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The New, Downlink Drilling Control System™ that Changes Conventional Drilling Operations

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Abstract
This paper covers the principles of a new downlink drilling control system and its advanced features. This system has changed the paradigm of conventional drilling operations. From viewing the set-up diagram, one can gain an understanding of the system's components. This new technology involves mechanical, electronic and software development. This system was primarily developed for controlling rotary steerable tools, but it can be used with many other types of downhole tools. The paper also discusses the application of this new technology in the drilling industry. Several of the automated features have been developed and are incorporated in the new downlink control system. The completed automated features can be considered as the initial stage of artificial intelligence in a drilling tool. A sampling of successful field tests is included along with a discussion of future developments.

Introduction
The drilling industry is a "traditional" industry in the sense that directional and horizontal drilling operations are primarily based on experience. Since the Rotary Steerable Tool was introduced into the drilling industry, drilling tool systems have had "artificial intelligence" capability combined with <u>network and internet</u> technologies. However, the industry is still faced with the challenge of finding an efficient and reliable communication technique that can integrate downhole formation evaluation ("FE") data and drilling data with surface real-time control and information systems. Recently a new downlink drilling control system has been developed. This system makes the drilling operation less complicated and more efficient. The new technology not only saves drilling time and drills a better well bore, but also thrusts future drilling automation into the here and now. The system has been tested in the field for about two years with excellent results. There are several key features that offer significant changes to conventional drilling operations. These features, which are both developed and under development, include the following:

- Simultaneous bi-directional communication between surface and downhole tools while drilling.
- Downlink control of multiple tools in the BHA or elsewhere in the drill string.
- Dual control option for downlink communication with the rotary steerable tool
- Ultra smooth well bore capability
- Real-time data exchange
- Remote control operation
- Automated inclination control
- Automated directional drilling (Automated 3D drilling based on a well plan)
- Automated directional drilling enhanced with "artificial intelligence" (Automated 3D drilling guided by formation evaluation and directional data)

Basic Downlink Control System Hardware Configuration
Figure 1 is the diagram of the Downlink Drilling Control System™ and the Downhole BHA Integration™. The Downlink Drilling Control System includes (Figure 1, starting at 1 o'clock, counterclockwise) the following hardware:

- Remote control computer
- Rig site computerized control system
- Surface transmitter skid
- Downhole receiver sensor
- Downhole tool control system
- Rotary steerable tool control system

Decisions for downlink commands are based on well planning information and FE/MWD data. In order to transmit downhole, a command is sent to the rig site computerized control system from the remote control computer via computer network communication facilitated by any communications medium such as satellite, radio, microwave or cable. For non-remote operation, the command is simply entered into the rig site computerized control system. The rig site computer control system activates the surface transmitter skid in order to create a proper sequence of negative pulses in the drill string. Once the pressure pulses representing a certain instruction are generated on the surface and transmitted to the end of the drill string, a downhole pressure sensor receives the signal and sends the signal to the downhole tool control system. The downhole control system decodes the command and sends the command to the specified downhole tool. In the case of a rotary steerable command, the rotary steerable control system will follow the command in order to make changes to the rotary steerable tool parameters.

In the case of numerous downlink compatible tools in the drill string, the Downlink Drilling Control System is capable of communicating with multiple tools in the BHA. In order to control multiple tools, each downhole tool must be equipped with downlink compatible firmware. Each downlink command is encoded with an identifier which enables the downhole control system to send the command to the appropriate tool. The downhole control system is capable of sending downlink commands to any number of tools in the BHA.

In regard to uplink and downlink communication, the uplink communication is NOT interrupted during Downlink Drilling Control System signal transmission. This feature permits <u>simultaneous bi-directional communication</u> between surface and downhole tools.

The surface transmitter skid consists of an automatically controlled valve which bypasses a portion of the drilling fluid, going to the standpipe, back to the mud pump return line. The valve is pneumatically actuated via the rig air supply. The automated control system, for the pneumatic actuator, is powered via low voltage signals sent from the rig site computer through intrinsically safe electronic barriers. The bypass procedure is automatically controlled by the rig site computerized control system. Figure 2 is the diagram of the rig site set up, and Table 1 lists the specifications for the surface skid.

Brief Explanation of the Rotary Steerable Tool (RST)

There are several different types of rotary steerable tools (RST's) in the current market. The distinguishing feature for the RST used with this drilling control system is that the tool points the bit. Most other types of RST's push the bit to one side of the borehole.

The basic mechanism for this type of RST consists of a deflectable rotating drive shaft in a stationary sliding housing. A cantilever bearing and a focal (pivot) bearing support the rotating shaft. An eccentric bearing is located between the cantilever and focal bearings. The eccentric bearing is supported by an adjustable eccentric ring set as shown in Figure. 3[1]. The eccentric rings can be rotated to displace the eccentric bearing to a desired displacement and direction with respect to the tool face. The displaced eccentric bearing deflects the drive shaft, which in turn points the bit in the opposite direction of the drive shaft deflection. This procedure is similar to orienting the tool face of a mud motor during slide drilling, with the exception of the RST having a downhole adjustable bend angle. As with a mud motor, the higher the deflection of the RST drive shaft, the higher the dogleg it can drill. The Downlink Drilling Control System can be used to adjust any combination of tool face and deflection to perform 3D rotary steering.

The Control System's Advanced Communication Features

The new control system utilizes two-way communications. Communication from the BHA to the surface is called ***uplink***. Similarly, communication from the surface to the BHA is called ***downlink.*** The downlink is achieved through mud pulses created by the aforementioned surface transmitter skid. The uplink is achieved through normal MWD mud pulse telemetry. The uplink and downlink can be executed simultaneously without interference with each other while continuing to drill. This capability is achieved with dissimilar uplink and downlink transmission frequencies. Additionally, a combination of noise filtration and signal recognition firmware is used to ensure reliable downhole detection of the downlink signal. Figure 4 shows actual test data of simultaneous downlink and uplink pulses. After receiving the raw data (Figure 4A), uplink signals and higher frequency noise are filtered to produce "clean" raw downlink data (Figure 4B). The filtered downlink data are conditioned to remove DC and other high frequency noise (Figure 4C). The data are then cross-correlated to produce well-defined pulse positions (Figure 4D). The sequence of intervals between the pulses defines specific command and data values.

The new system for controlling a rotary steerable tool (RST) is equipped with a dual control option for downlink communication. The first is the aforementioned downlink control and the second is a manual control mode. The two systems operate completely independent from each other, and control of the RST can be switched between the two modes as required. The manual mode involves pump cycling and rotation sequences of the drill string to send commands to the RST. The normal downlink mode is considered quite reliable. However, in the event of a downlink failure, the manual control provides a back-up method for controlling the RST. This back-up feature combination, which is unique in the industry, provides the ability to finish a job without tripping out of the hole in the event of a primary downlink failure. The net result is a significant cost saving particularly in offshore drilling operations.

Fast communication speed is another advanced feature of this system. The shortest command can be transmitted downhole in less than 30 seconds. The longest command is approximately 120 seconds for the present data structure. When more commands are added to the data structure, transmission duration will vary with respect to the current date structure.

The Downlink Drilling Control System data code is structured so as to maximize reliability. The downlink command starts out as electronic data from the surface rig site computerized control system and is converted to mud pulses, which are received by the downhole receiver pressure sensor. The receiver contains the firmware for filtering and processing valid mud pulse commands into an electronic message that is then forwarded to the downhole tool control system. The downhole control system decodes the message into a tool specific command and then sends the command to the appropriate tool in the BHA. In the case of an RST command, the command is sent to the rotary steerable tool which then adjusts its parameters per the command instructions.

Downlink commands are comprised of three intervals. These include “command”, “data”, and, “error-checking” intervals. The “command” interval indicates what tool to instruct and what type of change the tool will make; the second interval is the “data” interval, providing the magnitude of change the tool will make; and the third interval is the “error-checking” interval, which checks the instruction. For example, the “command” interval tells the downhole tool to execute a particular function, such as an RST deflection change or a new tool face setting. There are currently twelve different commands with the option of adding more commands as more functions or tools are added to the drill string. Examples of “data” values include RST deflection magnitudes and tool face settings. Depending on the application, data values can be several bits or a single bit. When these pulses are transmitted down the drill string, they might be deformed or interrupted. The “error-checking” interval is used to ensure that only valid downlink pulses are utilized.

In order to provide real-time confirmation of a downlink command, uplink verification is incorporated in this new system. Following receipt of a valid downlink command, the downhole tool control system sends a confirmation command to the surface via the uplink. If the uplink conformation matches the sent downlink command, a “successful command” message is reported at the surface. In the event of an unsuccessful command, the rig site computerized control system automatically re-sends the command and repeats the confirmation process. In the event of another unsuccessful command, a corresponding “command-unsuccessful” message is reported at the surface. It should be noted that automatic re-sending of the command is optional.

There are several considerations in regard to the data structure. First, the structure has to be comprehensive enough to cover all the necessary applications. Second, the structure should not be too large in that it will adversely affect the communication speed. The third consideration involves arranging the data structure for maximum efficiency. This Downlink Drilling Control System is relatively fast compared to similar systems. Careful design of the data structure contributed to the fast data rate capability.

The fast Downlink Drilling Control System data rate and comprehensive command base provide a way to very accurately control the RST tool face and deflection setting. There are at total of 17 deflection (bend) settings and 120 tool face settings. With additional commands, these settings can be adjusted to any number of values. Additional commands, however, do increase the total time required for sending a downlink command. The capability to accurately adjust the tool face and bend deflection any number of times while drilling provides the ability to drill an extremely smooth well bore. This capability is in contrast to conventional motor drilling where the bend angle is fixed and setting of the tool face becomes extremely difficult in deep or extended reach well bores.

The Real-Time Graphics User Interface Capability Combined With Real-Time Utilization of Geophysical, Petrophysical, and Drilling Engineering Personnel

Due to satellite technology, real-time data exchange is now available to multiple personnel in remote locations. The new Downlink Drilling Control System utilizes this technology in order to make real-time control available to multiple personnel in remote locations. Formation evaluation (FE) and directional drilling data, which is transmitted real time to the surface via uplink, can now be incorporated with mud log data, well planning data, and reviewed real time by the geophysicist, petrophysicist, and drilling engineer. All of the information can be integrated together to make a decision for controlling the drilling operation. Based on this comprehensive review, downlink commands can then be transmitted real time to the downhole drilling tools.

Figure 5 shows the real-time control function, communication status, and well-planning profile versus the real-time drilling profile. The real-time control system and real-time data exchange function as follows:

The uplink FE and directional data are transferred to the surface control computer where rig site personnel can view the information. At the same time, the same information is transferred via satellite to personnel located remotely from the rig. Rig site and remotely located personnel are now able to make a comprehensive real-time decision for the next drilling action. The action is implemented by sending a downlink command via the rig site computerized control system. When the changes are effected in the downhole tools, the drilling profile changes can now be viewed real time by persons at the rig site and in remote locations.

By comparison, in a previously typical operation, the drilling profile has been predetermined, and the directional driller follows the planned well profile without assistance from remote personnel. The ability to exchange data real time between rig site and remote personnel and then effect changes based on real-time decisions has completely changed the convention drilling operation to the point that the need for personnel to steer the wellbore trajectory are no longer required to be at the rig site, resulting in cost savings by requiring fewer people offshore, if the job is an offshore.

A real-time drilling display combined with a comprehensive graphics user interface has been implemented in the new drilling control system. In most drilling operations today, directional drillers and drilling engineers still mark the updated survey on the well planning wall-size plot to compare the data and make sure the drilling profile matches the well-planning profile. The new Downlink Drilling Control System has a comprehensive graphics user interface (GUI) (figure 5). The GUI display includes the following:

- Well planning profile
- Real time drilling profile
- 3D views of the profiles
- Anti-collision data
- Ellipse uncertainty profiles
- Drilling parameter settings
- Surface automated functions
- Downhole automated function “ON” indicator
- Command communication status
- Control and sending of downlink commands
- Other operational parameters as required

All of the integrated information can be displayed simultaneously on the directional driller’s and LWD/MWD engineer’s computer, as well as on the geologist’s and company representative’s computer. With real-time remote data exchange via satellite communication, the information can be viewed real time by geophysicists, petrophysicists and drilling engineers in locations that are remote from the rig site. The ability to integrate real-time drilling parameters and formation evaluation data with input from expert personnel in remote locations will reduce the decision-making cycle time and prevent costly mistakes.

Remote Control Operation

The Downlink Drilling Control System is equipped with remote control capability. For example, personnel in Houston can operate a rotary steerable tool on a job in Norway. Distance is no longer an issue. With the cost of offshore directional drilling personnel at a premium, the ability to simultaneously control two or more drilling jobs offers the potential for substantial cost savings. Cost is not the only issue. There are instances where it is desirable to have a highly experienced directional driller on more than one job at the same time. The only way to achieve this capability is through remote control operation. Furthermore, in complicated off shore drilling situations, a significant amount of communication can be required between the directional driller and multiple personnel in the onshore office. By having the directional driller work directly with the onshore personnel, a significant reduction in decision / rig time can be realized. Directional drilling commands are then sent via satellite to the Downlink Drilling Control System on the rig.

Fig 6 is a remote control flow chart. By way of satellite communication, the remote control computer will sequentially load drilling commands on the database of the offshore rig site computerized Downlink Drilling Control System. After the control system determines that the Downlink Drilling Control System skid is available for transmitting commands, it will send the command automatically. After the downhole receiver successfully receives the command, a confirmation signal will be sent via uplink to the surface computerized control system. The confirmation acknowledgement is then transmitted via satellite back to the remote control computer where the confirmation acknowledgement and real-time drilling profile will be displayed on the screen. The communication speed through the satellite has to be faster than the data broadcast speed. We have successfully performed remote control drilling on a recent job in Norway. The remote feature and successful practice in the field indicates that the time has come where one experienced directional driller may be able to drill two or more wells at the same time. This ability offers significant cost saving to the operating companies.

Automated Inclination Control and Automated Surface Functions

Currently, directional drilling decisions are primarily based on the driller's experience. Depending on a driller's experience, different people will adjust drilling parameters differently for a given drilling condition. In addition, different formations in various locations will yield totally unique drilling results. The challenge is to work toward drilling decisions based on knowledge as opposed to relying solely on experience. One solution is automated drilling functions, which control tools based on actual formation characteristics.

The new Downlink Drilling Control System includes an inclination "cruise control" function. The idea of the automated inclination control is that the rotary steerable tool (RST) will automatically adjust to the proper tool face and deflection in order to maintain a defined inclination. The system operates by first sending an inclination "cruise" command, which includes the specified inclination angle, tolerance, and sensitivity. Commands are sent via the downlink system to the RST. After the rotary steerable tool's control processor receives the command, it will monitor the *At Bit Inclination* sensor periodically. When well bore inclination or change rate of the inclination deviates from the specified value, the control processor will automatically adjust to the proper tool face and deflection in order to maintain the preset inclination within its defined tolerance.

Even though this system is not a fully automated drilling system, this feature has moved toward *knowledge based drilling,* a topic worthy of a future paper on its own. This function utilizes knowledge of inclination at the bit to accurately control the RST. As will be discussed later in this paper, the future of automated drilling will allow the computer controller to utilize all the formation characteristics in order to determine the RST parameter settings. This type of automation redefines the type of experience needed to operate such a system.

In regard to control of the well bore profile, automatic inclination control will make the well bore smoother because of the real-time parameter adjustment. When the inclination fluctuates, the rotary steerable tool will correct it back to the predefined inclination. The automatic function can detect minute fluctuations much earlier than that seen by the directional driller. Therefore, the inclination fluctuations will be much smaller than those made by a directional driller, thereby reducing the overall wellbore tortuosity and resulting drag. An added benefit will be increased rate of penetration due to the smoother well bore and better weight on bit transference.

In addition to the automated inclination feature, the new Downlink Drilling Control System does have limited automated surface features for drilling a well bore profile. The system can automatically adjust the tool face and deflection of the RST in accordance with a prescribed well plan. However, with the exception of automatic inclination control, the system cannot currently correct for deviations that occur in the actual well bore profile.

A prescribed well plan can be mapped with a set of commands that are used to define the drilling profile. The current automated surface system will then execute the set of commands sequentially or in parallel, depending on the required parameter adjustment. Future development of automated surface control will include the ability to correct for deviations that occur in the actual 3D well bore profile.

Field Successful Examples

Following is a brief sampling and discussion of some of the key field results demonstrated with the new Downlink Drilling Control System:

April 2000: Catoosa test facility in Oklahoma: Successful testing of the downlink communication system with simultaneous uplink.

February 2001: Catoosa test facility in Oklahoma: Successful testing of the new Downlink Drilling Control System.

March – April 2001: Offshore platform in Liverpool Bay on the West Coast of England:

The first commercial field test with this kind of drilling control system was a multi-lateral job with four legs. The Downlink Drilling Control System was used to successfully drill three of the four legs. The results were very encouraging.

November – 2002: On November 9th, 10th and11th daytime operation, Halliburton's rotary steerable system was successfully operated from the onshore drilling center located within the Conoco Phillips office building in Norway. The actual drilling occurred on well Ekofisk 2/4-X-49T2 of the offshore Ekofisk Alpha Platform, located about 200 miles from the drilling center. Throughout the three days of drilling on bottom at depths of 13,878 ft to 18,435 ft (4557 ft section), the remote control drilling system performed flawlessly with 100% uplink and downlink communication.

December – 2002: Offshore platform in the Gulf of Mexico off the coast of Louisiana:

The Downlink Drilling Control System was successfully used to operate a drilling formation tester tool and the RST. Measured depth was around 29,000 ft with a true vertical depth over 21,000 ft. Borehole hydrostatic pressures approached 18,000 psi.

Because this system can set the tool face very accurately, we can drill a well in a very narrow window as compared to a conventional motor. For the same reason, the new system makes it much easier to side track in a multi-lateral application. The accuracy of this system allows the tool kick off to be at a precise azimuth, which in turn can minimize the drilling time required to reach the target.

The new Downlink Drilling Control System is now our standard rotary steerable tool control system. The aforementioned automatic functions have been tested in several jobs with excellent results.

Future Developments

There are two major developments that will occur in the future. One is completely automated drilling and the second is automated drilling that utilizes artificial intelligence.

The new Downlink Drilling Control System has been integrated with information for drilling, well planning, anti-collision protection, etc. However, these functions are not fully developed for completely automated drilling.

In regard to completely automated drilling, this technology will utilize automated 3D drilling to drill a well based on a predetermined well plan. This system utilizes real time surface automated controls and has the option of including preprogrammed automated downhole controls. The downhole automated controls can be updated or mode switched real time via the Downlink Drilling Control System. The vision for this technology is to simply be able to load the well planning profile in the remote or rig site surface control computer and let the computer automatically set the proper drilling parameters for the rotary steerable tool based on the prescribed well plan. A directional driller is then only needed to monitor the well, or multiple wells, from a central onshore location. This type of technology offers significant potential savings in labor cost and has the ability to allow one person to control multiple drilling operations.

What’s significant here is that the industry now has a downlink system that is fast enough to allow for the steering calculations to be done on surface instead of downhole. Several advantages now come into play because of this breakthrough including the ability to fully understand what the automated steering control system wants to do before it executes the commands. This is significant because instead of finding out what the RST did after the fact, when perhaps it’s too late to correct the well trajectory back onto the plan, one can see what the intention of the system is and assess whether the human should over rule just like one does with the cruse control in a car.

In regard to completely automated drilling that utilizes artificial intelligence, this concept utilizes all the technology of the fully automated 3D-control system and incorporates real time formation evaluation data. By combining the 3D automated drilling control function with formation evaluation information, a level of artificial intelligence can be achieved in the automated drilling system. This system can be further enhanced by included formation evaluation information from off set wells. We refer to this new technology as *automatic geo-steering*. Much development has taken place in regard to software for formation evaluation and 3D automated drilling control. The challenge lies in how to best integrate the two technologies into one comprehensive automated system. This type of integration is technically achievable. The date at which time such a system will be available is strongly dependent on the demand for this type of technology. We believe this type of technology will ultimately save cost in drilling operations.

Summary

Only a few years ago, the concept of performing directional drilling without a directional driller on the rig would have seemed bizarre. Today, the directional driller can control a rotary steerable tool 300 or even thousands of miles from the rig. We now have the technology to remotely operate a rotary steerable tool, drilling a well on one continent with steering professionals on another for example. The new downlink control system has changed the conventional drilling paradigm.

Most industries have now entered the age of real time information technology exchange via e-link or satellite technology. The new Downlink Drilling Control System has done the same thing for drilling operations. We anticipate this tendency will accelerate as more rotary steerable tools, with evolving technologies, become available in the market.

The question, now, is whether customers can shift from the paradigm of conventional drilling practices and embrace the new technology. We are sure there are some who think this new technology is a rather crazy idea. There is an idiom in China which says that the first person who eats a crab must be a very brave man. We are looking forward to working with more “brave” people who are interested in benefiting from this new technology. When the drilling industry reaches the stage where operations are commonly controlled via real-time automated systems, we can then say that we have caught up with other industries that have benefited from such technology and that we are truly operating in ***e***-time.

Acknowledgements

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References

1. Tetsuo Yonezawa, Edward, J. Cargill, Tom M. Gaynor, J.R. Hardin Jr., Richard T Hay, Akio Ikeda and Yoshihide Kiyosawa, "Robotic Controlled Drilling: A New Rotary Steerable Drilling System for the Oil and Gas Industry", IADC/SPE #74458, 2002 IADC/SPE Drilling Conference Dallas, Texas, USA.

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Maximum operating pressure	10,000 PSI	(690 Bars)
Hydrostatic test pressure	15,000 PSI	(1034 Bars)
Operating temperature – For circulating fluid	33°F to 122°F	(1°C to 50°C)
Operating temperature – For lifting skid	-22°F to 122°F	(-30°C to 50°C)
Continuous flow capacity	195 GPM	(738 LPM)
Momentary flow capacity	390 GPM	(1476 LPM)
Skit "Weight"	2000 lb	(907 kg)
Skid length	6.0 ft	(1.83 m)
Skid width	2.5 ft	(0.76 m)
Skid height	3.5 ft	(1.07 m)
Supply air pressure (min/max)	100/200 PSI	(690/1379 KPa)
Circulating fluid	Filtered drilling mud	(8.34 – 18 lb/gal)
Operation region at rig site	Hazardous zone	

Table 1. Downlink Surface Skid Transmitter Specifications

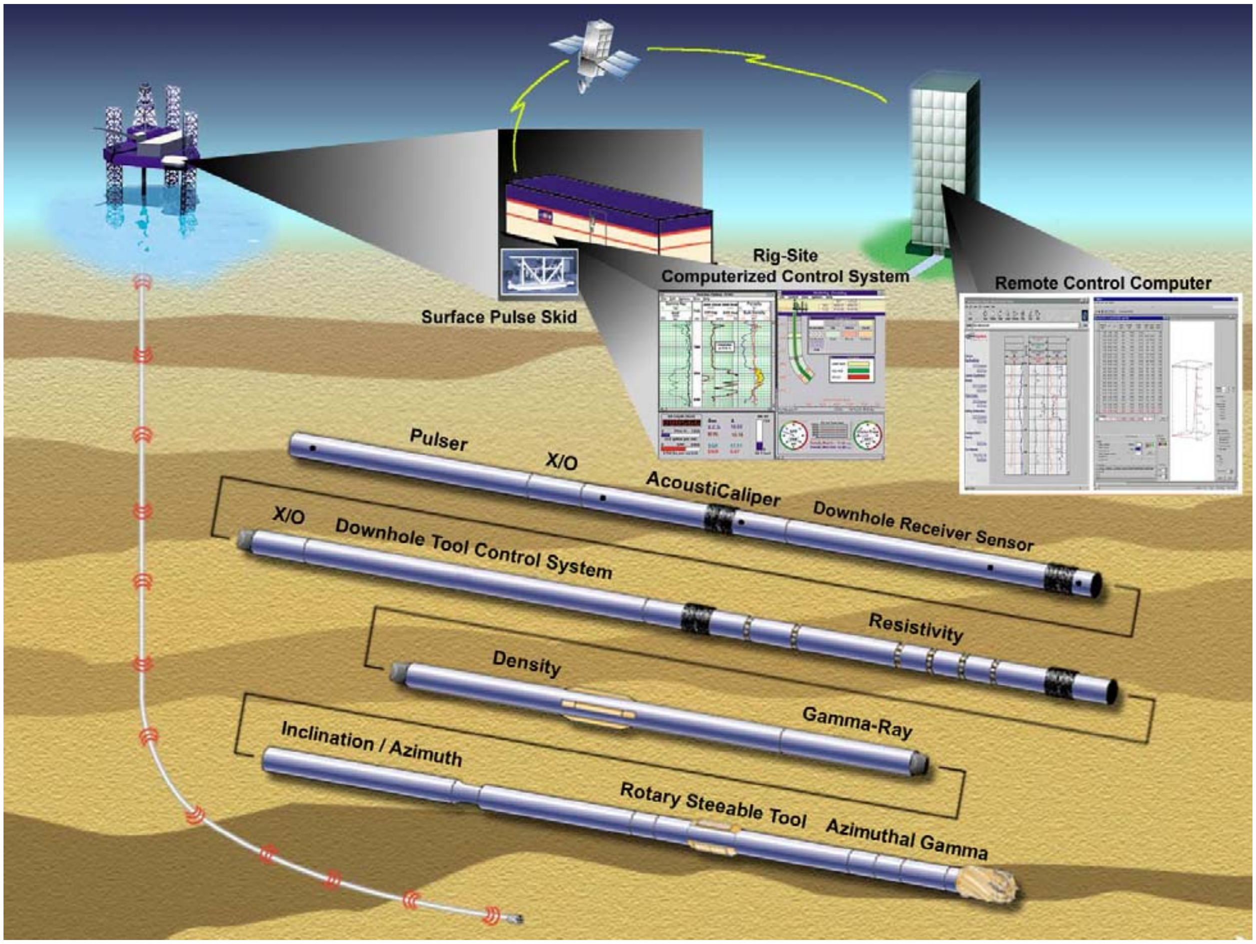
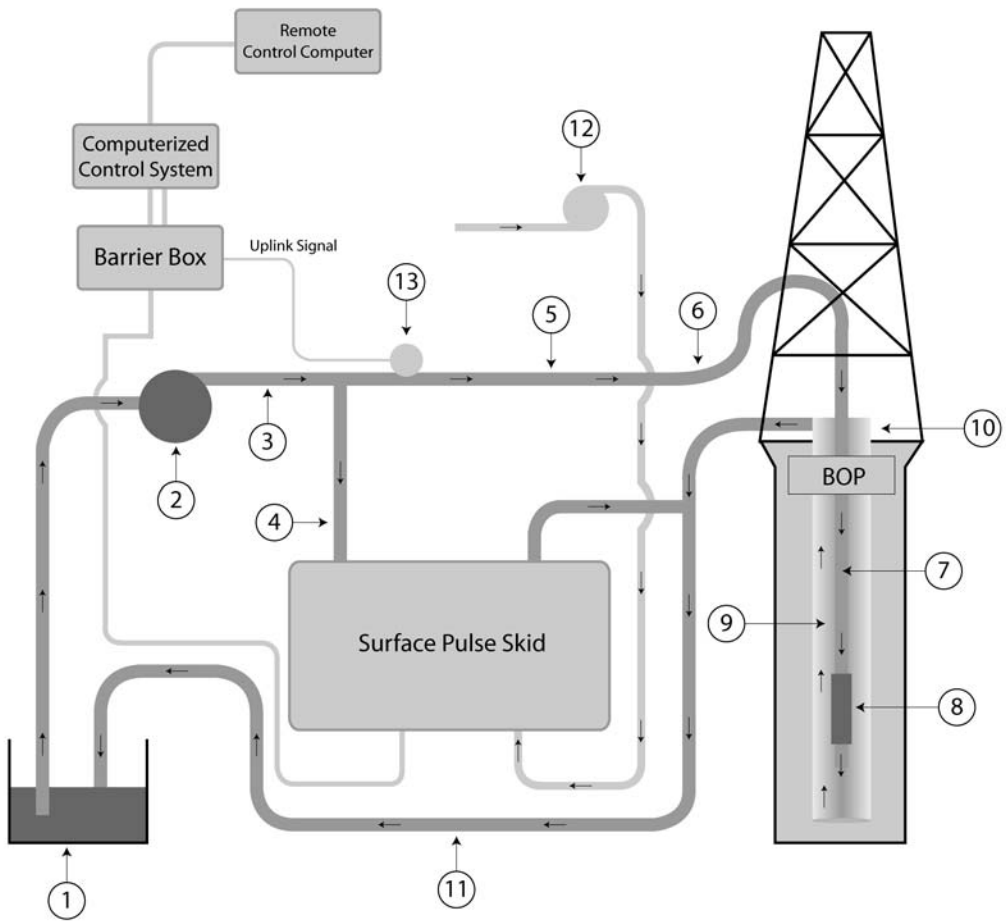


Figure 1. Downlink Drilling Control System and Downhole BHA Integration (adapted from Tetsuo, et al. [1])



1. Mud Tanks	2. Mud Pump	3. Fluid Flow	4. Surface pulse skid re-routes fluid to create negative pressure pulse.	5. Negative pulse flows directly to standpipe.
6. Standpipe carries downlink signal.	7. Fluid is pumped downhole through drill string.	8. Downhole receiver sensor.	9. Uplink signal.	10. Upstream fluid is collected in annulus reservoir.
11. Upstream drilling fluid is returned to tanks.	12. Air supply	13. MWD uplink sensor		

Fig 2. Down-Link Drilling Control System Rig site set up.

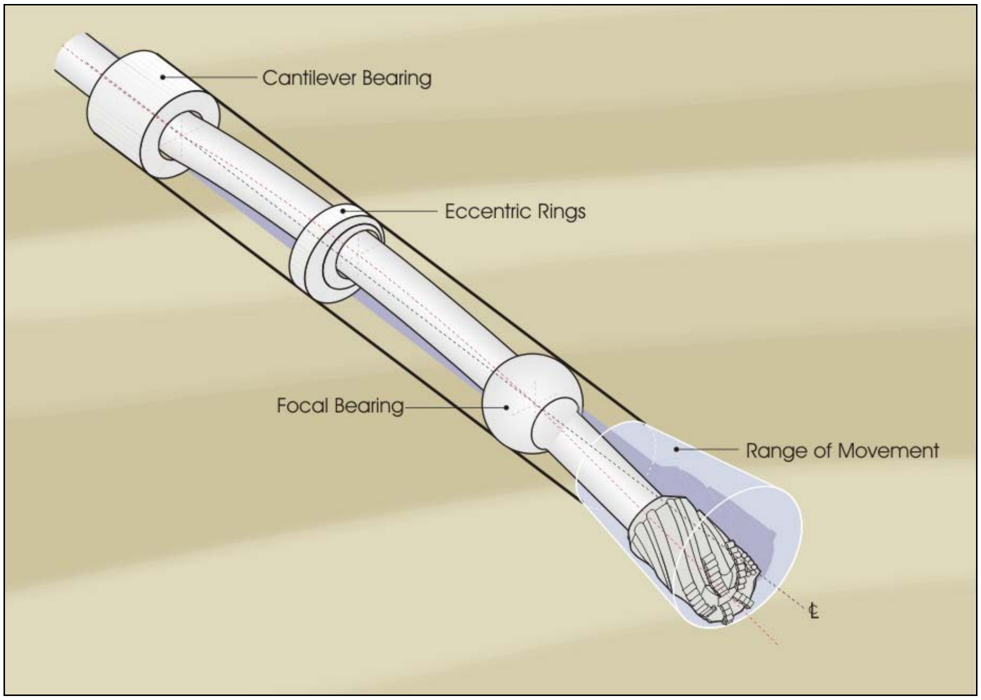


Fig 3. A points to Bit Rotary Steerable Tool Concept (Cited from Tetsuo, et al. [1])

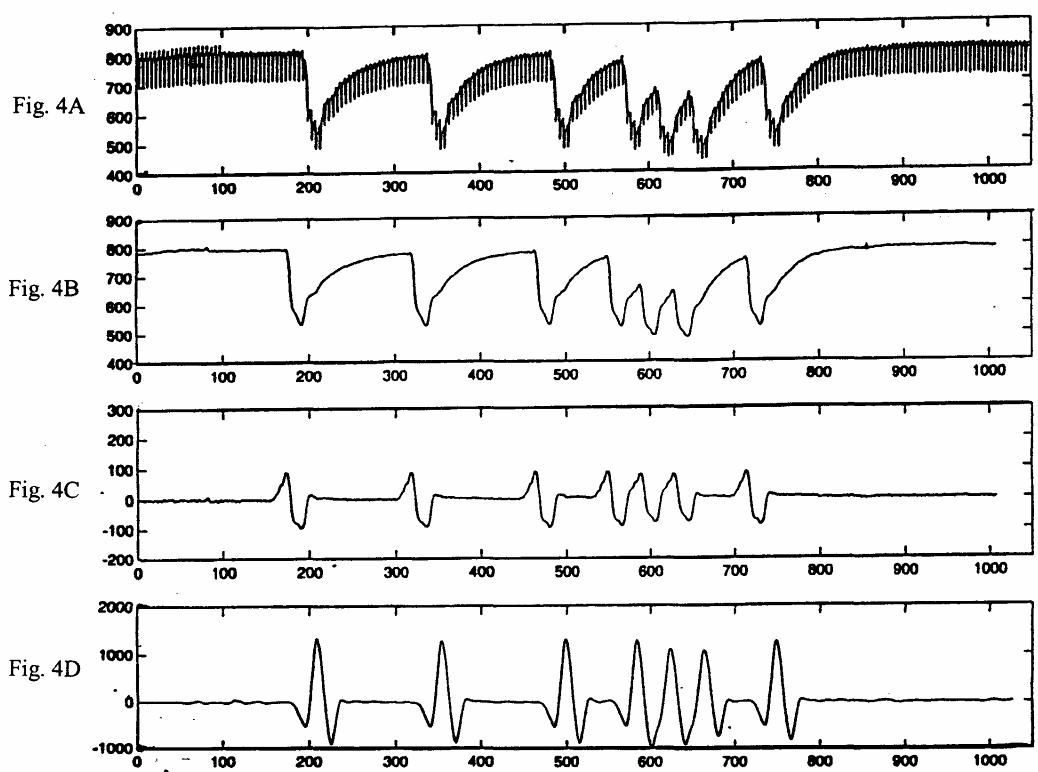


Fig 4. Downlink signal with Simultaneous Uplink

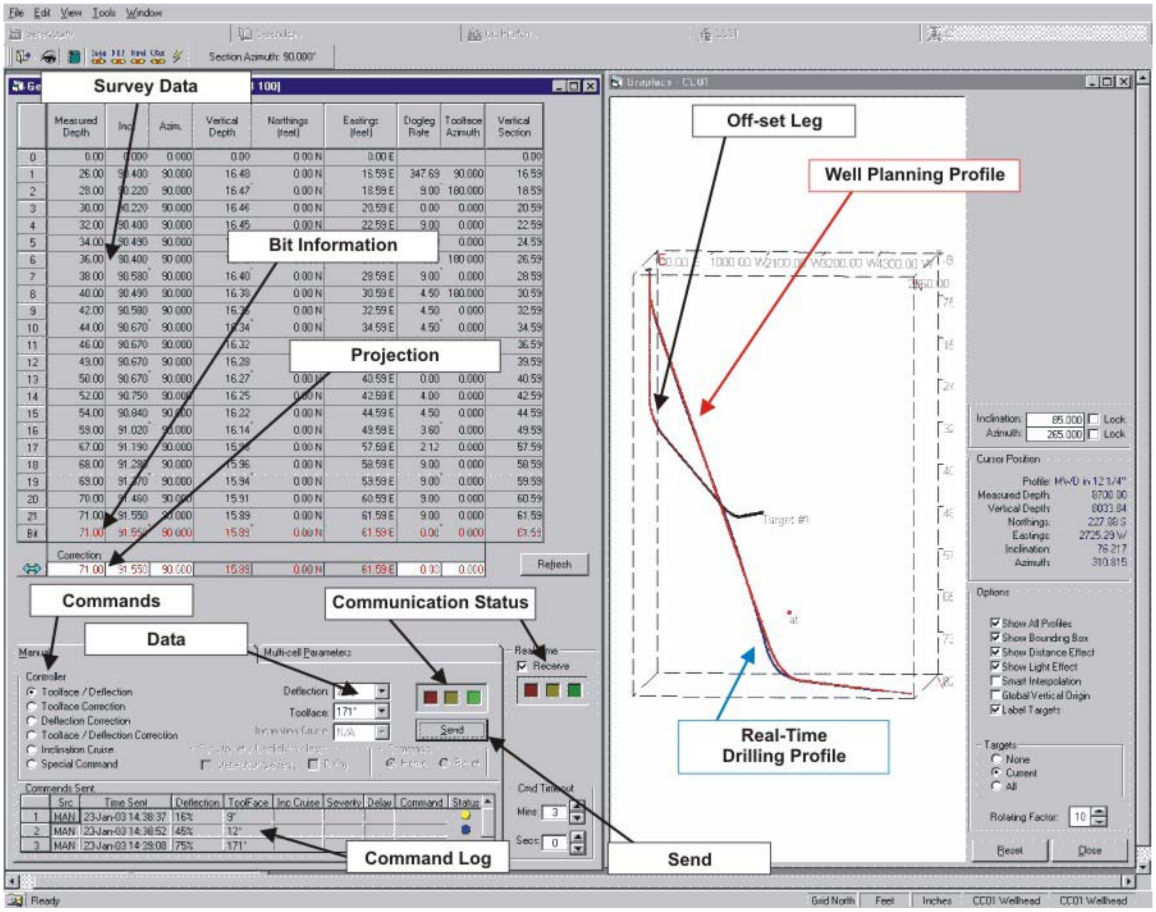


Fig 5. Downlink Drilling Control and Survey Data Display

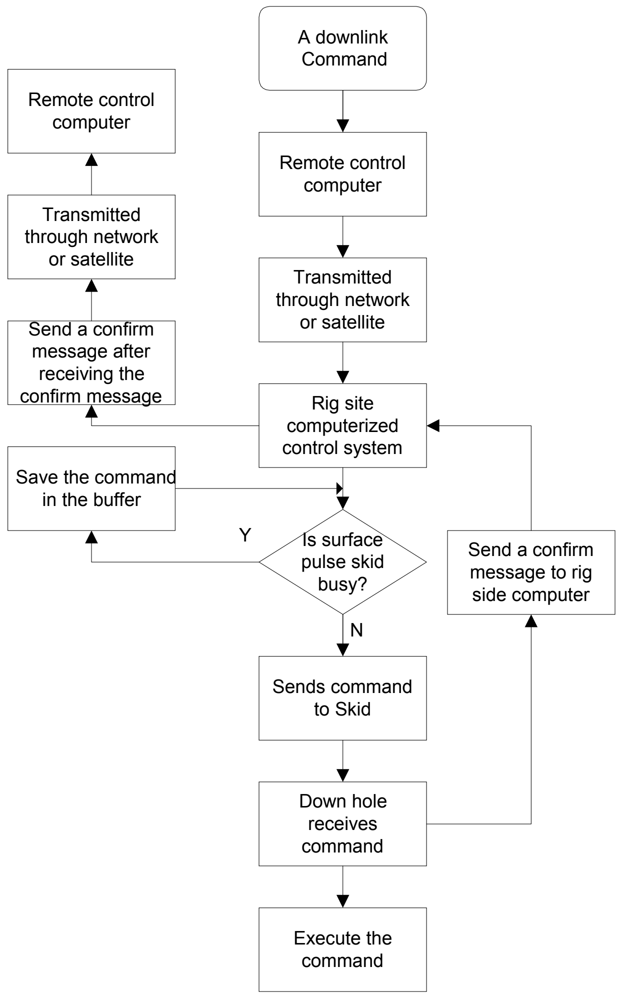


Figure 6. Remote Control Flow Chart