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Preface

The purpose of this document is to provide a general introduction to “Measurement While Drilling” technology and applications. The audience is expected to be engineers, scientists, and technical managers who are new to this field. This guide discusses MWD technology that is common across the oil services industry as well as specific to Baker Hughes INTEQ.

This document is produced by both the Technical Services Group and Advanced Development Group of the Drilling and Evaluation Technical Center. The material in this document is a result of the efforts of many people, both in the above mentioned groups and outside. Any questions or comments can be directed to:

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Measurement While Drilling

MWD History

What Is MWD?

Measurement While Drilling (MWD) systems measure formation properties (e.g. resistivity, natural gamma ray, porosity), wellbore geometry (inclination, azimuth), drilling system orientation (toolface), and mechanical properties of the drilling process. Traditionally MWD has fulfilled the role of providing wellbore inclination and azimuth in order to maintain directional control in real time. From the mid 1980s to the present time, formation evaluation MWD has paralleled and surpassed other aspects of drilling technology to the extent that it is now possible to replace very sophisticated wireline logs with real-time and memory-stored measurements while drilling.

Mud Pulse Telemetry

The MWD tool is normally placed in the bottom hole assembly of the drillstring, as close to the drill bit as possible. The MWD tool is an electromechanical device which makes the measurements described above, and then transmits data to surface by creating pressure waves within the mud stream inside the drillpipe. These pressure waves or pulses are detected at the surface by very sensitive devices (standpipe pressure transducers with pre-amplifiers) which continuously monitor the pressure of the drilling mud. These data are passed on to sophisticated decoding computers which deconvolute the encoded data from downhole. This whole process is virtually instantaneous, thus, enabling key decisions to be made as the wellbore is being drilled.

Other, more exotic transmission systems do exist e.g. drillpipe acoustic, electromagnetic and hardwire telemetry. But the vast majority of all commercial systems utilize mud pulse telemetry by generating either a pulse or a modulated carrier wave which is propagated through the drilling fluid at roughly the speed of sound in mud (i.e. 4000-5000 ft./sec or 1200-1500 m/sec). Mud pulse telemetry MWD tools use positive pulse, negative pulse or carrier wave (mud siren) schemes to transmit measured parameters from downhole to surface in realtime to aid in formation evaluation, directional control, drilling efficiency and drilling safety. Downhole information is registered by the MWD sensors and then passed on to the MWD tool microprocessor. The microprocessor then routes this
information to the surface by activating the tool transmission system. Mud pulse telemetry involves the modulation of the flow of mud through the drillstring by means of a mechanical valve or rotary valve mounted within the MWD tool. At the surface, the data are decoded and depth correlated. The data are then output to hard copy and graphical display, much like a wireline logging system. The true value of MWD can thus be appreciated by its provision of realtime dynamics and directional drilling data augmented by realtime formation evaluation measurements, which are considered equivalent and often times superior to sophisticated wireline logs.

As MWD tools and measurements have become more reliable and cost effective, the practice of replacing both standard (e.g. gamma ray, resistivity) logs and triple combo (which also include neutron porosity and formation density measurements) wireline logs has become common place.
The superior cost effectiveness of MWD logging is especially true for medium to high cost development wells and high risk drilling applications where problems with hole geometry, displacement and logging environment preclude the use of wireline logs other than those conveyed by drillpipe or tubing. This drillpipe-conveyed wireline process is both costly and time consuming, particularly when the high cost of fourth or fifth generation drilling rigs and platforms are considered.

Several key factors will drive the MWD vs. wireline decision making process:

- Deviation of wellbore
- Anticipated borehole conditions at logging time
- Risk of losing hole or tools during wireline operations
- Value of early data acquisition
- Rig costs and required operating time
- Ease of fishing (bottom hole assembly vs. wireline cut and thread)
- Value of realtime data to reservoir and geologic uncertainty

**Information Output**

Depending on the level and complexity of the MWD service used, applications include:

- Directional control
- Relief well drilling
- Bottom hole location
- Casing seat selection
- Gas influx identification
- Lithological identification
- Offset well correlation
- Coring point selection
- Invasion profiling
- Pore pressure analysis
- Precision geosteering in high angle wells
- Hydrocarbon identification
- Shallow gas control
- Reconnaissance and insurance logging in high risk wells
• Cost effective wireline replacement

Where drilling mechanics MWD is used, it may be possible to provide information to aid in the following:

• Drilling optimization
• Hydraulics optimization
• Bottom hole assembly damage avoidance
• Bit whirl analysis
• Influx monitoring (well kick)
• Swab and surge measurements while tripping (avoiding kicks or conversely formation damage)

**Early Systems**

**Pre War Development**

1927  First wireline log run in France by Schlumberger brothers
1929  Jakosky filed a patent on the concept of mud pulse telemetry
Early’30s  Karcher of GSI attempted continuous resistivity transmission by means of conducting rods fastened in drillpipe
Early’40s  Silverman of Stanolind Oil & Gas Co. used an electric cable inside drillpipe for data transmission
By 1950  Mechanical weakness of insulated subs/sensors and need for custom drillpipe led to abandonment of early telemetry systems. Mud Logging/wireline became accepted formation evaluation methods

**Post War Developments**

1950’s  Arp invented the positive mud pulse system, developed jointly by Arps Corp. and Lane Wells
Early ’60s  Above development resulted in a number of successful gamma ray/resistivity runs
Late ’60s  Redwine & Osborne developed a “While Drilling Monoelectrode Resistivity Log”
           Teledrift tool developed - mechanical inclinometer with positive mud pulse - still used today in North Sea
           Godbey of Mobil developed mud siren
           Flexodril system developed by IFP
Late ’60s  ELF worked on positive mud pulse telemetry system, leading to creation of Teleco which evolved into the industry benchmark for service, reliability and performance

By 1970  Design problems and lack of economic drivers led to decline in MWD research

Development in the Seventies

Early ’70s  Resurgence of interest in MWD driven by OPEC cartel and improved technology Development of SNAP logs by ELF (Early version of surface measured drilling dynamics - akin to ADAMS and DYNABYTE)

1971  First successful test of mud siren by MOBIL R & D

1970-73  B J Hughes running commercial Teledrift tool

1972  ELF and Raymond Engineering form a joint venture called TELECO

1978  First commercial MWD system - TELECO Directional MWD

1979  Gearhart Owen - NPT Dir/GR tool commercial

Typical Early Operational Specifications

Survey Time  4-5 minutes

Tool Face Update  2 minutes

Collar Size  7-3/4” to 9-1/2”

MTBF  50 Hours

Evolution - Development in the Eighties

1980  Schlumberger / Anadrill commercial with MST multi-sensor MWD licensed from MOBIL Gearhart commercial with NPT multi-sensor MWD

1981  Gentrix (EASTMAN) PPT directional MWD commercial EXLOG commercial with NPT multi-sensor MWD with memory

1983  Teleco introduce RGD commercial system

1984  NL Baroid commercial with RLL (Recorded Lithology Log) a recorded Electromagnetic resistivity / gamma ray log EXLOG introduce DHVM system - downhole vibration measurement
1984  Teleco, EXLOG, Anadrill, Gearhart all offering RGD services
1985  Teleco and Anadrill introduce Bit Mechanics Measurement
EXLOG commercial with retrievable Dir DMWD probe tool
1986  NL Baroid introduce Neutron Porosity measurement with RLL
       Gearhart introduce lateral and bit resistivity measurement
1987  EXLOG commercial with focused current resistivity
1988  Gearhart commercial with focused gamma ray sensor
1989  ENSCO enter MWD market - small RGD presence in GOM
1989  NL Sperry introduce triple combo MWD
       Anadrill/Schlumberger introduce triple combo LWD and MEL/SPIN software
       Teleco introduce Dual Propagation resistivity

Development in the Nineties

1990  Teleco commercial with triple combo MWD
1991  NL Sperry introduce EWR Phase 4 - multiple DOI EWR
       Western Atlas introduce 1 MHz RGD
       Anadrill purchase Positech - market as Slim 1 retrievable tool
1992  Anadrill introduce IDEAL (Integrated Drilling Evaluation
       and Logging) System with inclusion of RAB (Resistivity At Bit) and Acoustic Caliper.
        Baroid (NL Sperry) introduce Near Bit Inclinometer
        Baker Hughes acquire Teleco - new company merges with Eastman Christensen. World leading MWD and drilling performance company renamed EASTMAN TELECO
        Baker Hughes commercial with slim hole Dir/GR NaviTrak tool
        Baker Hughes INTEQ introduces Modular Drilling Dynamics sub
Baker Hughes INTEQ is formed. A fully integrated service company is formed through the merger of EASTMAN TELECO, DEVELCO, MILPARK DRILLING FLUIDS, EXLOG, and BAKER SAND CONTROL.

1994 Baker Hughes INTEQ introduce NaviTrak Short Radius MWD system and NaviGator reservoir navigation system.

1995 Commercial slim hole propagation resistivity (4-3/4” tools) developed - Sperry Sun Slim Phase 4 (memory only), Schlumberger ARC-5, Baker Hughes INTEQ NaviMPR. IDS and Halliburton develop prototype tools.

**Typical Current Operational Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey Time</td>
<td>90-130 seconds</td>
</tr>
<tr>
<td>Tool Face Update</td>
<td>9-18 seconds</td>
</tr>
<tr>
<td>Collar Size</td>
<td>3-1/8” - 9-1/2”</td>
</tr>
<tr>
<td>MTBF</td>
<td>300 Hours + Dir</td>
</tr>
<tr>
<td></td>
<td>200 Hours + FEMWD</td>
</tr>
<tr>
<td>Sensor Array</td>
<td>Slim Hole - DIR, DIR/GR, 2MHz and 400kHz RESISTIVITY (NaviMPR)</td>
</tr>
<tr>
<td></td>
<td>Large Hole - DIR, DIR/GR, DRILLING DYNAMICS, RGD, 2MHz and 400kHz RESISTIVITY (NaviGator), NEUTRON POROSITY, DENSITY, Pe, CALIPER</td>
</tr>
</tbody>
</table>
•Notes•
MWD Principles
Three Basic Telemetry Types

Positive Mud Pulse Telemetry

Positive mud pulse telemetry (MPT) uses a hydraulic poppet valve to momentarily restrict the flow of mud through an orifice in the tool to generate an increase in pressure in the form of a positive pulse or pressure wave which travels back to the surface and is detected at the standpipe.

Service companies and respective services using this telemetry method include:

- Baker Hughes INTEQ - D, DG, DDG, RGD, DPR, MPR, TC, NaviGator, DMWD, NaviTrak and NaviGamma
- Anadrill/Schlumberger - SLIM1
- Halliburton - Datadrill
- Sperry Sun - DWD/DGWD/FED
Negative Mud Pulse Telemetry

Negative MPT uses a controlled valve to vent mud momentarily from the interior of the tool into the annulus. This process generates a decrease in pressure in the form of a negative pulse or pressure wave which travels back to the surface and is detected at the standpipe.

Service Companies and respective services using this telemetry method include:

- Baker Hughes INTEQ - AccuTrak
- Computalog - D, DG
- Geolink - D, DG
- Halliburton - AGD/BDG, RGD
- Sperry Sun - MPT

Figure 2-2
Negative Mud Pulse Telemetry
Continuous Wave Telemetry

Continuous wave telemetry uses a rotary valve or “mud siren” with a slotted rotor and stator which restricts the mud flow in such a way as to generate a modulating positive pressure wave which travels to the surface and is detected at the standpipe.

Figure 2-3
Continuous Wave Telemetry

Service Companies and respective services using this telemetry method include:

Anadrill/Schlumberger - MWD and LWD
Other Telemetry Types

Electromagnetic Telemetry

The electromagnetic telemetry (EMT) system uses the drill string as a dipole electrode, superimposing data words on a low frequency (2 - 10 Hz) carrier signal. A receiver electrode antenna must be placed in the ground at the surface (approximately 100 meters away from the rig) to receive the EM signal. Offshore, the receiver electrode must be placed on the sea floor. Currently, besides a hardwire to the surface, EMT is the only commercial means for MWD data transmission in compressible fluid environments common in underbalanced drilling applications. While the EM transmitter has no moving parts, the most common application in compressible fluids generally leads to increased downhole vibration. Communication and transmission can be two-way i.e. downhole to uphole and uphole to downhole. The EM signal is attenuated with increasing well depth and with increasing formation conductivity.

Figure 2-4
Electromagnetic Telemetry
Service Companies and respective services using this telemetry method include:

- Geoservice - D and DG
- Sperry Sun/Geoscience - D and DG
- Mitsubishi/JNOC - Experimental system

**Acoustic Transmission**

Acoustic transmission systems can be described as active or passive. An active acoustic system generates a downhole sonic telemetry signal which propagates up the drill string. Though data rates are generally very high, significant attenuation of the acoustic signal occurs at drillpipe connections. Thus, “repeaters” (acoustic amplifiers) are often required in the drill string as well depth increases. Passive acoustic systems make use of pre-existing downhole acoustic energy (such as bit noise) as a seismic energy source for seismic while drilling measurements.

**Fluidic Vortex**

The fluidic pulser generates a vortex within a chamber by momentarily restricting the mud flow, thus creating a turbulent flow regime. The resulting change in pressure loss can be switched on and off rapidly, circa 1 millisecond, and the resultant pressure wave created can be of high amplitude (145 psi).
Coding / Encoding Schemes

Enhanced Return to Zero Technique Telemetry

Unipolar pulses are generated from a baseline in combinatorial patterns within a fixed time interval or by employing phase shift keying (PSK). The original MWD system would transmit a number of pulses, or pressures surges, which could be detected and decoded at surface. By the late seventies new systems were introduced which enhanced mud pulse telemetry with two new concepts, time-analog and binary return to zero. These conventional mud pulse systems have three common features:

- Unipolar Pulses
- They all Return to Zero
- All Rely on Constant Pulse Width

Enhancements to common RZ methodologies have led to the development of M-ary Phase Shift Keying (MPSK) and Combinatorial Coded (CC) telemetry.

Digital Encoding Techniques

Three additional encoding schemes are now available for optimum mud pulse telemetry:

- Non Return to Zero (NRZ)
- Delay Modulation (Miller)
- Bi-phase

The encoding schemes listed have common attributes:

1. All are implementations of binary encoding schemes.
2. These techniques use change in state, or transition, for each data bit instead of using pulses like RZ code.
3. Each transition must occur within a relatively short time window, or bit cell.
4. The success in using these methods hinges on the digital signal processing capabilities of the surface computer decoding the data stream. Hand decoding is usually not an option.
Tool Configurations

There are a wide variety of MWD tool configurations dependent on application, measurement specification and drilling environment.

Five differing configurations are defined:

- Clear 2” ID / Centrally Located
- Modular / One Piece
- Battery / Turbine
- Retrievable / Non retrievable
- Memory / Real Time

Clear 2” ID / Centrally Located

Some MWD tools, such as the Baker Hughes INTEQ AccuTrak tool, has a clear 2” ID through bore which permits unobstructed mud flow, allowing virtually any type of LCM to pass by/through the MWD tool, and if necessary it is possible to effectively string-shot below the MWD tool.

Modular / One Piece Multi-sensor

Modular MWD systems were designed to address the growing need for a broader, more flexible range of service levels. The key to a modular MWD system is the interconnection of the tool modules over a single conductor power and data bus. This is accomplished by using either a stab-in connector or a tool shoulder ring connector in order to provide connections for the addition or deletion of tool modules to the drillstring, including custom components, such as full or undergauge stabilizers, if necessary. By having this type of architecture, it is possible to build the required level of
service from a simple directional service to a full triple combo MWD service. As with other major MWD service companies, Baker Hughes INTEQ MWD utilizes a modular concept that is offered in two systems:

- a **collar mounted** system which utilizes a dedicated drill collar
- a **probe mounted** system that is placed in the ID of a standard monel collar.

These two systems enable the provision of MWD services for slim hole directional, real-time, multi-sensor, and recorded only MWD services for the oil and gas industry. Modular MWD systems of the nineties provide significant computational processing power, with both transmission sampling and recording formats that are programmable at the wellsite.

**Collar Mounted MWD Systems**

Generally, collar mounted MWD systems are available down to 6-3/4” collar sizes (i.e. they are suitable for 8-1/2” to 9-7/8” hole sizes and larger).

![Collar-based Directional (D)](image-url)
Modular MWD components can be selected to build two major service levels (each with expandable options):

**Directional (D) / Directional Gamma (DG)**

These collar mounted services provide real-time directional and directional-gamma tool data using mud pulse telemetry. Power is provided by a downhole turbine.

**Real-time and memory-stored Multi-Sensor**

This group of services combines several tools to provide real-time formation evaluation and directional information. Data are transmitted in real-time by mud pulse telemetry and are also stored (at higher data rates) into downhole memory to enable enhanced log definition following bit trips.

**Probe MWD Systems**

Typically, this is a battery operated, negative or positive pulse MWD system designed for simplicity of operation and ease of maintenance. The tool's sensors and electronics are fitted inside either a 1-3/4 inch or 2 inch (51mm) OD protective housings or “barrels”. The adjoined barrels are placed inside a standard Non-Magnetic Drill Collar (NMDC) and are stabilized with integral rubber centralizers (fin or flex style). Although initially designed for slim hole applications, the MWD probe systems are used in all BHA dimensions. Current configurations permit these types of tools to be run in collar sizes ranging from 3-1/8” up to 9-1/2”.

Probe MWD components can be selected to build two major service levels:

**Directional**

These services provide real-time directional and temperature data, using mud pulse telemetry. Power is provided by a lithium battery pack.

**Real-time Multi-Sensor**

This group of services combines a gamma-ray module with the standard MWD configuration to provide both real-time formation evaluation and directional information. Slim hole, advanced propagation resistivity (including downhole memory) is also available in a probe style system targeted for the 4-3/4” collar size.

**Battery / Turbine**

With battery operated MWD systems, power is usually supplied by lithium chloride batteries. This enables the tool to operate while tripping and also enables operation independent of mud flow hydraulics. Turbine powered systems generate power by the flow of mud, so they will only operate within preset flow ranges. It is necessary, therefore, to have circulation for
the tool to operate. The following summarizes the characteristics of both systems:

**Table 1: Battery versus Turbine-Powered MWD Systems**

<table>
<thead>
<tr>
<th>Battery Powered</th>
<th>Turbine Powered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Battery</td>
<td>Mud turbine/alternator</td>
</tr>
<tr>
<td>Power hour limits</td>
<td>No time limits</td>
</tr>
<tr>
<td>Power with and without circulation</td>
<td>Must circulate to power system</td>
</tr>
<tr>
<td>150 degC operating limit</td>
<td>125 degC operating limit</td>
</tr>
</tbody>
</table>

**Figure 2-7**

*Navi-Gamma and Directional Gamma Systems*
Retrievable / Non Retrievable

There are many play offs when attempting to categorize the relative advantage of a retrievable, versus a “dedicated” non retrievable, MWD tool. Ultimately, the choice is governed by drilling application and operational costs.

A fully retrievable MWD system offers flexibility, convenience and reduced lost-in-hole liability. Typically, a probe is shipped to the wellsite by truck or helicopter and made up on the catwalk. The system is then run into place to a landing shoe in a non-dedicated non magnetic drill collar. If a tool failure does occur, the tool can be retrieved from downhole on a sand line and is easily replaced by running a back up tool into place without the need to trip the drillstring. Typically, these types of tools are simple robust directional MWD tools. Recently, a gamma ray capability has been made available with the Baker Hughes INTEQ NaviTrak Gamma tool. For the future, an electromagnetic resistivity capability is expected. The niche market for this type of device is remote location, slim hole and medium-to-short radius horizontal drilling applications.

The non retrievable MWD system is typically more sophisticated and reliable than its retrievable counterpart. This is due to the dedicated nature of the tool and its encapsulating collar. As the tool is locked down, it is inherently more reliable and able to operate in higher mud flow regimes. In addition, the capability exists to use add-on sensors as with the modular tool design described earlier, so that a particular set of tools can be made up for a specific drilling application. Theoretically, this add-on capability is...
also possible for retrievable tools, although this is a topic for future development.

**Memory / Real Time**

Most commercial real-time and recorded only formation evaluation tools have an enhanced memory capability. This system provides for storage of raw data and permits storage of data at higher rates than is possible with real-time transmissions. The memory system is also used for retrieval of formation data if only toolface data are transmitted when steering. Data storage also provides data recovery in case of transmission problems. For example, if real-time data are lost due to surface detection problems, memory data can be used to fill in the missing information. The chances of memory filling up on long bit runs is a possibility but rare in today's market where MWD memory systems are normally between 0.5 and 8 Megabyte.

**Memory Only Services**

A number of service companies offer a recorded only service level which is designed to provide downhole recorded formation evaluation at a lower cost than real-time data acquisition. Ideally, this service will be utilized where costs are critical since formation evaluation data are essential for discriminatory purposes, but are not needed in real-time. Formation evaluation data are continuously logged into the tool memory on a time basis, regardless of rig operations. When the tool is retrieved at the surface, the memory is dumped through a high speed sidewall data port. These data are then matched with a prerecorded time/depth array and a log is produced in a matter of minutes. Since this is a recorded only service, it can operate independently of a mud logging unit in a safe working area or from a third-party logging unit.

The basic level of recorded only service will include a natural gamma ray log and a 2 MHz electromagnetic resistivity sensor (DPR). Additional enhancements include advanced propagation resistivity (MPR), neutron porosity (MNP) and formation density (MDL) measurements.

**Applications**

- Lithological identification
- Formation bed boundary and thickness determination
- Casing seat selection
- Shale formation estimates in reservoir rocks
- Low cost insurance logging in high risk wells
- Permeability/sedimentology studies
Real-time Multi-sensor

Real-time multi-sensor MWD services are designed to meet the needs of today's demanding drilling environment. Levels of service range from simple directional to full real-time formation evaluation with enhanced downhole recording. For example, in a surface hole section, directional control may be the only MWD requirement. In contrast, an extended reach horizontal well could utilize full formation MWD for insurance purposes. By using full formation evaluation to provide real-time logs for evaluation, it is possible to make cost effective decisions in critical reconnaissance drilling situations. In today's challenging drilling environments the MWD logs obtained may ultimately serve as the definitive log if the well is lost. For more details on real time MWD service configurations, refer to the PEI MWD comparison tables.
Reliability

Reliability is the probability of a product performing without failure, a specified function under given conditions for a given period of time.

A unit of measure is Mean Time Between Failure (MTBF). The Baker Hughes INTEQ method for calculating MTBF strictly adheres to the guidelines laid down by the Society of Petroleum Engineers (SPE) endorsed in publication 19862 “Recommendations for MWD Tool Reliability Statistics”. In this respect, the reliability standard is expressed as follows:

\[ Reliability = MTBF = \frac{\text{Operating Hours (Perfect Hours)}}{\text{Failures}} \]

Factors Affecting Reliability:

- Shock and Vibration
- Downhole Temperature
- Complexity of Tool
- Drilling Practices
- Telemetry System
- Service Company Quality Assurance (TQM)
- Competition
- Training
Magnetic Interference/Spacing

The MWD directional survey instrument is used to monitor the direction (magnetic) and inclination (the angle of the tool's long axis from vertical) of the borehole.

In the MWD drilling environment, there are many sources of magnetic interference that can cause inaccurate directional measurements. A ferromagnetic steel object that is placed in a magnetic field will become magnetized. The amount of induced magnetism is a function of the external field strength and magnetic permeability of the object. In order to prevent magnetic interference, the directional survey instrument is housed in a non-magnetic stainless steel collar. The MWD tool is usually arranged in a section of the bottom-hole assembly (BHA) which is made up of a series of non-magnetic collars to reduce the impact of the drilling assembly's steel components on the magnetic field at the location of the survey sensor.

It is possible to optimize the position of the survey instrument by estimating the pole strength for various BHA configurations, based upon downhole field measurements. However, even if the correct non-magnetic collar spacing is used, there could still be other sources of magnetic interference which will cause erroneous directional readings. These include “hot spots” in the non-magnetic steel or areas of mechanical damage caused by rethreading/welding or manufacturing impurities. A continual quality assurance procedure ensures that such anomalies are not present in MWD collars and stabilizers. More significantly, other BHA components may be made of magnetic material and/or already have magnetic anomalies that affect azimuth readings. Other sources of magnetic interference may be caused by proximity to iron and steel magnetic materials from previous drilling or production operations, magnetic properties of the formation, and concentrations of magnetic minerals (iron pyrites, etc.) in excess of six percent.
Azimuth Correction Technique

It is often advantageous to reduce the number of non-magnetic drill collars so that the directional and formation evaluation sensors can be located closer to the bit. (This also eliminates the extra cost of using monel collars.) This will assist in real-time decision making by allowing readings to be made as soon as possible following formation penetration. To address this problem, a number of methods have been devised for making corrections to magnetic surveys. The following correction techniques are designed to reduce the influence of spurious magnetic fields associated with the BHA:

Magnetic Azimuth Correction Algorithm

This is a proprietary method by which magnetic azimuth can be calculated in the event that the z-axis magnetometer reading is corrupted by a spurious longitudinal field resulting from an insufficient length of non-magnetic BHA components. The tool senses such a spurious field as a bias on the z-magnetometer measurement. The method requires the operator to specify expected values for total magnetic field and dip angle, and it then computes the azimuth angle which is consistent with a magnetic field vector as close as possible to the expected value. Accuracy of this azimuth angle is dependent on the accuracy of the input nominal values for the earth's magnetic field and gravity field. The corrected magnetic azimuth accuracy is dependent on the surface location of the well and the direction and inclination that is being drilled. At higher latitudes and higher inclinations and the farther the direction is from north or south, the accuracy of the corrected azimuth will degrade. The operator will have to decide whether to use the corrected azimuth or the uncorrected azimuth based on concerns for azimuth accuracy.

Rotation Algorithm

This is a refinement to the Magnetic Azimuth Correction Algorithm above, which makes use of downhole tool rotation to reduce errors caused by bias in x-axis and y-axis magnetometers, in addition to the z-axis magnetometer bias. Also, accelerometer bias errors on the x-axis and y-axis can be reduced with this procedure. Such biases may be caused not only by calibration drift, but also by magnetic hot spots in the drill collar or by magnetic junk affixed to the outside of the collar. This method requires a minimum of three surveys at different toolface angles, to define a circle centered at a point which represents the transverse biases.

This method can reduce errors caused by magnetic anomalies which rotate as the survey tool is rotated. It does not reduce errors which do not rotate, such as interference from an adjacent casing string.
Hydraulics / Drilling Factors

There are a number of sources of interference in the MWD drilling environment, although the main ones are as follows:

**Mud Pump Noise**

Excessive noise, either from the mud pumps or high torque mud motors can, in rare instances, create unacceptable signal to noise ratios. In order to prevent this, some MWD companies deploy surface measurement of pump strobes in order to characterize a mud pump signature. This is then used in the surface decoder as a pump subtraction filter. In many cases, the pump subtraction filter can be used to detect premature pump damage before any other physical signs are available.

**Rig and Drillstring Noise**

Drillstring vibration will, typically, generate high frequency noise which can lead to a dramatic deterioration of the transmitted signal. Very often, by simply making adjustments to the WOB and RPM, it is possible to avoid damaging critical torsional and lateral resonance. A number of vibration prediction programs are available which can estimate critical RPM for a given drilling assembly. It is also possible to use high frequency surface measurement devices, such as the Baker Hughes INTEQ ADAMS and DynaByte technology provided by the Drilling Dynamics Group. (The Drilling Dynamics Group within Baker Hughes INTEQ uses EXLOG (now part of Baker Hughes INTEQ), ARCO and ELF patented surface measurement technologies)
Maintenance / Training

Periodic Maintenance
Standard Procedures
Data Tracking
Design Simplicity

all add up to

Quality Assurance System
Preventive Maintenance Decreases Costs

Calibration

Calibration is defined as the verification of a measurement to an approved national and/or international standard.

This is a very important subject that will be explained in greater detail on an individual basis for each of the sensors described in sections III and IV.
Formation Evaluation MWD

Definition

MWD instrumentation provides information for directional control and formation evaluation analysis. Formation evaluation MWD provides accurate, quantitative measurements of resistivity, gamma ray, neutron porosity and formation density.

Sensor Information

Natural Gamma Ray

Introduction

All of the earth's rock formations exhibit varying degrees of radioactivity. The gamma ray log is a measurement of the natural radioactivity of the formations. The measurement of this natural radioactivity has been a basic wireline log parameter for many years. Gamma ray logs are used as the depth reference log for correlation with other log information. Since natural gamma ray is a fairly simple measurement to make, this was the first commercial MWD formation evaluation measurement to be made available in the mid-1970's.

Measurement Principle

Two basic types of detectors are used by MWD companies to measure gamma rays:

The Geiger Muller tube is a gas ionization counter consisting of a metal cylinder with an insulated axial wire passing through its center. The cylinder is filled with a non-conductive gas. A high voltage power supply maintains an electrical potential between the central wire and the cylinder. The main detection mechanism is photoelectric absorption or recoil electron ejection from Compton scattering in the metal shield. For gamma rays absorbed near the inner radius of the cylinder, there is some probability of the ejected electron escaping into the gas to provide the initial ionization of the detector gas molecules. Electrons, freed in this way, are accelerated by the radial electric field, collide with gas molecules, and
produce additional free electrons. A fraction of the electrons are collected at the central wire, producing a voltage pulse. The detection efficiency of such detectors is not high, even so the method can be improved by the incorporation of gamma ray absorbers (such as silver) to an inner lining of the cylinder.

With the more efficient scintillation detector used in Baker Hughes INTEQ tools, a crystal of thallium-doped sodium iodide emits light flashes or scintillations when a gamma ray interacts with the crystal. A high voltage photomultiplier tube captures the scintillations, amplifying them into an electrical signal in the form of a count rate. Gamma rays are measured over a specified time in order to collect enough counts to reduce statistical scatter.

Applications

The measurement of natural gamma ray activity is used to estimate the shale content of sedimentary rocks. This lithology discrimination is possible because of the presence of radioactive isotopes (potassium, thorium, and uranium) in the minerals associated with rock types. The number of gamma rays emitted per unit time is a function of the concentration and distribution of these isotopes, and can be correlated in a general way to lithology. The following type log reveals gamma ray response by formation type. Note that actual gamma ray levels will vary widely by location, even so, the log is still useful for discriminating sand (or non-shale lithologies) from shale.

Figure 3-1
Natural Gamma Ray Activity
In addition to providing lithologic discrimination, the gamma ray sensor provides:

- Formation bed boundary and thickness determination
- Well to well structural correlation of beds
- Depth control and casing seat selection
- Estimation of shale fraction in reservoir rocks
- A primary log for sedimentological studies
- Monitoring of injected radioactive materials
- Depth location of radioactive casing PIP tags

**Calibration**

Count rates from the photomultiplier tube are scaled to API units. The primary calibration standard for the natural gamma ray sensor is the API Gamma Ray Calibration Facility in Houston, Texas.

Baker Hughes developed a technique for transferring the calibration of the API pit to a portable wraparound calibrator (Meisner, et. al., 1985). Background counts are determined with a nonradioactive empty calibrator in place. The empty calibrator is then exchanged for a calibrator containing a gamma ray source with a spectrum equivalent to the API pit, and a ten minute count rate is performed. The values are then corrected for the attenuation caused by the replacement of the air in the collar with water and the attenuation caused by the drill collar itself.

**Environmental Corrections**

The gamma ray measurement is affected by three environmental variables:

**Background Radiation from Drilling Fluid**

Most drilling fluids have negligible radioactivity; however, saturated potassium chloride mud systems (KCl) have a significant level of radiation from naturally occurring radioactive potassium isotopes (potassium is highly soluble and can enter the formation). Bentonite (gel additive) is rich in thorium and uranium. Some low grade barite may also have natural activity. These contaminants produce offsets on the log which are particularly noticeable if levels of potassium are rapidly changed. Although it is possible to correct for this offset, the correction is seldom performed as it is very difficult to ascertain precise downhole concentration levels which vary with fluctuations in mud properties.
**Mud Density**

Increases in mud density will increase the attenuation of gamma rays from the formation to the tool. Charts and real-time algorithms are available to correct for this effect.

**Hole Size**

An increase in borehole diameter attenuates the gamma ray tool's detector response, due to an increased volume of drilling fluid between the tool and the formation. Charts and algorithms are also available to correct for this effect.

**Correction Standards**

It is standard Baker Hughes INTEQ practice to apply the environmental corrections for mud density and hole size. Two separate SPWLA standards are in use, one for wireline tools, (8-inch hole, 10 lb/gal density) and one for MWD tools, (10-inch hole, 10 lb/gal density). Baker Hughes INTEQ can provide real-time correction for either standard.

**MWD and Wireline Gamma Ray Comparisons**

Some fundamental differences exist between MWD and wireline gamma ray data, and only rarely do the logs overlay exactly. Statistical variations associated with MWD logs are often considerably less than those of wireline because wireline logging speeds are greater (1800 ft/hr) than MWD average rates of penetration (200 ft/hr).

MWD bed resolution is improved, compared with wireline, because of the slower logging speeds. MWD formation measurements are carried out before significant hole enlargement occurs, resulting in data requiring less correction. Also, MWD logs suffer less mud volume attenuation since the gamma sensors are housed in drill collars that typically have larger OD's than the wireline sondes. Differences are often noticed in run-by-run comparisons of wireline gamma ray logs due to centralization practices.

Detected radiation, particularly the lower energy gamma rays of thorium and uranium, is more attenuated by the thick metal housing of the MWD collar. MWD collars range from wall thicknesses of 1” to 3”, while wireline gamma ray tool housings are typically 1/8” to 3/8”. Thus, the MWD measured gamma ray spectrum is biased to enhance potassium relative to thorium and uranium. For this reason, the MWD gamma ray data will be lower than wireline values in formations rich in thorium and/or uranium. After borehole correction, the two types of logs may have identical values, particularly in formations with spectral characteristics similar to the API pit.
A wireline versus MWD gamma ray comparison is shown below from a well drilled in West Texas. Here, the corrected logs practically overlay as would be expected since both logs correct for mud density and hole size. Spectral biasing is negligible in this case. Note that the NaviGamma MWD log shows better resolution and character due to slower logging speeds.
Formation Resistivity

Introduction

The basic measurement used in open hole log evaluation to determine if hydrocarbons are present in a formation is electrical resistance. Electrical resistance is the ability to impede the flow of electric current through a substance. The formation matrix is normally considered an ideal insulator and makes no contribution to formation conductivity. The main conductor, encountered in the earth's formations, is salt water. This saline water occurs in the formation as free water in the pore space, water adhering to the surface of the rock matrix, or as hydroxyl, ionically bound to clay minerals.

Measurement Principle

A variety of measurement principles are used by wireline resistivity tools to look at resistivity over different physical scales. A broad range of the electromagnetic spectrum is used in resistivity tools to solve different problems. These cover a variety of tools, from the Formation MicroScanner® (FMS-a Schlumberger wireline tool) – which has a pad of tiny buttons measuring resistivity every few millimeters across the borehole, from which a pictorial image of the surface resistivity of the borehole wall may be computed, to ultra long spacing tools designed to detect resistivity changes caused by large scale geologic features such as salt domes or casing in adjacent wells.

Applications

All current MWD resistivity tools attempt to provide a measurement of $R_t$, the true resistivity of the rock and fluids in a reservoir, before its steady state is affected by the presence of fluids introduced into the rock by the process of drilling the borehole. Wireline tools usually “see” the formation after a stable physical equilibrium is established between the borehole fluids and the reservoir fluids. A shallow measurement is made to measure the resistivity of the rock saturated with mud filtrate (invaded zone) to enable comparison with deep measurements that are intended to measure uninvaded formations.

The key to the application of resistivity logs is that it is impossible for a resistivity tool to differentiate between an increase in resistivity caused by fluid changes and an increase in resistivity caused by additional rock and hence less fluid volume. Hydrocarbon fluids in rocks usually contain some water, and the relationship between porosity, resistivity, and water...
saturation is key to basic resistivity analysis in the Archie equation. This equation is the foundation of most log interpretation techniques:

\[ S_w^N = \left( \frac{a}{\Phi^m \times R_w} \right) \frac{R_t}{R_w} \]

Where:
- \( R_w \) = interstitial water resistivity
- \( \Phi \) = porosity of the formation
- \( S_w \) = water saturation
- \( R_t \) = true formation resistivity
- \( n \) = saturation exponent, normally taken to be equal to 2
- \( a \) = formation constant (0.62 for sands, 1.0 for compacted formations)
- \( m \) = cementation exponent (2.15 for sands, 2.0 for compacted formations)

In the above water saturation equation, the fraction including the terms \( a \), \( m \) and porosity is referred to as the formation resistivity factor (F).

Key real-time uses of MWD resistivity, beyond water saturation estimates, include estimating changes in pore pressure from changes in resistivity, due to shale compaction.

**Calibration**

Calibration of resistivity tools is traceable to national standards for resistance. A geometric constant, the “K” factor, is used for a given tool size and sensor type to convert the resistance measured by the tool to apparent resistivity. A finite element method of computer modeling, verified by empirical measurement, is then made on the response of each tool type in order to construct environmental correction charts. Some tool geometries allow direct calibration by placing fixed resistor values between the measuring electrodes of the tools, while others tools are calibrated in a large tank filled with water of known resistivity in a zero radio frequency interference environment. Details of calibration techniques are given for each sensor.

**Environmental Corrections**

The resistivity measurement can be affected by several environmental factors.
Borehole Fluid

The resistivity of the borehole fluid may range from a non-conductive oil or air, to a salt-saturated water based fluid. Different tool physics are appropriate for different fluids. Some tools require a conductive fluid (Short Normal, Focused Current) while others perform optimally in non-conductive fluids (Electromagnetic). The Baker Hughes INTEQ DPR tool performs well in all fluid types (both conductive and non-conductive media). The resistivity of the mud filtrate has an impact on tool response to invaded zones.

Hole Size and Tool Size

Some wireline tools utilize contact pads to ensure wall contact, but this is not applicable to propagation resistivity MWD technology. Hole size thus affects tool response, and hole washouts may cause anomalous responses.

Bed Thickness

Different tool configurations produce differing responses to thin beds. The ability of a tool to resolve a bed is known as its vertical resolution. In the majority of cases, vertical resolution and depth of investigation are converse relationships in tool design. One factor in the success of the 2MHz propagation MWD tools is a good depth of investigation with acceptable vertical resolution.

MWD and Wireline Resistivity Comparisons

MWD resistivity devices are used primarily for reconnaissance logging for pore pressure, hydrocarbon detection, and correlation purposes. One key difference between MWD tools and wireline tools is formation exposure time. For MWD, this is often an hour or less, where for wireline it is usually several days. The assumption is made that invasion on MWD logs is minimal, unless very high permeability are encountered. For this reason, a narrower range of tools is needed to measure $R_t$.

Short Normal Resistivity (SNR)

This MWD service is offered commercially by Baker Hughes INTEQ and Anadrill.

During the late seventies, MWD companies looked for a resistivity measurement which could be easily made using existing technology. The 16-inch short normal measurement was chosen as it was thought to have very useful applications for pore pressure evaluation in the Gulf of Mexico. Teleco and Anadrill constructed very similar sensors while EXLOG used a longer insulation sleeve to improve sensor response in saline muds. The short normal (SNR) tool has a typical operating range from 0.2 to 50
ohm-m and provides a basic resistivity measurement in water based fluids where formation resistivity is close to mud resistivity.

**Measurement Principle**

This MWD tool is very similar to the equivalent wireline tool, except that the return electrode is located on the drill collar itself, rather than a surface return electrode. The SNR tool is a series measuring device. Formation resistivity is measured by passing a constant current from the emitting electrode (A) to the return electrode (N). Please refer to Figure 3-3 on page 3-10. The voltage between the measuring electrode (M) and the return electrode or ground (N) is measured, and formation resistivity is derived from Ohm’s Law:

\[ R = \frac{k \times V}{I} \]

Where:
- \( R \) = apparent formation resistivity
- \( I \) = current between A and N electrodes (held constant)
- \( V \) = voltage measured between M and N electrodes
- \( k \) = tool geometric constant

On the SNR sensor, the A and M electrodes are spaced 16 inches apart on an insulated portion of the collar. The return electrode N is the drill collar itself. Normally, mud temperature and mud resistivity are also measured so that environmental corrections can be made.

Short Normal Resistivity applications include:
- correlation of marker beds
- identification of casing and coring points
- identification of hydrocarbon zones
- shallow gas detection
- pore pressure determination from shale resistivity
Calibration

Calibration is carried out using an “electrode harness” into which precision resistors are inserted to simulate different formation resistivities. The system response to these resistors provides the calibration curve from which formation resistivities are determined.

Service Base Calibration: A series of resistors are selected for the full range of resistivities.

Wellsite Procedures: It is not normal to perform a full calibration as described above (IS system is needed), but if required some companies can provide a wellsite calibration kit.

Short normal resistivity sensors are best suited to fresh-water muds and relatively low formation resistivities. At high $R_b/R_m$ ratios, the borehole and formation begin to act like parallel resistors, with an increasing amount of the measurement current flowing through relatively low resistivity borehole rather than the formation. This borehole effect can be corrected for automatically using software algorithms.
Focused Current Resistivity (FCR)

The laterolog technique, commonly used in wireline logging, provided the basis for improvements to short normal MWD. In 1987, Exploration Logging (EXLOG) introduced a laterolog-style MWD tool. This Focused Current Resistivity (FCR) tool added focusing current electrodes above and below the measurement electrode to force the measurement current deeper into the formation.

This type of sensor was offered by EXLOG as part of its multi-sensor MWD tool. As this type of measurement is no longer available commercially with an MWD service, it is felt there is little need to dwell on this type of sensor for too long. However, the development of this type of sensor was an important milestone in MWD, so some time will be given to an overview of this technology.

The focused current resistivity (FCR) sensor was designed to perform optimally in salt saturated muds, providing excellent thin bed resolution and improved response in formations where $R_t$ is in excess of 200 ohm-m

Measurement Principle

The FCR sensor uses the same measurement principle as the guard or laterolog tool of the wireline industry. The sensor utilizes three current emitting electrodes: two focusing and one measurement current electrode. Current is focused into the formation by forcing the voltage of both the focusing electrodes and the measurement electrode to have the same potential. A disc of investigating current perpendicular to the axis of the tool, is focused horizontally into the formation. The current from the focusing electrodes prevents the measurement current, from flowing vertically in the borehole. Like the SNR the FCR is a series measuring device. The current disc passes through the borehole fluid, then into the formation. Both output voltage and current from the measurement electrode are measured. Formation resistivity is calculated from Ohms's Law using the current and voltage of the measurement electrode. The resistivity is converted to an apparent formation resistivity using the “$K$” factor of the tool.
FCR applications include:

- quantitative $R_t$ in salt saturated muds
- quantitative $R_t$ in presence of nearby conductive beds
- improved thin bed delineation over SNR
- correlation of marker beds
- identification of casing and coring points
- identification of hydrocarbon zones
- pore pressure determination from shale resistivity
Toroidal Resistivity

Toroidal Resistivity is offered commercially by Halliburton Geodata. Anadroll/Schlumberger also use the toroidal principle in the RAB tool.

The toroidal resistivity tool is based on a proposal by JJ Arps. The tool utilizes the collar as an electrode to provide two resistivity measurements: a focused lateral resistivity measurement and a trend resistivity at the drill bit. The tool utilizes four toroidal coils covered and protected by insulating shells. A voltage applied from the drive toroid induces an alternating current in the drillstring, which is reversed in polarity about the drive toroid. Current leaving the drillstring flows through the annulus and formation and returns to the drillstring at a point where the polarity is opposite. Essentially, induction drives a current along the collar and two sets of receivers measure this current. Tool performance in lateral mode depends on the length of BHA below the receivers. As the distance from the lower toroid to the bottom of the hole increases, the bit measurement becomes less distinctive, and at lengths of 20 feet or more the bit resistivity almost ceases to respond to changes in formation resistivity (K factor is therefore BHA dependent). With oil based muds an axial bit measurement is still possible, because of the contact of the drill bit with the formation (interstitial water). However, it should be noted that axial bit measurement will not be possible with the bit off bottom.

Figure 3-5
Toroidal Resistivity
Electromagnetic Wave Propagation Resistivity

Electromagnetic Wave Propagation Resistivity is offered commercially by Baker Hughes INTEQ (DPR, RNT, MPR), Anadrill/Schlumberger (CDR, ARC5), Sperry Sun (EWR and EWR-Phase 4), and Halliburton (CWR, SCWR).

NL Industries introduced the first 2-Mhz propagation resistivity MWD tool in 1983. With one transmitter and two receivers, the EWR measurement was effected by comparing the phase difference between the two receivers. For the purposes of this document, the 2-Mhz DPR tool will be used as a benchmark in describing how propagation resistivity tools operate. The Baker Hughes INTEQ Dual Propagation Resistivity (DPR) sensor also uses a one transmitter, two receiver configuration. It has been designed for maximum reliability in the MWD drilling environment and is ideally suited for oil base and low salinity muds over a wide range of formation resistivities.

Recent developments in propagation resistivity include compensated, multi-transmitter, fully-digital electronics tools and additional, deeper reading transmission frequencies. In this regard, Baker Hughes INTEQ now offers Multiple Propagation Resistivity (MPR) and the Reservoir Navigation Tool (RNT/NaviGator service).

Measurement Principle

The Dual Propagation Resistivity (DPR) tool is a 2-Mhz electromagnetic wave propagation device that provides two resistivity measurements at different depths of investigation. The tool contains two receiving antennas which are spaced 27.5 and 34.5 inches (69.85 and 87.63 cm) from the single transmitting antenna. Additionally, a gamma ray scintillation detector is provided for lithology identification.

As the 2-Mhz radio wave travels through the formation and across the two receiving antennas, the phase difference (measured in degrees) and amplitude ratio (measured in decibels, relative to air) of the signal are measured. Resistivities are then derived using a resistivity transform.
Signal Characteristics

Although the 2-Mhz frequency of the transmitted signal remains constant as it travels through various formations, the velocity and amplitude of the signal change with resistivity. In high resistivity formations, the 2-Mhz signal has higher velocity and is less attenuated (the signal wavelength is also relatively long). As formation resistivities decrease, the signal slows...
and is increasingly attenuated (and in order to maintain constant frequency, the signal wavelength shortens).

**Phase Difference Measurement**

The DPR sensor measures these signal changes by detecting the difference in phase, or phase shift, between the two receivers which are spaced 7 inches (177 mm) apart. This receiver spacing is only a small fraction of a wavelength in high resistivity formations, resulting in small phase differences in high resistivity formations. Conversely, larger phase differences occur in low resistivity formations.

**Amplitude Ratio Measurement**

The transmitted DPR signal is dramatically attenuated (signal amplitude decreases) as it propagates through a conductive formation. The signal is attenuated very quickly in low resistivity formations, and to a lesser extent in high resistivity formations. By comparing the signal amplitude at the near and far receivers, the DPR sensor measures the attenuation that occurs between the two receivers. This attenuation or amplitude ratio measurement, like the phase difference measurement, is subsequently converted to resistivity.
DPR Signal Characteristics

Low Resistivity Media

Figure 3-7
DPR Signal Characteristics

Note high wave amplitude and shorter wavelength (lower wave velocity) which results in larger changes in attenuation and phase difference across the DPR's receiving antennas.
DPR Signal Characteristics

High Resistivity Media

Figure 3-8
DPR Signal Characteristics

By measuring both the phase difference and attenuation between the two receivers, the DPR sensor provides two resistivity measurements with different depths of investigation: a shallow phase difference and a deep attenuation measurement. The lines of constant amplitude around the transmitter are very wide, resulting in the depth of investigation of the amplitude ratio measurement being greater than the transmitter to receiver spacing, (namely 27.5”). In contrast, the lines of constant phase form a sphere radiating from the transmitter. This results in a depth of investigation approximately equal to the transmitter to receiver spacing.

Depth of investigation (DOI, expressed as a diameter) for propagation resistivity MWD measurements is strongly dependent on and positively related to formation resistivity. For the DPR phase difference measurement, depth of investigation ranges from 23 inches in low resistivity formations to over 50 inches in higher resistivities. For the amplitude ratio measurement, the DOI range is roughly 40 to 60 inches, depending on resistivity.
Applications

The DPR sensor provides accurate resistivity measurements with minimal borehole effects over a wide range of borehole conditions and formation resistivities.

DPR applications include all those associated with Short Normal Resistivity and:

- Resistivity measurements in oil and water-based muds
- Dual depth of investigation for invasion profiling
- Moveable hydrocarbon detection
- Excellent vertical resolution (6-inch bed delineation and 2-foot full resolution) for thin bed evaluation in conductive beds
- Accurate $R_t$ measurements for water saturation calculations
- Pore pressure determinations from shale resistivity

Calibration

Calibration of the DPR tool can be thought of as a three step process: temperature characterization, acquisition of base offsets, and tank measurements. To adequately compensate for the effects of downhole temperature, each sub is subjected to a thermal calibration to characterize the tool electronics under temperature. The DPR sub is placed on a non-conductive rack, whereupon raw phase difference and attenuation in air are measured as the sub is slowly heated from ambient temperature to 125 degC (250 degF). The sub is allowed to cool and the procedure is repeated. The temperature offsets from the two characterizations must be repeated within specified tolerances else the tool is sent for maintenance. Final temperature offsets are derived by averaging the phase and attenuation measurements from both characterizations.

Base offsets are obtained next by recording raw phase difference and attenuation in air and correcting to 25 degC (77 degF). To verify the calibration, tool measurements are then acquired in a special water tank of known resistivity. The temperature and base offsets are subsequently entered into the surface system computer by the field engineer and are used to correct raw measurements in real-time using the MWD temperature output. At the wellsite, a zero conductivity airhang measurement is performed before and after logging to ensure that tool drift occurring since shop calibration is within acceptable limits.
Environmental Corrections

Borehole Corrections

Before phase difference and attenuation values are transformed to resistivity, the measurements are first corrected for both hole size and mud resistivity.

Dielectric Effects

This is perhaps the most poorly understood aspect of propagation resistivity MWD services. While conductivity is the ability of a material to conduct an electric charge, dielectric permittivity is the ability to store an electrical charge. As formation composition changes, so do dielectric “constants”. Dielectric effects are often responsible for observed separations between the phase difference and attenuation resistivities. Dielectric effects tend to boost attenuation resistivities and diminish phase difference resistivities. However, given that dielectric effects are present, attenuation resistivities are affected to a greater extent.

To correct for dielectric effects, Baker Hughes INTEQ employs an empirical relationship based on a theoretical complex refractive index model (CRIM) which relates relative dielectric constant to $R_t$ for clean reservoir rock of several different porosities. The CRIM empirical relationship has been validated with field data from several different lithologies and geographic areas. It is important to note that CRIM is designed to correct for dielectric effects in reservoir rocks only. This implies that the correction is not effectively applied in shales.

Bed Thickness Correction

In thinly bedded reservoirs, resistivity measurements may be adversely affected by overlying and underlying lithologies. Bed thickness correction charts are available in the Baker Hughes INTEQ interpretation chart book. For more accurate estimations of true resistivity, the resistivity response in thin beds can be enhanced using an inversion program.

Eccentricity Correction

When the tool becomes eccentered and a large contrast exists between mud resistivity and true formation resistivity, the resistivity response may become unreliable. While it is difficult to accurately quantify the amount of eccentering, charts are available to help determine if the resistivity response may be affected by eccentering. The charts are intended for pre-well planning (e.g. BHA and mud selection) to avoid situations which may promote an eccentered tool response.

Invasion Correction

This is perhaps the most common correction applied to both wireline and MWD resistivity data. Typically with MWD, the well is logged before any
appreciable mud filtrate invasion. However, invasion corrections can be applied by using the Baker Hughes INTEQ interpretation chart book.

**MWD and Wireline DPR Comparison**

The following figure is a comparison of the DPR response to the induction tool response in a porous reservoir sand. MWD and wireline gamma rays are plotted in track 1. The phase difference and attenuation resistivities are plotted in track 2 (2-cycle logarithmic scale), and the wireline SFL, deep and medium induction are plotted in track 3 (2-cycle logarithmic scale). Note that across the two intervals the DPR log response exhibits superior vertical resolution and the induction log has been dramatically affected by invasion. The benefits to pre-invasion MWD logging are apparent.

![Figure 3-9](image_url)
Geo-steering

During the last few years, the technique of horizontal well drilling owes much of its success to advancements in drilling technology. Highly accurate directional survey sensors have made possible the drilling and production of horizontal wells. With the addition of commercial electromagnetic resistivity tools, it is now possible to navigate the well path in order to stay within the most productive zone. This is achieved by modeling the response of the electromagnetic resistivity tool, based on either offset data or pilot hole resistivity logs, which are then used for precision navigation of the drill string by comparison with real-time data.

Modeling Data

The modeling of the DPR data uses a method developed by Jian Qun Wu and refined by Hal Meyer of Baker Hughes INTEQ. This model is based on the response of a wireline induction tool which has been modified to accommodate the geometric spacing (receiver to receiver spacing is 7.5 inches, and receiver to transmitter spacing is 27.5 inches) of the DPR tool. The program can compute phase angle and attenuation resistivity for multi-layered sequences, provided a measurement of true resistivity and formation dip angle is input for interbedded formations. Normally, either offset or reference well log data is used as input for $R_t$.

A common propagation resistivity feature that is used as a navigation aid is the polarization horn, large resistivity peaks that are observed with both the phase and attenuation resistivity. These horns or peaks commonly occur at dipping bed boundaries, usually above 60 degrees, where there is a significant degree of contrast between relative $R_t$ for the adjacent beds. It is believed that polarization horns are caused by a charge build up that results from the discontinuity of the electric field across bed boundaries. This occurrence, common to 2-MHz electromagnetic resistivity devices, is caused by the operating physics of the tool and is not a measurement of formation resistivity. In practice, polarization horns can be used to detect approaching bed boundaries and, with more refinement, can even be used to navigate the well path along fluid or gas contacts.

Applications

This technique is used for precision geosteering in either high-angle or horizontal drilling applications. By making minor course corrections, and using all the information (real-time data vs. model data), it is possible to stay within zones of interest. Because each well application is unique, no fixed set of rules will apply in all cases. It is necessary to interpret data on an individual basis. Detailed modeling at the well planning stage is mandatory to properly evaluate the need for geosteering applications.
MWD Geosteering Log Example

The following model and log example illustrate an example of geosteering using the DPR log response. The first illustration shows the dipping bed model response. The projected well path enters the reservoir sand at 87 degrees, maintains 90 degrees for 500 feet (152m) and then exits the sand at 93 degrees. Bed boundary detection features in the form of polarization horns are present. Because this model follows a symmetrical well path (i.e. entry and exit across the same boundary), the bottom of the log is a mirror image of the top. Due to the model’s response, including polarization horns at bed boundaries, navigating the drilling assembly with the DPR tool should be effective.
The following log example shows the actual “real-time” DPR log for the well. MWD gamma ray is in track 1, phase difference and attenuation resistivities in track 2, and borehole inclination and well path (TVD) in track 3. As a reference, the drill bit to sensor offsets were 46 feet (14 m) for the directional measurements and 31 feet (9 m) for the DPR resistivity measurements. Note the correlation to the modeled response. The most notable bed boundary feature are the dual polarization horns at the top and bottom of the log. The separation between phase difference and attenuation resistivities is not as obvious on the real-time log as it is on the modeled response. A characteristic drop in resistivity does occur however, on the
inside of each horn. Since entry and exit occurred across the same boundary, there is symmetrical logging response. However, the dual horn at the lower part of the real-time log is compressed relative to the upper horns and the model. This is due to a steeper exit angle than that modeled. This is illustrated by the plot of borehole inclination and well path (TVD) in track 3. The well path plot also confirms entry and exit from the reservoir sand.

Figure 3-11
Phase Difference and Attenuation Resistivity Log
This reservoir sand is separated into an upper high permeability member and an underlying low permeability member. One objective of the drilling assembly was to avoid drilling into the underlying low permeability member. To do this, the drilling assembly was turned upward and inclinations greater than 90 degrees were achieved (see plot of borehole inclination). Since the assembly was building upward in a slightly downward dipping formation, the drilling assembly exited the gas sand into the overlying shale. This was recognized on the DPR log by an initial drop in resistivity which showed the drilling assembly was approaching the bed boundary. Attempts were made to drop angle (see plot of borehole inclination) but it wasn't enough for the drilling assembly to remain in the zone of interest (note the lag between borehole inclination and well path). Exit into the shale is clearly identified by the dual horns on the lower portion of the log. The premature exit from the gas sand was the combined result of a slightly higher than desired well path and the bed dip exceeding the anticipated 2°/100 feet.

NaviGator

The NaviGator reservoir navigation system integrates dual frequency propagation resistivity MWD and industry leading drilling systems technology for premium geosteering applications.

Figure 3-12
NaviGator Tool

The propagation resistivity sensor resides below the motor power section and above the adjustable kick-off (AKO) sub, only 15 feet from the bit. The NaviGator power section is the industry proven Navi-Drill Mach 1 steerable mud motor. The rig floor adjustable AKO permits the directional
driller to select build up rates for long and medium radius well applications.

In addition to propagation resistivity, the near-bit sensor array also includes dual gamma ray and inclinometer sensors. The compensated (two transmitter, two receiver) propagation resistivity sensor derives phase difference and attenuation resistivities using standard 2-MHz and unique 400 kHz transmission frequencies. The new, lower frequency extends the depth of investigation of the tool, improving early bed boundary detection capability for precise positioning of the wellbore. The four compensated quantitative resistivities allow accurate determination of $R_t$ under a variety of conditions.

Figure 3-13
NaviGator Resistivity Compensation

With an additional transmitter, the NaviGator provides compensated measurements. The above diagram shows how four raw phase (or attenuation) measurements are combined to create one compensated, borehole corrected resistivity measurement. With its two frequencies (traditional 2-MHz and new, deeper reading 400-kHz) the NaviGator
makes 16 raw measurements which are converted to 4 quantitative, 
compensated resistivities.

NaviGator service benefits and applications include:

- Available for 8-1/2” to 12-1/4” hole sizes
- Fully digital electronics measure with significantly improved 
  resolution for improved accuracy
- 400 kHz frequency offers optimal bed boundary detection for 
  geosteering
- Dual oriented gamma ray sensors
- Near-bit inclinometer measurement while rotating and sliding
- Hardwire link between resistivity sensor and modular drill collar
- Real-time and memory-stored data acquisition
- Operates in all mud types

**Multiple Propagation Resistivity (MPR)**

Baker Hughes INTEQ has set a new industry benchmark for propagation 
resistivity logging with the introduction of Multiple Propagation 
Resistivity (MPR) technology. The new MPR systems provide eight 
quantitative resistivities by combining compensated antennas (four...
transmitters and two receivers) with two operating frequencies and fully digital electronics.

Figure 3-15

MPR Data Flow

The figure above illustrates the MPR 2-MHz raw measurements and the compensation scheme that is applied to the data. The same compensation technique is also used for the NaviGator tools, the difference being that the MPR incorporates two additional short spacing transmitters (for 32 raw values and 8 compensated resistivities). Compensation allows influences on the measurement, such as the deforming effects of pressure on a receiver antenna, to be canceled out. While both the MPR and NaviGator tools use digital electronics (which leads to substantial accuracy improvements over the analog DPR technology), the MPR also uses a rugged, collar integrated antenna design which is an improvement over the circumferential antenna grooves of the DPR and NaviGator tools.

MPR service benefits and applications include:

- The 2-MHz phase difference resistivities offer fine vertical resolution for defining thin beds and fluid contacts
- The unique 400-kHz frequency investigates more deeply into the formation for better estimates of $R_t$, improved geosteering, and greater immunity to environmental and formation effects
- Fully digital electronics measure with significantly improved resolution for improved accuracy
- 4-3/4” and 6-3/4” tools available for hole sizes between 5-7/8” and 9-7/8”
- Rugged, collar integrated antennas
Formation Evaluation MWD

- Real-time and memory-stored data
- Offers eight quantitative depths of investigation
- 6-3/4” MPR is compatible with modular porosity tools

Neutron Porosity MWD Tools

Overview

Reservoir evaluation requires porosity data to quantify the volume of hydrocarbons. The Archie equation resolves water saturation from resistivity and is the basis of log analysis. A fundamental component of the Archie equation is porosity. Reservoir rock is composed of matrix and void space. Porosity can be defined as the percentage of void space in a given volume of rock which could be occupied by water, oil or gas.

For the purposes of this document, the Baker Hughes INTEQ Modular Neutron Porosity (MNP) tool will be used as the benchmark in describing how neutron porosity tools work. Other commercially available neutron porosity tools include the Anadrill/Schlumberger CDN (Compensated Density Neutron) tool, the Sperry Sun CNP (Compensated Neutron Porosity) tool, and the Halliburton CNEU (Compensated Neutron) tool.

Measurement Theory

The concept of using neutrons to investigate the earth’s formations is at least fifty years old. In order for neutrons to be useful as probes of the earth’s formation, they need to interact with the target nuclei in the matter they are traversing.

In the wireline, and more recently in the MWD industry, a chemical source which emits neutrons as it decays is used to bombard the formation with high energy neutrons. They are slowed down from energies of several million electron volts (e.g. 4.5 MeV) to a thermal energy of 0.025 eV (electron volts) through a process called elastic collision (they are scattered from the nuclei). The element which plays a dominant role in the slowing down (collision) process is hydrogen. In effect, the neutrons lose and transfer energy when they collide with another particle of equal mass or smaller, such as bound hydrogen nuclei in the form of water or hydrocarbon. The energy loss is equivalent to the amount of hydrogen present in the formation - thus it is possible to derive a hydrogen index. The hydrogen index is defined as the ratio of the density of hydrogen nuclei in the formation to the density of hydrogen nuclei in water. In this respect, it is possible to infer that porosity is a function of the number of neutrons absorbed by hydrogen present in the porous portion of the rock. It should be noted that hydrated clays will also show an elevated porosity. Neutron
tools are sensitive to the presence of hydrogen but insensitive to its mode of containment in the formation.

The following table summarizes the basic physical principle of neutron porosity measurement:

<table>
<thead>
<tr>
<th>Neutron Classification</th>
<th>Energy</th>
<th>Physical Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast (Source)</td>
<td>4.5 MeV (average)</td>
<td></td>
</tr>
<tr>
<td>Intermediate</td>
<td>100 eV to 10 KeV</td>
<td>Slowing by Elastic Collision</td>
</tr>
<tr>
<td>Slow (Epithermal)</td>
<td>0.1 to 100 eV</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>0.025 to 0.1 eV</td>
<td>Thermal Diffusion and Capture</td>
</tr>
</tbody>
</table>

**Neutron Porosity Detection and Measurement**

The Baker Hughes INTEQ MNP tool uses a five Curie Americium 241 Beryllium chemical source (equivalent wireline compensated neutron tools use 16 or 20 Curie sources) and two spaced point sidewall mounted scintillation type neutron detectors. The MNP is a modular sub, meaning it can be added or removed from the MWD tool string at the wellsite. MNP tools are available in two configurations to enable operation in differing hole sizes.
Tool diameter Fluted upsets at the detectors.
6-3/4”
8-1/4”
7-1/2”
11-1/4”

**Modular Neutron Porosity (MNP)**

- **Casing Sizes**
  - 6 3/4” and 8 1/4”
- **Hole Sizes**
  - 8 1/2” for 6 3/4”
  - 9 7/8” for 6 3/4”
  - 12 1/4” for 8 1/4”
- **Nominal Sub Length**
  - 6.4 feet
- **Max. Temperature**
  - 257 deg F
- **Memory updates**
  - Every 30 seconds for formation data

From the discussion of neutron interactions, it can be seen that a neutron porosity can be inferred from the hydrogen index of the subject formation. The difference between a near and a far detector is used to measure slow neutrons, (epithermal or thermal) those which have had interactions with the nuclei in the formation. The dual spaced or compensated neutron tools are less sensitive to environmental effects such as hole size, mud weight and mud salinity than a single thermal neutron detector. This is because these borehole parameters have a similar effect on both the near and far detectors, and thus have little effect on the near/far detector neutron count ratio. One can think of the near/far ratio as being a measurement of how quickly the number of neutrons decreases with increasing distance from the source, that is, a measurement of the neutron flux gradient. In low porosity formations, the number of neutrons will decrease gradually with increasing distance from the source, giving a low near/far ratio. In high porosity formations, the neutron population decreases rapidly with increasing distance from the source, yielding a high near/far ratio. A transform is constructed through modeling and by empirical measurement for different hole/tool size combinations and lithologies.

Traditionally, wireline tools have used helium 3 detectors. Geiger-Muller tubes are also used in some MWD and older wireline tools to detect
neutron capture gamma rays. The Baker Hughes INTEQ MNP uses an innovative method which utilizes scintillation detectors. To understand why this is advantageous, it is necessary to discuss how other detectors function.

**Geiger-Muller Detectors**

Because of the high vibration environment associated with MWD, one MWD company has employed G-M tubes to detect neutron capture gamma rays. While this eliminates problems associated with “microphonics” seen with Helium-3 detectors, it does lead to complications with environmental corrections, especially for borehole and formation salinity effects.

**Helium-3 Detectors**

These are gas-filled ionization tubes filled with Helium-3. They are fairly efficient and reliable in the wireline environment. However, in the high vibration drilling environment associated with MWD, the central anode wire in the He3 tube can vibrate and produce spurious noise pulses. Since the output signal pulse of such detectors is small, vibration induced or “microphonic” noise pulses cannot easily be distinguished from actual pulses resulting from neutron detection.

**Scintillation Detectors**

In order to avoid problems associated with Geiger-Muller and He3 detectors, Baker Hughes INTEQ has developed a neutron detector that uses a photomultiplier attached a Lithium-6 scintillator, coupled with a spectrum analyzer. Lithium-6 is a lithium isotope that has a very high capture cross section for thermal neutrons and a reasonable capture cross section for epithermal neutrons. When a neutron is captured, the resulting lithium-6 nucleus is unstable and decays to triton and an alpha particle with a combined kinetic energy of 4.78 MeV. These high energy particles ionize the glass matrix and produce light flashes or scintillations. A photomultiplier tube converts the scintillations into electrical pulses which are proportional to the energy of the scintillation. The scintillation crystal will also react to natural gamma rays. Typically, energy from neutron scintillation is large compared to energy from gamma scintillation. By using a multi-channel analyzer, it is possible to distinguish the two detection types. Spectral processing enables stripping or discrimination of unwanted gamma rays.
Environmental Considerations

Environmental corrections are modeled using Monte Carlo Neutron Photon (MCNP) computer simulation techniques. The modeling results are then experimentally verified. Thus, it is possible to make real-time corrections for:

- Matrix Effect
- Mud Weight
- Annulus Effect
- Salinity
- Temperature
- Gas Effect

Through a rigorous process of theoretical and empirical modeling, it is possible to determine how the tool responds to changes in its environment in order to correct for those environmental responses.

Calibration

Primary and secondary calibration is performed at the local MWD repair and maintenance base. This complex process subjects the tools to a number of different porosity and environmental conditions in order to derive a primary calibration factor.

Verification

A field verifier is used at the wellsite in order to confirm that the tool has held its shop calibration, both prior to and following runs in the hole.
Gas Detection with Neutron Near/Far Count Overlay

Following is a special application example of gas detection, using propagation resistivity and neutron porosity tools.

The objective in this case was to identify and differentiate a gas sand from overlying and underlying “tight” sands. A resistivity tool cannot make this distinction since both cases will show a high resistivity response. Typically, the combination of neutron porosity and formation density measurements would be used to identify the hydrocarbons. However, in this case, the density tool configuration conflicted with the bottom-hole assembly and the anticipated performance of the planned BHA.

The neutron porosity tool and a technique known as neutron near/far count overlay was used to identify the gas. Essentially, raw counts from each neutron detector (there are two, a near and a far detector) are acquired in real-time, normalized in a nearby water sand and plotted together. The curves will have a tendency to separate through a gas zone. It is important to note that this technique only works well through zones that have very clean sands. Since the neutron porosity measurement is affected by clay/shale, the technique becomes less definitive as the shale content in the sand increases.
Formation Density MWD Tools

Overview

Measuring porosity is an essential part of evaluating any formation. MWD companies provide two primary methods of determining porosity. One is the previously discussed neutron porosity tool and another is the density tool which applies gamma theory. Two methods are used because neither method is capable of directly measuring porosity. Both methods obtain inferred porosity after assumptions are made about the properties of the rock being measured and the fluid that is in the rock. Since rock matrix and fluid content affect the two tools differently, using both methods eliminates much of the guesswork which enables the log analyst to confidently use the porosity data obtained.

Of the two porosity measurements, the density tool approach involves the fewest assumptions. Only two formation properties have to be known: the matrix (rock) density and the fluid density. If these two values are known, it requires only a simple conversion to obtain a fluid filled porosity value. The density tool provides two important measurements: the formation density and the photoelectric cross section (Pe). These two measurements can be used with the neutron porosity measurement, resistivity measurements, and the natural gamma ray measurement to allow both quantitative and qualitative log analysis of fairly complex reservoirs. Thus, we have introduced the fundamental measurement parameters that are derived from a triple combo MWD measurement system.

For the purposes of this document, the Baker Hughes INTEQ Modular Density Lithology (MDL) tool will be used as the benchmark in describing how density tools work. Other commercially available services include the Anadrill CDN (Compensated Density Neutron) tool, the Sperry Sun SFD (Simultaneous Formation Density) and SLD (Stabilized Leitha Density) tools, and the Halliburton CDEN (Compensated Density) tool.

Measurement Theory

The density tool measures the formation density by using a shielded chemical source (2 Curie, Cesium 137 source, the same as most wireline density tools) that bombards the formation with gamma rays. The formation density is a function of gamma ray count rates (and energy level) measured at a near and far (short and long spaced) detector. The wireline counterpart of this tool is a pad contact device (containing the source and detectors) which is held in place by a spring-loaded, solenoid-activated caliper arm (this also provides the basic single-axis, wireline measurement of borehole diameter). It is important to minimize the thickness of mudcake between the tool and the formation in order to obtain the most accurate estimate of formation density with minimal required environmental
corrections. In order to resolve this difficulty, the Teleco MDL tool achieves “pad contact” by locating the short and long spaced MDL detectors under a full gauge stabilizer. This design approximates the pad configuration of wireline density tools.

**Gamma Ray Interaction**

As previously stated, formation density is a function of gamma ray count rates and energy level. There are two types of gamma ray interaction which are of interest: Compton scattering and the photoelectric effect. The photoelectric effect becomes the dominant process for gamma ray energies below 100 keV. The Pe is a result of the interaction of a gamma ray with an atom in formation. In this process, the incident gamma ray is absorbed and transfers its energy to a bound electron. A Pe measurement clearly distinguishes between different elements within the formation, making it possible to discriminate between sandstone (Pe=1.8), dolomite (Pe=3.1), and limestone (Pe=5.1). Thus, this is an important mechanism by which the MDL tool is made sensitive to the lithology of the formation.

Moving up the gamma ray energy scale (though the actual source-emitted gamma rays from density tools will interact first via Compton scattering until they progressively lose energy and become subject to photoelectric absorption), the dominant process becomes Compton scattering which involves interactions of gamma rays and individual electrons. It is a process by which only part of the gamma ray energy is imparted to the electron so that the gamma ray’s energy level is reduced with each interaction. This process is fundamental in understanding how the density measurement is made. This energy domain is the principle area of interest for probing the formation deeply enough to obtain a density measurement that is between several MeV to several hundred KeV. This is also called the mean free path of radiation. For typical formation densities of 2.0 and 3.0 gm/cc, the mean free path is between 4 and 20 cm. Another gamma ray interaction is pair production. Like the photoelectric process, it is one of absorption rather than scattering. But for the purposes of density measurements this process has negligible effect and thus will not be discussed in any more detail.
Modern wireline tools use Sodium Iodide (NaI) scintillation detectors. This practice has been adopted for the MWD environment and is utilized by the Teleco MDL tool. This is also the preferred detection method of Anadrill/Schlumberger, but Sperry Sun have opted for Geiger-Muller tube detectors.

The density measurement is the density the gamma rays see on the path from the shielded source to the detectors. The MDL tool design insures that, in an “in gauge” hole, the gamma rays are focused to travel only through the formation. This means that the density measured by the count rate at the detectors is the true formation density. Because the tool functions like a wireline tool, it is possible to compensate for “out of gauge” conditions by using conventional “spine and rib” type processing. A spine and rib algorithm has been computed for each hole size/tool size combination available. The spine is derived by plotting long/short spaced counts, and the rib is computed for differing mud cake densities and thicknesses. The modeling and empirical measurement necessary to obtain these so called ribs is of crucial importance to the design of the MDL tool.

By using state of the art technology, the MDL tool is able to make a full spectral measurement of data from the short and long spaced detectors. This allows for a much more thorough investigation of the gamma rays observed by the detectors than is available from more conventional
technology. In addition, a proprietary method is used for spectral autogain stabilization.

**Environmental Considerations**

Environmental corrections are the result of nearly two years modeling effort using super Cray workstations and empirical modeling techniques described above. The modeling results are then experimentally verified. Thus, it is possible to make real time corrections for Mud Weight, Mud Cake Thickness, Annulus Effect and Temperature.

In the interests of timing, it is not felt necessary to dwell on this subject other than to say that through a rigorous process of theoretical and empirical modeling, it is possible to determine how the tool responds to changes in its environment in order to correct for those environmental responses.

**Calibration**

Primary and secondary calibration is performed at the local MWD repair and maintenance base. This complex process subjects the tools to a number of materials of differing bulk densities (aluminum, magnesium, limestone, granite, etc.) and hole size/tool size combinations, as well as environmental conditions, in order to derive a primary calibration factor.

**Verification**

A field verifier is used at the wellsite in order to confirm that the tool has held its shop calibration.
**Triple Combo Applications**

<table>
<thead>
<tr>
<th>Application</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directional control</td>
<td>Thin bed/dipping bed analysis</td>
</tr>
<tr>
<td>Detailed correlation</td>
<td>Quantitative porosity analysis</td>
</tr>
<tr>
<td>Lithology identification</td>
<td>Lithology analysis</td>
</tr>
<tr>
<td>Coring point selection</td>
<td>Water saturation analysis</td>
</tr>
<tr>
<td>Hydrocarbon detection</td>
<td>Hydrocarbon type</td>
</tr>
<tr>
<td>Pore pressure analysis</td>
<td>Moveable hydrocarbon indicator</td>
</tr>
<tr>
<td>Invasion Dynamics</td>
<td>Oil/water contact recognition</td>
</tr>
<tr>
<td>Bed Boundary Proximity</td>
<td>Geosteering</td>
</tr>
</tbody>
</table>
Data Integration at the Wellsite

Our industry today is more receptive than ever to technology which lowers the cost of hydrocarbon exploration and production. A strategic focus of Baker Hughes INTEQ is to develop and manufacture products which achieve this goal. Baker Hughes INTEQ has introduced DrillByte, a service which provides an integrated information management system to meet the demands of drilling and engineering decision makers.

A totally integrated information service is an essential factor in successfully locating hydrocarbons while drilling exploration and development wells safely and economically. The provision of useful information in a timely manner requires the DrillByte system approach to data management through a central integrated database which can store all the engineering and geological information.

Prior to the drilling process, large volumes of offset well data, in many formats from different sources and vendors, can be easily entered into DrillByte for pre-well planning. During drilling, essential information must be provided at the point of need and, through the use of the Wellsite Information Transfer Specification (WITS), data from many sources can be combined.

Information output from DrillByte is in a format that can easily be interpreted so decisions can be made correctly and quickly. DrillByte uses a high-resolution graphic user interface to simplify operation of the system for local and remote users, enabling them to concentrate on interpretation and evaluation. Sophisticated but user-friendly engineering and geologic applications are provided with the DrillByte service for processing the data to enhance the evaluation process.

The use of the UNIX operating system and information transfer standards permits data communication links, in either real-time or batch mode, to be readily established between different service contractors and the DrillByte system during and after the drilling of the well. The use of UNIX and careful adherence to new computer standards will also permit the DrillByte software to be run on a wide range of hardware, with scalable performance, from a number of major vendors.

To date, EXLOG (now Baker Hughes INTEQ), has invested forty man years in the development of DrillByte. This investment will continue as new applications are developed to meet the requirements of our clients at the wellsite and in their offices.
Drilling Performance MWD

Definition

Drilling Performance MWD is instrumentation which provides information for directional control and drilling efficiency. Drilling performance MWD provides accurate inclination, azimuth, toolface, weight at bit, torque at bit, temperature, and penetration rate.

This data is used to provide:
- real-time directional control
- reduce downtime for surveys, reduce dogleg severity
- reduce risk of differential sticking
- make operation more cost effective (rig day rate)
- MWD now accepted as the definitive survey of record

Sensor Information

Historically, the factor which stimulated the growth of MWD in the 1970s was the development of accurate real-time directional survey measurements of the wellbore position. MWD tools utilize orthogonal arrays of magnetometers and accelerometers to resolve hole inclination and direction. Highly accurate depth tracking systems measure the drillstring and/or block height position and are used to calculate wellbore coordinates at any given point along the well path.

MWD tools are currently used as real-time steering tools for orienting and monitoring progress when making kick off or course correction runs with downhole motors.

Measurement Principle

Wellbore position is expressed in terms of a three dimensional coordinate system with axes aligned north/south, east/west, and vertically. The attitude of an MWD tool, in relation to the wellbore, is expressed in terms of inclination, azimuth, and toolface angles. Inclination and azimuth angles
describe the orientation of the tool's long axis which coincides with the
direction of the wellbore. The toolface angle describes the angle by which
the tool, and therefore the BHA deflection device, is rotated within the long
axis of the borehole.

**Inclination**

Inclination is the degree of deviation from a (down) vertical orientation, 0°
is vertical and 90° is horizontal. It is also possible to measure angles greater
than 90°, particularly useful in horizontal well applications.

**Azimuth**

Azimuth direction is the angle projected in a horizontal plane between the
long axis and north. For example, a hole drilled due north has an azimuth
of zero, while a hole drilled to the west will be reported as 270 degrees
azimuth. Magnetic survey tools determine azimuth with reference to
magnetic north. A declination correction must be applied if azimuth is to be
referenced to true north. An additional correction may be required in order
to properly reference grid north.

**Toolface**

In directional drilling, inclination and azimuth measurements are used to
determine the position and direction of the wellbore. When a deflection
tool with a turbine or steerable motor is used to change the direction of the
hole, it is essential to know the orientation of the tool with respect to a
fixed point. This orientation is known as “Toolface”

**Gravity Toolface (High Side)** - Hole inclination above 3 degrees

Toolface angle is generally reported with reference to the high side of the
hole. This angle is properly known as “gravity toolface.” This is the
clockwise angle through which the reference point on the tool has been
rotated from its highest point. In other words:

Toolface angle = 0° - the bent sub or steerable motor is pointing upwards,
    the hole inclination is expected to increase with
drilling, but the azimuth should remain steady.

Toolface angle = 90°- the hole azimuth should turn to the right

Toolface angle = 270°- the hole azimuth should turn to the left

Gravity toolface with respect to high side is used to enable a deflection tool
to control the build/drop angle and the azimuth on high inclination holes.

The appropriate offset for the reference mark on the deflection tool is
measured when making up the assembly and is then automatically added to
the toolface angle reported. Data is output in real-time to a drill floor
mounted directional drilling display, which shows toolface data tracked on a 0-360 degree dial, along with the latest inclination and azimuth. More advanced service displays can also output drilling parameters and graphical displays.

As with azimuth, the concept of “high side” or gravity toolface becomes meaningless when the hole is vertical. In these situations, an alternative measure of toolface is required. Magnetic survey sensors make use of “magnetic toolface” for this purpose.

**Magnetic Toolface** - Low Inclination Holes less than 3 degrees

Magnetic toolface is the clockwise angle through which the tool's reference mark has rotated from magnetic north. The magnetic toolface is used to orient the MWD tool during the initial kick off when inclination is low and hence, azimuth and high side (gravity toolface) are poorly defined. All Baker Hughes INTEQ tools automatically change from magnetic toolface to gravity toolface at hole inclinations above 3 degrees. However, this crossover point is programmable at the wellsite. Other MWD companies have similar flexibility or maintain the 3 degree crossover convention.

**Measurement Theory**

Attitude of a tool can be determined by measuring the directions of gravity and magnetic field vectors with reference to a coordinate system fixed with respect to the tool. These directions are measured by using arrays of three orthogonal accelerometers and magnetometers.

When insufficient non-magnetic collars are in use, it may be advantageous to disregard the measured longitudinal component of the magnetic field, since the spurious field caused by the proximity of magnetic BHA components is closely aligned with the axis of the drillstring. In this case, it may be best to measure only two axes and solve for the third axis (or z-axis) by using a local total magnetic field value (HTN). Baker Hughes INTEQ offers the D-RAW service for this specific application. In normal use, three-axis measurements will lead to improved accuracy, although this may be dependent in part on attitude. This also permits use of the measured field strength as a cross-check on survey accuracy.

**Measurement**

Baker Hughes INTEQ MWD directional survey packages are equipped with a single tri-axial magnetometer and three uni-axial accelerometers. In addition to the measured attitude angles, the tool can transmit measured magnetic field, magnetic dip angles, and gravity field strength as checks on survey accuracy. All Baker Hughes INTEQ directional tools can be configured to pulse raw values, so that magnetic correction algorithms can be applied to compensate for insufficient non-magnetic collar spacing. Magnetic correction algorithms are discussed in Section II.
Calibration

The primary calibration is performed in a specially constructed non-magnetic building. The calibration stand is used to orient and rotate the sensor module in each of three axes through 360°.

The calibration process is as follows:

1. Rotation around the z-axis provides x and y analysis data.
2. Rotation around the y-axis provides x and z analysis data.
3. Rotation around the x-axis provides y and z analysis data.

The data is processed to yield a set of bias, scale factor, and alignment values for the six sensors. These values from different temperatures are used to build a thermal correction model. The correction model is installed in the sensor package to produce thermally modeled results.

Primary Verification

Primary verification of directional accuracy includes many of the same steps required for calibration. This verification process accurately determines the maximum allowable error in degrees for a finite set of orientations.

By analyzing total field residual errors, it is possible to determine what residual bias scale factor and misalignment are still inherent in the actual sensors or module. The check process determines the residual total field errors, which may include different types of aberrant sensor outputs.

Precise fixturing also allows for testing of the calibrated sensor module, using accurate positioning to absolute orientations for computed inclination, azimuth, and toolface.

Secondary Verification

An operational verification is performed each time the tool passes through the local Baker Hughes INTEQ service base. The qualification consists of monitoring the measured total fields as the tool is rotated about its major axes. Uncompensated errors in the sensors show up as sinusoidal variations. Tools which fail these qualification tests are returned to the manufacturer for repair and recalibration. In addition, all tools are returned for recalibration at six-month intervals, regardless of usage. Baker Hughes INTEQ service bases have the necessary equipment and software to perform complete calibrations which will assure accurate and timely readings.
Pressure Transducer

These electromechanical devices, which convert hydraulic pressure to either a voltage or a current, are used for downhole and surface measurement of pressure. Sensor works by the Wheatstone Bridge concept: a hollow expandable cylinder or diaphragm is wound with copper wire, as the cylinder expands, so does the wire leading to increased resistance and a decrease in current.

Temperature

This is a solid state device in the downhole electronics which is calibrated to measure temperature over the range from -40 to 175 degrees Celsius.

Downhole Weight on Bit / Torque on Bit

Drilling data are particularly important in deviated and horizontal boreholes. Drilling mechanics tools, such as the Baker Hughes INTEQ Drilling Dynamics Gamma (DDG) tool, is able to measure downhole weight on bit, torque on bit, bending moment, gamma ray, temperature, pressure, and provide full directional control in real-time. The WOB, torque and bending moment are measured in the same sub which has bonded strain gauges orientated in the direction of the strain to be measured - the WOB and bending moment gauges are placed parallel to the drill collar axis, the torque gauges are positioned at 45 degree angles. Thus, it is possible to discriminate axial and torsional strain and bending moment. The other measurement parameters are housed in the upper transmitter sub. A fully modular version of this tool (Modular Drilling Dynamics - MDD) is now available.
Downhole Shock and Vibration

This Baker Hughes INTEQ service is termed VALID (Vibration ALert INDicator). The VALID assembly is a three-axis accelerometer system that is located in the Modular Tool Controller (MTC) upper pressure plug and adapter assembly. Its purpose is to monitor and report downhole shock and vibration. Through mud pulse telemetry, the driller and field service engineer will be made aware of excessive shock and vibration so that the drilling conditions can be changed before bottomhole assembly damage occurs.

Baker Hughes INTEQ, in a joint venture partnership with MELCO (Mitsubishi Heavy Industries Corporation), have developed a prototype “next generation” DDG tool. This tool is able to measure both static and dynamic downhole drilling parameters based on a wellsite, operator specified initialization program. These sensors include strain gauges, accelerometers, a magnetometer, and pressure and temperature gauges. The data is processed and compressed, then, on command, sent to a pulsing or recording tool for transmission to surface and/or downhole storage. The processing of data may be as simple as calculating a time average WOB or as demanding as performing real-time mathematical functions such as complex algorithms to obtain a optimal WOB, RPM, and SPM for maximum efficiency and ROP. Prototype tools were constructed and a successful field test and technical paper have been completed.
Applications

Directional Drilling
Both the DDG and MDD may be used in horizontal and extended reach drilling to provide near bit WOB, torque, and gamma data for direct indications of doglegs, torque and drag, casing wear, keyseating and fatigue failure.

Drilling Optimization
Both the DDG and MDD can provide information that allows the driller to improve his drilling rate. Combination of both downhole information and surface interpretation software can be used to improve overall drilling efficiency.

Avoidance of Drill Pipe Damage
Based on dynamic information, VALID can detect and alert the driller when the BHA is in a resonant condition.

Swab and Surge Measurement
Accurate pressure measurements recorded during tripping, used in conjunction with new models such as DEA 31, can be used to optimize subsequent tripping speeds.

Influx Monitoring
Annulus pressure sensors, in conjunction with other sensors, can detect influx and provide important information for subsequent well control. It should be noted that an independent gas influx sensor is presently in development. This type of device monitors the pressure wave created by the Baker Hughes INTEQ MWD positive pulse transmission system and compares the standpipe and annulus signal which are typically out of phase by 180 degrees. If attenuation of the higher odd harmonics associated with the mud pulse signal are detected in the annulus, this may be attributed to an influx of gas into the wellbore.

Research Functions
Used by itself, or with other systems such as the ADAMS or DynaByte drillstring harmonics surface measurement systems, the DDG or MDD can provide the raw data for basic research in areas such as bit hydraulics, bit whirl, recession, eccentricing and stick/slip.
-Notes-
MWD Market

MWD Marketplace

The growth in the worldwide drilling markets during the last two decades, combined with advances in technology and the need for fast, accurate, reliable data at the wellsite, has spawned the growth of Measurement While Drilling. Improvements in reliability and measurement capability during the late eighties has led to significant expansion. The growth market for MWD was in long reach directional and horizontal drilling applications. The additional benefits of FEMWD to drilling performance and efficiency was quickly recognized by operators. The integration of performance drilling systems is estimated to grow due to the needs of cost reduction through consolidation of services.

Following is a table representing total annual MWD market size in millions of US dollars. Growth rates are averaging 13 percent per year with more sizeable gains accruing following the consolidation years of 1991 through 1993.

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Internationally, the UK North Sea appears to have reached a plateau of sustained activity with little or moderate growth. In other parts of Northern Europe, most notably Norway, Denmark and Holland, activity levels continue to grow to some extent at the expense of intermediate wireline logging. This growth is also nurtured by the problematic types of wells drilled in these areas where MWD is used for “insurance logging” purposes. Furthermore, government bodies, such as the Norske Petroleum Directorate (NPD) in Norway, have deemed that in many instances the MWD log can and is used as the definitive log of a hole section (under the assumption that the log is complete, that is, no MWD failures occur).

Other growth areas such as West Africa, Latin America, the Middle East and, to some extent, the Far East have become the areas of increased interest with redeployment of MWD equipment from the Gulf of Mexico. If economic conditions are favorable, Mexico and more importantly the Gulf of Campeche may gain surprising notoriety as activity levels increase.
Venezuela promises to be an area for tremendous MWD growth in the next several years as multi-national oil companies have re-entered the market and PDVSA intend to dramatically increase the country’s production potential.

To a very limited extent, the newly formed Commonwealth of Independent States (CIS) are beginning to show flurries of activity for MWD, but this is impeded by low confidence in the market place and more importantly by guarantees of payment in hard currency. The recent social, political and economic upheaval in the CIS has led to a dramatic downturn in the oil and gas industry and subsequent oil production. After having been the world's leading oil producer in the late eighties, the industry is now in a state of dramatic decline. As a result, the Ministry of Oil and Gas and associated institutions are very keen to form joint venture alliances with Eastern and Western financial institutions and international oil companies. Confidence levels are hindering progress, but as alliances continue to grow it is felt that the former Eastern Block and CIS countries could be a real “wild card” for potential growth of MWD markets. The Peoples Republic of China is another intangible which, once again, is felt to have significant long term growth potential.

The MWD industry has recently expended significant R&D funds to small hole propagation resistivity tools (for hole sizes from 5-7/8” to 6-3/4”). Baker Hughes INTEQ, Sperry Sun, and Anadrill/Schlumberger are considered to be the dominant players in this emerging trend toward advanced FEMWD sensors for small hole applications.

The slim hole MWD market (hole sizes of 4-3/4” or less) is receiving increased attention as operators trend towards smaller and smaller hole sizes. The main applications for slim hole drilling include coiled tubing, re-entry and short radius. While the cost savings benefit of slim and small hole drilling can range from 25 to 75 percent, other collateral benefits include:

- Reduced environmental impact
- Smaller, more mobile drilling rigs
- Higher build rates to maximize lateral sections

The MWD market also has shown a significant demand for geosteering MWD tools. Geosteering is the real-time interactive steering of horizontal and high-angle wells using FEMWD data. Propagation resistivity MWD tools are particularly suited for this application, as pre-well modeled responses (using offset or pilot well data) can accurately predict actual real-time MWD log responses. Hence, well path adjustments are made on-the-fly to guide the wellbore to its optimum geological destination. The geosteering process is in stark contrast to geometrical drilling applications.
which directionally steer wells to pre-determined and potentially, sub-optimal locations.
Conclusion

The annual MWD market is fast approaching the round figure of $1 Billion US. MWD technology is showing tremendous potential to further invade an open hole wireline logging market, which is currently in excess of $1 Billion US.

Technology Will Continue to Drive the Drilling and Exploration Process.

The MWD Market Will Continue its Growth by Using Technology to Increase the Efficiency and Decrease the Cost of Drilling and Evaluating Wellbores.
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(English only, no patents)

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