \frac{\angle CT + \angle CE + \angle TE}{2} = 45.5^\circ \quad (5)$$

$$r = \pm \sqrt{\frac{\sin(45.5-19) \sin(45.5-42) \sin(45.5-30)}{\sin 45.5}} = \pm 0.102 \quad (6)$$

$$\tan \frac{CTE}{2} = \tan \frac{90+x}{2} = \frac{\pm 0.102}{\sin(45.5-42)} = \pm 1.6708 \quad (7)$$

$$x = 28.2^\circ \text{ or } 151.8^\circ$$

Therefore, the direction of hole drift is 28.2° or 151.8° .

It is thus seen that the solutions of 327.3° and 151.8° are erroneous, and that the average of the remaining two readings which are of the same magnitude, or 30.45° is a representative value for the direction of the hole drift. The measurement of the drift of the borehole in this example is, therefore, 19° N 30.45° E. For more accurate readings, a plurality of scanning cycles are performed and the results averaged.

The foregoing calculation may be done automatically with a properly programmed conventional digital computer, or with a particular special purpose digital computer. Alternatively, the foregoing computations may be done by conventional analog computers or by hand.

The electronic scanning and measuring circuitry disposed in section 56 of the present device will now be described in detail. FIG. 7 is a block diagram of the basic circuitry. The 60-wire cable 114 which contains the wires leading from the 60 latitude rings in the constraining member 82 are fed to the input of a 60-channel multiplexor 130. Multiplexor 130 is sequentially stepped through each of the 60 wires to sequentially interrogate each of the 60 latitude rings 110. This stepped interrogating action is under the control of an internal counter which is timed by a 1-second clock pulse fed from an analog-to-digital converter 132.

The common terminal of the multiplexor 130 is fed to the input of the eight-level analog-to-digital converter 132. The output of the converter 132 senses the voltage level provided by the multiplexor 130 and generates digital output pulses on leads 134-138 which are representative of gated voltage levels. As will later be described, the converter 132 is operated by a 125-msec. clock output from a gated clock 140 in order to step through eight trials beginning with the most significant bit. Each bit value generates a voltage proportional to its weight which is compared with the input analog voltage from the multiplexor 130. The converter generates pulses on lead 142 which becomes a 1-second clock pulse for control of the remainder of the circuitry.

The output of the analog-to-digital converter 132 is fed to the input of the control logic 144. The control logic 144 sequentially monitors the output leads 134-138, only moving on to monitor the next lead when an output pulse is received.

After receiving an output on the lead being monitored, the control logic circuit 144 emits an output pulse and moves on to monitor the next output lead. The pulse emitted by the control logic circuit 144 serves to reset the multiplexor 130 via lead 146 and also to fire the solenoid driver 148. The firing of solenoid driver 148 controls the operation of the pressure pulsation valve 46 in order to telemeter pressure pulses uphole in the manner previously described. The resulting output of pressure spikes caused by operation of the valve 46 comprises three solenoid actuations spaced apart in time, commonly termed asynchronous pulse position modulation (PPM), the time spacings being proportional to the particular latitude rings 110 being contacted by the points T, N and E on the compass sphere 90.

FIGS. 8a-h are sample timing diagrams for portions of the operation of the circuitry shown in FIG. 7. FIG. 8a illustrates the output from the gated clock 40, broken down in eight-cycle intervals. FIG. 8b is the power-on reset which initiates a scanning cycle. The remainder of the waveforms 8c-h will be explained in the description of FIGS. 9-12.

Referring to FIG. 9, the 60-wire cable 114 from the latitude rings 110 of the member 82 are fed into multiplex switches 150a-h, five of which are not shown for simplicity of illustration. In a preferred embodiment, switches 150a-h are eight-channel multiplex switches with output enable control and one-out-of-eight decoder circuitry. A suitable switch for each of the circuits 150a-h is the MOS monolithic eight-channel multiplex switch manufactured and sold as the 3705 Integrated Circuit Package by Fairchild Semiconductor of Mountain View, Calif.

The output from the switches 150a-h is fed via lead 152 and appears across the resistor 154 to the input of the analog-digital converter 132. The logic input to the switches 150a-h is controlled by the 1-second clock output of the converter 132. This clock output is fed via lead 156 to the CP terminal of a three-bit binary counter comprising three J-K flip-flop circuits 158a-158c. The clock output is also fed via lead 156 to a second three-bit binary counter comprising three J-K flip-flop circuits 160a-c. Although not shown for simplicity of illustration, the $\bar{C}_D$ inputs of each of the flip-flop circuits 158a-b and 160a-c are connected to receive the pulse solenoid signal from the control logic circuitry 144 to cause each of the flip-flop circuits to be DC preset.

The flip-flop circuits 158a-c and 160a-c are wired as a binary counter by connecting the $\bar{Q}$ output of each of the circuits to the JK input of the adjacent flip-flop circuit, in addition to wiring the top JK input of each circuit to a "true" level, these interconnections not shown for simplicity of illustration. Additionally, the power voltages applied to the circuitry are not shown for ease of illustration. Suitable circuits for use with the invention for the flip-flop circuit 158a-c and 160a-c are the TT μ L 9000 J-K flip-flop circuits manufactured and sold by Fairchild Semiconductor of Mountain View, Calif. The counter 158a-c keeps track of which of the eight-channel switching circuits 150a-h is presently being addressed, while the second counter 160a-c defines which channel within a particular switching circuit 150a-h is to be turned on.

The Q output of each of the flip-flop circuits 158a-c are connected to an input of the respective AND-gate 164a-z, the output of which is respectively connected through inverter circuits to an OR-gate 166a-z. The output of each of the OR-gate 166a-z are fed to the logic input of the switching circuits 150a-h. A number of the gates 164a-z and 166a-z have been omitted for clarity of illustration. Suitable circuits for gates 164a-z and 166a-z are the TT μ L 9002 circuits sold by Fairchild Semiconductor.

The Q and $\bar{Q}$ outputs of the flip-flop circuits 160a-c are connected according to logic code to inputs of a plurality of gates 168a-h. Gates 160a-h comprise NOR-expansion elements, with an emitter element of each of the elements being connected to an input of one of the AND-gates 16a-z. In the preferred embodiment, the NOR-expander elements 168a-h comprise a TT μ L 9006 element manufactured and sold by Fairchild Semiconductor of Mountain View, Calif.

The resulting output from the multiplexor circuit shown in FIG. 9 is fed via the lead 15 across the resistor 154 to the input of the analog-to-digital converter 132. A bias resistor 170 is connected to a source of DC voltage at the output level. While a particular embodiment of the multiplexor has been described in detail, it will be understood that any suitable conventional analog multiplexor capable of handling the analog large input from the present device may be alternatively utilized.

FIG. 10 illustrates the eight-level analog-to-digital converter 132 wherein the analog input from multiplexor 130 is fed via lead 156 to the negative input of high-speed differential comparator circuit 174. The power-on reset signal from the control logic 144 is fed to the preset input of an analog-digital converter 176. The 125-microsecond clock from clock 140 is fed via an interface 178 to the clock input of the converter 176. The output from the comparator 174 is fed through a diode 180 to the comparator return input of the converter 176. The anode of the diode 180 is connected through a resistor 182 to ground. The first reference input of the converter 176 is connected to ground, while the second reference input is connected to the positive bias voltage.

The analog-digital converter 176 utilizes the voltage-summing successive-approximation encoder technique described in detail in the publication *The Electronic Engineer*, Feb. 1969, page 71. This technique, according to the present invention, provides eight possible output levels each spaced one thirty-second of a volt (31.25 microvolt) apart. The 125-microsecond clock steps the converter 176 through each of the eight levels beginning with the most significant bit, or bit eight. Each of the bit values generates a voltage proportional to its weight by gating a preselected voltage into the resistor ladder network 184. The output from network 184 is fed to the positive input comparator 174. If this voltage is larger than the input and log voltage appearing on lead 156, the comparator 174 determines this fact and eliminates the weight being tested. The converter 176 is then stepped to the next smaller weight until the level of the input and log voltage is determined.

After the last of the eight trials, an output pulse is generated from the converter 176 which is fed to an interface circuit 186 and is fed to other parts of the system as a 1-second clock (see FIG 8c). The bias applied to the reference 2 input of the converter 176 adds a 1/64 volt to ensure that the data at 1/32-volt intervals falls between the 1/32-volt levels of the converter 176. The outputs appearing on bits 4, 2 and 1 are applied via leads 188, 190 and 192 to the input of the control logic circuit 144.

The comparator 174 may comprise any suitable high-speed differential comparator circuit, but in the preferred embodiment comprises a comparator circuit sold under the title *Liner Integrated Circuits* μ 710 by Fairchild Semiconductor of Mountain View, Calif. The ladder network 184 may comprise a conventional 12.5 k Ω ohm ladder network manufactured and sold by the Negadyne Corporation of Rochester, N.Y. or by Angstrom Precision Inc. of Van Nuys, Calif. The converter 176 may for instance comprise the 3751 Integrated Circuit converter manufactured and sold by Fairchild Semiconductor of Mountain View, Calif. The interface elements 178 and 186 are utilized to interface between the integrated circuitry and the MOS FET circuitry and may for instance comprise the 9924 and 9925 Integrated Circuit Interface elements manufactured and sold by Fairchild Semiconductors of Mountain View, Calif.

The eight-level sensing provided by the converter 132 is necessitated by the possibility of multiple contacts by the contact points T, N and E with a single latitude ring on the member 82. The contact possibilities of the device of the invention are summarized by the following truth table, wherein a "1" indicates a "contact" with a latitude ring and an "0" indicates "no contact":

Combination	102(20 μ hos)	104(10 μ hos)	106(5 μ hos)
0 μ hos	0	0	0
5 μ hos	0	0	1
10 μ hos	0	1	0
15 μ hos	0	1	1
20 μ hos	1	0	
25 μ hos	1	0	1
30 μ hos	1	1	0
35 μ hos	1	1	1

The converter 132 thus is able to sense multiple contacts of the latitude ring of the invention and still determine which of the contact points are presently being sensed. As an example, refer to FIG. 6 wherein contact points T and N both contact the sixth latitude ring. In this case, resistors 102 and 104 are in parallel and will be gated when the converter 132 is in its sixth position. Assuming that resistor 102 equals 50K and resistor 104 equals 100K, the parallel combination of the resistances is 30 μ hos. the bias resistor 170 of the multiplexor 130 adds another 2.5 μ hos.

The particular values of the resistances 102-106 and 170 may of course be varied for different applications, but in this case have been chosen to make the series resistance of the contacts and the multiplexor 130 negligible. With most of the voltage applied across resistor 170 dropped across the contact and bias resistors, the resistors act like a 32.5-microamp current source into the sensing resistor 154 of the multiplexor 130. As a result, 13.64 volts, or 208.65 microvolts appears across resistor 154. Of this, one-eighth volt is due to resistor 102, one-sixteenth volt is due to resistor 104 and one sixty-fourth volt is due to the bias voltage. The converter 132 senses this voltage to provide an indication according to the truth table that contact points T and N are in contact with the same sixth-latitude ring.

The control logic circuit 144 comprises a J-K flip-flop circuit which receives as an input the 125-microsecond clock from the gated clock 140. Bias voltage is applied to the J-K inputs of the flip-flop 200 through a resistor 202 and a capacitor 204. The resistor 202 and capacitor 204 act as an R-C timing network on the DC reset line of the flip-flop circuit 200. Once the capacitor 204 charges to above 1.7 voltage, the flip-flop 200 will be switched synchronously by the next 125-microsecond clock pulse. This conditioning operation should take about 25 microseconds. The $\bar{Q}$ output of the flip-flop circuit 202 acts as the power-on reset (FIG. 8b) which is fed to the remainder of the circuitry as previously described. The $\bar{Q}$ output of flip-flop circuit 200 is also fed to the $\bar{C}_D$ of the flip-flop circuits 208 and 210 which constitute a fully decoded binary counter. The $\bar{Q}$ output of each of the counters is connected to the J-K input of the adjacent flip-flop circuit, with the top J-K input wired to a "true" level. In the preferred embodiment, the flip-flop circuits 200, 208 and 210 comprise the TT μ L Integrated Circuits 9000 manufactured and sold by Fairchild Semiconductor of Mountain View, Calif.

The Q and $\bar{Q}$ outputs of flip-flop circuits 208 and 210 are fed to logic circuits comprising AND-gates 214a-d and OR-gates 216a-d. In practice, the gates 214a-d and 216a-d may comprise the logic circuit manufactured and sold as TT μ L 9002 Integrated Circuits by Fairchild Semiconductors of Mountain View, Calif. The outputs from the gates 216a-d are designated P₁-P₄ (see FIG. 8e-f) and correspond to the pressure spikes 120-126, shown in FIG. 5. The inputs from the converter 132 are respectively fed to ones of AND-gates 220a-c whose outputs are connected to an OR-gate 222. The output of the gate 222 is a pulse solenoid signal (FIG. 8d) which is fed to remaining parts of the system and is also fed to the input of the flip-flop circuit 210. The 1-second clock signal is fed to an OR-gate 224 to provide clocking to the system. Gates 220a-c may for instance comprise the integrated circuits manufactured and sold as TT μ L 9003 and the gates 222 and 224 integrated-circuit gates sold as TT μ L 9004 by Fairchild Semiconductor of Mountain View, Calif. The outputs P₁-P₄ are fed to the inputs of gates 220a-c to provide an indication of whether or not the pulses have been telemetered.

The pulse solenoid signal thus occurs during the power-on reset signal and also during the following 1-second clock pulses: the state P_1 when the signal "4" is found by the analog-digital converter 132; or state P_2 when the signal "2" is found by the analog-digital converter 132; or when the signal state P_3 is found with the "1" signal found by the analog-digital converter 132.

FIG. 12 illustrates the solenoid driver 148, with the pulse solenoid signal being fed to a pretriggerable monostable multivibrator 230. Multivibrator 230 provides an output pulse with high accuracy and with a very wide duration range in dependence upon the level of the DC input. In the particular configuration, multivibrator 230 is adjusted by an R-C network 232 to provide a 360-millisecond pulse (timed from the trailing edge of the pulse solenoid signal) via lead 234. The one-shot pulse from the monostable multivibrator 230 is fed to the solenoid driver circuit 236, which may for instance comprise a high-voltage, high-current driver. In the preferred embodiment, the multivibrator 230 comprises the retriggerable monostable multivibrator manufactured and sold as Multivibrator TTL 9601 by Fairchild Semiconductor of Mountain View, Calif. while the driver 236 comprises the high-voltage, high-current driver SH2001 manufactured and sold by Fairchild Semiconductor of Mountain View, Calif.

The output from the driver 236 operates the pressure valve 46 in the manner previously described, in order to control the transmission of pressure uphole for reception, detection and recording. Once recorded, the intervals between the pressure pulses are determined to determine the hole drift as previously noted.

Further explanation of the operation of the present circuit in generating two pulses may be illustrated by FIGS. 8a-h. The power-on reset causes generation of a pulse solenoid signal as shown in FIG. 8d. The 1-second clock pulses shown in FIGS. 8c occur during every eighth clock pulse, as shown in FIG. 8a. Additionally, the pulse solenoid signal shown in FIG. 8d occurs when state P_1 is found with state "4," in the manner previously described. Additional pulses will be generated in state P_2 when "2" is found, or when P_3 is found with "1." The solenoid time shown in FIG. 8h is actuated by the trailing edge of the pulse signal shown in FIG. 8d.

It will be seen that other types of position-determining apparatus may be alternatively utilized in the present invention in place of the electrical contact circuitry described. For instance, a light beam may be focused upon a plurality of photoelectric cells which are disposed on the concave side of the clamping member 82. Moreover, other configurations of electrical contact points according to the invention may be utilized in place of the particularly specified configuration. For example, a measurement of the magnetic longitude may also be provided according to the invention in addition to the measurement of latitude.

The present invention thus provides an improved directional surveying system compared to conventional procedures, by obtaining individual measurements at higher frequencies without a loss of drilling time. The use of a magnetic measuring device which is maintained in a frozen or constrained position while drilling, and in an unrestrained or free position when circulation has stopped, makes it possible to make accurate measurements when the drill pipe is standing still, thereby not involving any loss in drilling time. The receipt of the signals from the bottom of the borehole after circulation has resumed is easily and efficiently done with a time-driven pressure recorder which registers the output pressure of the mud pumps.

The pressure recorder may be started at the same time that the mud circulation is resumed after making a drill pipe connection, and the recorder may be stopped when the required number of pulse cycles and time intervals between the cycles has been recorded. Additionally, if at any time during the drilling operations, it is desired to verify the angle and direction of the borehole drift, it is necessary only to stop rotation and circulation, wait the required short interval and resume circulation and rotation. As previously noted, systems

may be provided which automatically calculate and plot the angle and direction of the borehole from the transmitted pressure pulses.

Whereas the present invention has been described with respect to a specific embodiment thereof, it will be understood that various changes and modifications may become apparent to one skilled in the art, and it is intended to encompass those changes and modifications as fall within the scope of the appended claims.

I claim:

1. In a drill system, the combination comprising:

a. structure defining a chamber in the region of the drill bit of said drill system,

b. reference means movable within said chamber and including structure for maintaining said reference means in a preselected orientation with respect to magnetic north,

c. means responsive to mudflow of said drill system for clamping said reference means in position, and

d. means disposed in the region of said drill bit for detecting the relative positions of said reference means and said drill bit while said reference means is clamped.

2. The combination of claim 1 and further comprising:

means for telemetering indications uphole of the relative positions of said reference means and said drill bit to define the inclination and direction of said drill system.

3. The combination of claim 2 wherein said means for telemetering comprises mud-valve means, and means for modulating said mud-valve means in accordance with the relative positions of said reference means and said drill bit.

4. The combination of claim 1 wherein said reference means comprises a generally spherical member with a magnetic element embedded therein and includes means to maintain said member within a preselected region of movement.

5. The combination of claim 4 wherein said reference means is suspended in quantity of liquid contained within said chamber.

6. The combination of claim 4 wherein said reference means includes a cutout portion within which a pin member rigidly suspended from said drill system is pivotally connected.

7. The combination of claim 6 wherein said cutout portion is generally conical, with the end of said pin member pivotally connected at the apex of the cutout portion.

8. The combination of claim 4 and further comprising:

a clamping member having a spherical cutout portion adapted to receive said spherical member and operable in response to changes in mudflow of said drill system for selectively abutting said spherical member in a clamping relationship.

9. The combination of claim 8 wherein said spherical member comprises:

A plurality of electrical conductive points thereon, said clamping member including a plurality of means for sensing the position of said electrically conductive points.

10. A system for surveying the drift of a directional drill comprising:

a generally spherical reference member adapted to move about a pivot relative to said drill to seek a reference orientation within said drill,

means for maintaining said reference member in a stationary position within said drill during drilling operations,

means for releasing said reference member in response to temporary cessation of drilling operations to enable said reference member to move relative to said drill to seek said reference orientation, and

means operable during drilling operations for detecting the relative position of said reference member with respect to said drill.

11. The system of claim 10 and further comprising:

clamping means slidable within said drill and having a portion adapted to abut against said spherical reference member for maintaining said reference member in a stationary position within said drill,

port means disposed uphole and downhole from said reference member for sensing variances in the mud pressure flowing through said drill, and bellows means connected to said port means for selectively moving said clamping means into and out of engagement with said spherical reference member in response to variances in the mud pressure.

12. The system of claim 10 wherein said spherical reference member includes three conductive portions on the exterior thereof, one of said conductive portions being disposed on the upper portion of said reference member and the remaining two conductive portions being disposed along lines intersecting at a right angle at said first conductive portion.

13. The system of claim 12 and further comprising:

a plurality of rings disposed on said clamping means for sensing the position of said conductive portions on said spherical reference member.

14. The system of claim 10 wherein said generally spherical reference member includes a generally conical cutout portion in the lower portion thereof,

a pin member rigidly connected at one end to said drill and extending into the conical-shaped cutout portion and attached at the apex thereof for pivotally supporting said spherical reference member.

15. The method of surveying the inclination of a directional drill comprising:

maintaining a reference member in a stationary position within said drill during drilling operations,

releasing said reference member in response to temporary cessation of drilling operations such that said reference member seeks a predetermined reference orientation relative to magnetic north,

clamping in response to resumption of drilling operations said reference member in a stationary position after said reference member has reached its predetermined reference orientation, and

detecting during drilling operations the relative position of said drill with respect to said reference member while said reference member is clamped in a stationary position.

16. The method of claim 15 wherein said reference member seeks said predetermined reference orientation due to the attraction of the earth's ambient magnetic and gravitational fields.

17. The method of claim 16 wherein said step of detecting comprises:

detecting the position of at least three conductive portions on said reference member, and

distinguishing each of said conductive portions from one another by measuring the electrical resistance provided by said conductive portions.

18. The method of claim 16 and further comprising:

telemetering the detected relative positions of said drill with respect to said reference member uphole during drilling operations by imparting coded pulsations into the drilling mud of the drill system.

19. The method of claim 16 and further comprising:

monitoring the variance in the mud pressure of said drill caused by initiation and cessation of drilling operations, and

controlling the state of freedom of said reference member in response to variances in the mud pressure.

20. In a directional directional detection system for a drill, the combination comprising:

a generally spherical reference member having a magnet embedded therein for seeking a reference orientation within said drill due to the attraction of the ambient magnetic field of the earth,

said reference member including a plurality of conductive points distributed on the exterior surface thereof,

resistance means connected to each of said conductive points, and

means including a plurality of concentric conductive rings for contacting said conductive points to detect the position of said conductive points by measurements of the magnitude of said resistances.

21. The combination of claim 20 and wherein said means for detecting comprises:

a member having a concave portion adapted to receive a portion of said spherical reference member and including said conductive rings thereon for contacting said conductive points on said spherical reference member.

22. The combination of claim 21 wherein said conductive points on said spherical reference member comprise:

a first point position at the uppermost point of said spherical member and including second and third conductive points disposed along lines intersecting at a right angle at said first point position.

23. The combination of claim 21 and further comprising:

multiplexor means for generating analog signals representative of the conductive rings which are in contact with said conductive points,

means for converting said analog signals into digital signals, and

means responsive to said digital signals for generating control signals.

24. The combination of claim 23 and further comprising:

mud valve means operable in response to said control signals for transmitting mud pulses uphole representative of the position of said reference member.

* * * * *

55

60

65

70

75

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,622,971 Dated Nov. 23, 1971

Inventor(s) Jan J. Arps

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

- Col. 6, line 59, "nd" should be --and--.
- Col. 7, line 1, "sin(48-19)sin 48-47)sin(48-30)" in the equation should be --sin(48-19)sin(48-47)sin(48-30)--.
- Col. 8, line 17, "clock 40" should be --clock 140--;
- line 72, "16a-z" should be --164a-z--.
- Col. 9, line 2, "lead 15" should be --lead 152--;
- line 52, "Liner" should be --Linear--;
- line 53, "μ710" should be --μA710--;
- line 55, "12.5 k Ωohm" should be --12.5 k ohm--.
- Col. 10, line 1, above "Combination" insert --Parallel-- and above "10⁴(10μmhos)" insert --Resistors--;
- line 6, in 4th column insert --0--.
- Col. 11, line 13, "imput" should be --input--.
- Col. 12, line 37, before "quantity" insert --a--.
- Col. 14, line 12, cancel "directional" (first occurrence);
- line 34, "he" should be --the--;
- line 36, "dispose" should be --disposed--.

Signed and sealed this 20th day of June 1972.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents