Slide 1 (0:14) Introduction

This presentation is about the history of borehole surveying and we’ll use it as an opportunity to go through some of the various categories of survey tool, some of which are still used today.

Slide 2 (0.31) Texas 1896

Borehole surveying really began in Texas back in 1896, when two ranchers were drilling very close to their boundary fence. It’s very difficult to drill a perfectly vertical well, and although they both thought they were drilling a vertical well, once they started producing – when the chap on the left was pumping the chap on the right was losing pressure and vice versa. So they both thought they had drilled under the fence and were stealing each other’s oil.

Slide 3 (0:35) Survey the wells

So as you might imagine, in Texas in 1896, this was resolved in the usual way and all the charge hands from both the wells were involved in the fight and the Sherriff was called and he didn’t know what to do. So it actually ended up in court. And in the court the judge said ‘You’ll have to survey these wells’. And the question then of course was ‘How on earth do you survey an oil well?’ And the world’s first survey tool for downhole oil well was born – it was a jam jar!

Slide 4 (0:59) First survey tool

No ordinary jam jar! The jar had a cover laid over the top of it and rings were marked on the cover, a small frame was then set above the cover with a spike mounted in the frame. The surveyor would then lower it down to a certain depth in the well, would then pull a little slipknot and the spike would drop into the jam jar. If the well was truly vertical, you would expect that when you recover it to surface, the hole in the cover would be right in the centre. If it wasn’t truly vertical, the jam jar was inclined, then the spike would make a hole somewhere else. And if it was very badly inclined, the spike may not [even] be in the jam jar. And so we started to survey oil wells.

In this case both wells deviated quite badly but of course they didn’t know in which direction.

Slide 5.1 (1:05) 1920s

In the 1920s a man called John Eastman decided to improve on the jam jar. He said, why don’t we take a glass bottle and we’ll mount in the bottle a copper plate with squares marked on the plate (very carefully engraved). And the copper plate was suspended in a mild acid. When that was lowered down the oil well it meant that the acid would stay horizontal regardless of the inclination of the bottle and when it was left there for a couple of minutes the acid would burn a green line where it was in contact with the copper but when you brought it to surface you could then use a protractor to fairly accurately measure off, to a degree or two, what the inclination of the wellbore was at that depth.

This was very successful and John Eastman started a company then which eventually became Eastman Christianson and is now Baker-Hughes, one of the major directional drilling companies in the world.

Slide 5.2 (1:33) 1930s

His competition was Elmer Sperry and he wanted to be a little more scientific. He wanted to include direction as well as inclination. And so he devised a system where a little camera could be lowered down the hole to look at a magnetic compass, and then you would see the direction of the well but superimposed on top of that was a little plumb-bob mounted over a series of rings, not unlike the ones on the cover of the jam jar, and you could see which way the plumb-bob was pointing as well. And so by developing the film at surface you could now get a measure of the inclination and the direction of the well.

Now if you were operating underneath the rig and there was a lot of steelwork underneath the rig, then the magnetic compasses wouldn’t be very accurate and so he devised a little gimbal-mounted gyroscope which you could point at north, switch on a little electric motor and it would work up to speed. And then as you ran down the well bore it would continue to point at north and give you a reference from north downhole.

And that was called the Surwell free-gyro or photomechanical mechanical and gyro survey tool, which is a really snappy title, and Elmer Sperry then partnered up with Sun Oil and formed the company Sperry-Sun, which is now part of the Halliburton Group and again a major directional drilling operation.

Slide 5.3 (0:29) 1960s

The 1960s saw the first accelerometers and magnetometers being used downhole and the only thing that’s moving in these is electricity. So they could be potted and made extremely robust. In the drilling environment it’s not uncommon to see several hundred g’s of shock, so these can be designed in such a way that they could continue to use them operationally while the drilling was going on.

Slide 5.4 (0:54) 1970s

The 1970s so the first surface-reading gyros. That’s quite an achievement; that’s a gyroscope operating at the end of a very long cable and of course the voltage drop and the attenuation on the signal coming back the other way was a major thing to overcome but successful SRGs were introduced in the 1970s and we now had a tool that we could read directly from surface.

Now, the slide [illustration] say MWD also in the 1970s. I would say that most of the research was done in the 1970s but it wasn’t common to see an MWD survey before 1980. MWD is measurement while drilling and that’s magnetic compasses or magnetometers anyway mounted inside the drilling assembly with a mud-pulse telemetry system sending the information to surface.

Slide 5.5 (0:50) 1980s

In the 1980s we saw the first Rate Gyros, and I’ll say more about these later on, but as the name suggests a rate gyro measures the rate of change of azimuth. We can run these continuously down a well bore because as we run them down the inside of the drill pipe, or run them inside casing, they measure the rate of change of azimuth against time. So, if we integrate that with time, we get an azimuth survey. And the length of the cable it’s being run on is then the measured depth. So, we get azimuth, from the rate gyro, we get inclination from normal inclinometers inside the gyro (similar to the ones in MWD), and we get the measured depth from the length of the cable.

Slide 5.6 (1:14) 1990s

Then the 1990s saw electronic memory and drop gyros. A rate gyro, when you hold it still, still thinks it’s turning because the earth is turning - and from the forces it experiences when it’s stationery it can work out the direction to the polar axis. So it’s capable of creating its own reference by finding north by itself when it’s stationery and then running in continuous mode thereafter. Electronic memory and drop gyros are gyros that operate in a similar principle, usually the north-seeking principle, but they are made quite rigged so that they can be dropped down the inside of a drill pipe. They are programmed to take a reading, let’s say every 60 seconds, and then while you’re tripping drill pipe out of the hole you can take your readings backwards as you come out of the hole. When that’s recovered to surface you then have readings of inclination and direction against time. You tally that up with the pipe tally, which tells you how much measured depth you had in the wellbore at any given time. So these don’t take up any significant critical path time during the drilling operation as you are tripping anyway.

Slide 5.7 (0:05) 2000s

And then the 2000s has seen some fairly major breakthroughs. We’ll come back to that later on.

Slide 6 (1:37) Extinguishing a blowing-out well

This is an interesting picture. This is a picture of a blowing out well back in 1935. A relief well was drilled from the rig seen in the foreground here and it says it was completed on the 25th of July 1935 by H John Eastman and William G Ames. Now, in order for them to hit that other well from a distance like that you would need a pretty accurate survey tool.

They didn’t actually aim straight at the bowing out well. What they would do back then is they would drill deliberately to the left of the blowing out well at a depth where the kill mud in the relief well would more than balance the pressure of the blowing out well. By drilling to the left of it they would then trip out of hole and run in with very heavy drill collars, deliberately. And now as you ream back and forwards the heavy drill collars are resting on the low side of the hole – you get much more friction on the low side than you do on the high side and they effectively want to roll to the right. And so by reaming back and forwards you are essentially sawing through the earth and eventually you are going to hit the blowing out well and with the heavy kill mud in the hole it will rush in the hole an put out the oil field fire. Of course you’ve got to be pretty confident that you start to the left, otherwise you’ll saw forever and never kill the other well.

Slide 7 (2:20) Key points in surveying history (1950 onwards)

Here’s a slide that shows some of the key points in surveying history: free gyros introduced back in the 1950s (actually we’ve had free gyros really since the time of Elmer Sperry back in the 1930s but practical, reasonably accurate free gyros were introduced before we even had directional drilling). And then in 1962, the introduction of the positive displacement motor with a bent sub – that was the beginning of directional drilling. Prior to that all we could do was make the wellbore rise and fall but we couldn’t control the azimuth of it. Whereas with a PDM and a bent sub now we can control the direction of the well as well. Wireline steering tools came in the 1970s, MWD towards the end of the 1970s, and that’s quite important because sometimes we look at old databases and we see surveys in there that have Default tool: MWD, well, actually if it’s prior to 1980 MWD hadn’t been invented yet. So it was probably an old film red compass, not nearly as accurate as a modern MWD system. North seeking gyros, in the early 1980s; steerable motors coming in with bent housings in the mid-1980s, big step forward there. And of course rotary steerable systems coming in in the mid-1990s. I remember seeing the first proto-type of the first rotary steerable system and thinking, that’ll never work, it’ll never catch on and now we’re using them every day of course. And then in 2002 the introduction of the first gyro while drilling tool: a ruggedized gyro designed to provide the same measurements as you get from an MWD system but without the concerns of magnetic interference or lack of knowledge of the earth’s magnetic field and a great tool if you’re drilling close to another well because of course the gyro doesn’t care about the magnetic interference from other wells. We now have gyro while drilling capable of going up to horizontal and still give reasonably high accuracy.

Slide 8 - Mid well (1:39) Survey applications: Mid-well

Mid-well 90% of the time we’re steering the well down through the various geological layers trying to get down to our final target and we’ll just use MWD. However, if there’s a collision avoidance issue and we need to be higher accuracy mid-well then we would normally use an in-field referencing survey which would provide us with a more accurate assessment of the earth’s magnetic vector, locally, and from that we end up with MWD that’s roughly twice as good as it would be otherwise. It’s sometimes referred to as enhanced MWD.

For MWD quality control we would use a magnetic multi-shot tool. And a magnetic multi-shot tool is exactly the same instrument as goes into an MWD system but it’s in a very slim drop tool that looks a little bit like a javelin. We drop it down the inside of the drill pipe; it continues down under its own weight, or is pumped down, into a non-magnetic collar that sits at the top of the bottomhole assembly and within that non-magnetic collar it takes its readings, let’s say every 60 seconds, and while you’re tripping out of hole the magnetic multi-shot tool will be taking your observations and recording them against time – a little like drop gyros. However, if we need to reduce uncertainty before we arrive at the target, nothing beats the gyro. If need to drop down the uncertainty, the envelope around the well path then a gyro is always going to be the best solution.

Slide 8 – top-hole (0:51) Survey applications – Top Hole

Survey applications – their priorities change during the development of the well bore. And at the start of the well the key priority is not to collide with any other wells. This involves surveying the conductors themselves, and because they are steel the only things we can do is measure them with a gyroscope. So if we have driven conductors or even pre-drilled and laid conductors, we’ll use a gyro inside the conductor to give us a more accurate position for the so-called vertical part of the well.

If it’s a clear kick-off, and by that I mean that there’s no magnetic interference from other wells or other casings around us then we would just use MWD. If it’s a tight kick-off and there is magnetic interference we would use GWD (gyro while drilling).

Slide 8 – Total depth (0:29) Survey applications – Total depth

As we approach total depth then we’re getting towards the reservoir itself. If it’s an easy target most of our wells will still be drilled with MWD; if it’s a tough target or close drilling (and by that I mean close drilling to a boundary, to a geological fault, or even another well or an appraisal well) then we would want a bit of extra accuracy in there and so we might finish the well using an MWD plus an in-field referencing survey as well.

Slide 9 (0:52) Photomechanical multi-shot

This is a picture of an old photo-mechanical multi-shot tool. Some of these had a flat disk with rings marked on the disk and a plumb-bob; some of them looked like a mushroom and they floated on oil and the camera just saw rings on the head of the mushroom as the mushroom stayed upright and the camera tilted over.

They also had a magnet in the head of the mushroom and so in the picture on the right you can see the inclination is where the centre point of the circle is – count the rings out to measure the inclination - and the direction is given from the meridian lines on the disk. The film is developed at surface. You took your readings downhole but you didn’t know what your results were until you were back to surface.

Slide 10 (1:20) Magnetic drop tool

This is a magnetic drop tool, like the one I described earlier. The longitudinal springs are there to take the shock as the drop tool impacts a little ‘o’ ring or ‘crow’s foot’ set in the bottomhole assembly to receive it. The lateral springs (spring centralisers) are really just there to keep it parallel to the non-magnetic collar. So the [idea] of the non-magnetic collar may only be three inches but the tool is maybe only an inch and a half, so we need to keep it parallel.

You’ll notice in the picture that there are two EMS (electronic multi-shot) probes, a lower and an upper one. Both are identical and so you would expect that if you were in a magnetically clean environment that you would get identical readings from the two EMS probes. If there’s a difference between the readings downhole then clearly you’re sitting in some kind of magnetic gradient and you would have to decide whether or not the disagreement between them was enough for you to fail that survey or was sufficient enough that it would pass quality control checks.

Slide 11 (0:08) EMS tool

This is just a picture of the guys getting an EMS tool ready and you can they’re very very slim in diameter.

Slide 12 (1:37) Compass vs Magnetometer

A compass, as opposed to a magnetometer, has moving parts and is a delicate instrument so we can only use it to take measurements after the event. A magnetometer on the other hand, the only thing that’s moving is electricity so we can make it very robust and measure while we’re drilling.

The cartoon on the right there is just to demonstrate the principle of how a magnetometer works. Essentially, there’s a solid metal core, and when you pass current through a coil (that’s wrapped around the metal core) you can magnetise the core. If you pass the current in the opposite direction, you can magnetise the core with the opposite magnetic polarity. However, what you fin is that when you pass a current in one direction it will take more current than it does in the other direction to fully magnetise the core. And that’s because you’re magnetising the core against the earth’s magnetic field as opposed to going with the earth’s magnetic field. So the difference in current that’s required to magnetise the core is a direct measurement of the earth’s magnetic field component along the axis of that magnetometer.

In order for us to measure the earth’s magnetic field, which is a three-dimensional vector, we actually need three magnetometers mounted at right angles to each other. And with three magnetometers mounted orthogonally like that no matter what the orientation of the three magnetometers we can always work out which way’s north.

Slide 13 (0:17) Accelerometers

Accelerometers are little weighing machines that measure the earth’s gravitational field. If you them vertically they’ll measure 1G; horizontally, nothing at all, and if you hold them at any other angle you’ll measure 1G x *cos* that angle

Slide 14 (2:06) Modern magnetic sensors

Today our gravity and magnetic sensors have become very sophisticated and, incidentally, very small but incredibly accurate. Here’s a modern day accelerometer – and this particular one would be a quartz-hinged accelerometer. The components are really very simple in principle. There’s a permanent magnet with a proof-weight system suspended between the permanent magnets with an electromagnet wrapped around the proof weight. That’s mounted on a cantilever which has a hinge at one end and has little exciter pick-offs at the other end. And should it deflect downwards at all the pick-offs detect that and pump more current through to keep the proof weight central. So it’s an immediate feedback.

The orientation you see in the picture there – it would measure 1G. If we were to turn it on its side, the cantilever would just be a pendulum and there would be no side force on it at all. It would measure zero.

The reason we use quartz for the hinge… it’s quite interesting. If we use another material like steel then over time it would deteriorate in accuracy. It would just become weaker. Whereas quartz remains at its full strength and the day it first gets a fracture and then just dies. And from our point of view that’s actually better. We’d rather have one that’s working perfectly or silent and not something that deteriorates over time.

For the magnetometers, very often use two cores but we wind them in opposite directions so we can measure the difference in current that it takes to magnetise them. So the cores are identical but it’s still the same principle, we’re measuring the strength of the earth’s magnetic field along the axis of the magnetometer.

Slide 15 (0:43) North reference

Gyroscopic effects – these are much more interesting. When we mount a gyro in a gimbal (a sort of double-hinge that allows it to rotate any way it wants) and spin the gyro up there’s a large centrifugal force acting on all the mass in the rim of the gyro and it really does not want to change its orientation. And so, if we point a gyro at north, switch it on, bring it up to speed, then it will maintain that north reference, and mounted in a gimbal, attached to the housing of the rest of the instrument, it then means we’re carrying a north reference with us own the hole.

Slide 16 (0:23) A gimbal

This is a gimbal. So if we spun the wheel up to high speed – and in practice we use speed in downhole instruments of hundreds of revs per second (not per minute) - no matter what we do with that gimbal on the outside the little wheel itself will stay in the same plane of orientation.

Slide 17 (2:04) Conventional gyro

This is a conventional gyro. This one looks like a Humphrey gyro. It has a little Vernier scale on the front and a film is used – again, to take a picture of the orientation of the central gyro against the outside housing. The important thing with conventional gyros is they don’t know where north is – you have to tell it where north is. One of the ways of doing that is to have a gun scope and it’s mounted on the tool and you can then line up on a reference point whose direction you know; or today you could send someone to the horizon on the same longitude as you on a GPS and now you know that he’s true north of you. You can line up on that and then switch the gyro on and you’ve got your reference angle, from which it won’t deviate.

Now there is an experience that people have in using conventional gyros – they tend to drift with time and part of that drift is just mass imbalance in the instrument itself but part of the drift is because the gyro is set at a particular orientation when it’s first switched on which it wants to maintain but of course the earth is turning and so the direction to north is changing over the course of the day and this makes the gyro look as though it’s drifting of the order of 15 degrees per hour at the equator. Well, that’s not a serious problem though in that we can run the gyro down the wellbore, stop every now and again, take observations for maybe two or three minutes, measure that drift rate over time, correct for the drift afterwards so we can measure all the way into the wellbore and all the way out again and make sure there our in-run survey and our out-run survey are both drift-corrected and end up lying on top of each other.

Slide 18 (2:11) Gyroscopic effects

Gyroscopic effects. This is an interesting gyroscopic effect – a gyro forced to torque around its x axis, when spinning around the y axis, will start to rotate around the z axis. That’s a very confusing sentence but a good illustration of this would be if you held a bicycle wheel in your hand and someone spun the wheel up really fast you would find it’s very easy to move forwards or to move backwards but as soon as you try to torque – in other words if you try to change direction – you’re effectively applying a torque around the z axis [and] it will presses around the y axis and it would be almost impossible to keep the bicycle wheel vertical. If you turn to the right, it will tilt in your hand to the left, and if you turn to the left it will tilt in your hand to the right.

That effect is known as gyroscopic precession and we can actually use that measure the rate of change of orientation against time. You can imagine a tiny little bicycle wheel and you’re holding it in your hand and as walk along and it’s spinning very fast, every time you change direction, the fast you change direction, the greater the force is on your hand. If we measured these vertical forces against time what we’ve actually measured is the rate of change of azimuth against time. So if we integrate that with time we actually end up with an azimuth survey. That’s how a continuous gyro survey works it integrates the rate of azimuth change against time to measure its current direction. Now these same tools, if you hold them still, the earth is still forcing them to turn and the forces it experiences can be resolved into a gravitational force and the earth’s turn rate, creating another force. So we can work out the direction to the polar axis. A rate gyro is also a north-seeking gyro capable of finding its own reference when you hold it still for maybe a couple of minutes or something like that.

Slide 19 (0:18) Video

If the gyro is spinning around the y axis (the red axis), and if a torque is applied to the x axis (green axis), then it will slowly rotate around the z axis. And we’ve got a very interesting video to demonstrate that.

Slide 20 (1:55) Continuous gyro

Here’s an example of a continuous gyro and if we zoom in on that we’ll see, here’s the drive motor back here and the gyro itself is this small disk at the front of the gyro. When I initially described the precession forces I talked about a vertical gyro that we were turning horizontally – in practice it makes sense for us to have the gyro spinning around the axis of the wellbore and then we’re measuring our rate of change of azimuth and we’re measuring our rate of change of inclination by putting pickoffs on the above and below side and on the left and right side. That acts as an extra QC on the movement of the gyro in that we can measure the change in inclination created by integrating these forces during a whole section in both axes and we’ll get an azimuth change and an inclination change. We can then compare the inclination change with what the inclinometers are saying and that’s a good QC check that the gyro is functioning correctly. Now with a gyro like this, if we hold it still, as long as we’re not horizontal, we can determine the earth’s horizontal rate of rotation and we can determine gravitational forces. And the resolution of these will tell us where true north is.

Unfortunately, if we get the gyro up to horizontal the horizontal component of the earth’s rate is also at 90° to the gravitational force and we can no longer resolve the two. So we can’t north-seek when we’re horizontal, we have to have some inclination in the wellbore to do that.

Slide 21 (1:08) North-seeking gyros

So in summary, a north-seeking gyro is simply a highly-sensitive rate gyro which measures the earth’s rotation and senses direction to the polar axis. This usually takes about one to two minutes stationary sensing so is often only used in top-hole, up to about 15° of inclination after which the survey is run in continuous mode. Now we should also point out that as we approach the North Pole or the South Pole the gyro is becoming less and less accurate because the horizontal component of the earth’s rotation is getting less and less. When we’re at the equator, the earth rotates at about just over 15° per hour, and when we get up to the North Pole that rate (the horizontal component of rotation) is zero. So at any latitude the actual rate of rotation that the gyro experiences is equal to 15° x the *cosine* of the latitude. So, of course, less and less sensitive as we get to higher latitudes.

Slide 22 (1:54) Gyroscopic tools

Here are some different ways of running a gyro. In all of these examples, the gyro is exactly the same tool (happens to be a Scientific Drilling keeper gyro in this case). In the one on the left we’ve got spring-loaded centrollers for operating in very large casing sizes or conductors. They just make sure that the gyro is absolutely parallel to the casing. In smaller casing sizes (20”, 18 5/8”) we’ll put a spring opposite the rollers to push the whole unit against one side of the casing and then it’ll run parallel to the centre line but it will actually run touching one side of the casing. In smaller hole sizes again the spring would just be opposite the rollers and in high-angle or running inside drill pipe we’ll just have rollers so we minimise the friction.

Now of course one of the limitations of running a gyroscope in-casing is that it’s gravity that’s taking it down the wellbore. There’s a cable running behind it so if we get up to 55 or 60° of inclination gravity will continue to pull that cable down the hole but when we get to that sort of angle the friction starts to build up on the low side of the hole and it’s very difficult to run a gyro beyond about 60° of inclination in casing. In drill pipe we don’t really have that problem because when we run down the inside of the drill pipe we can encourage the gyro down the well by turning on the pumps and pumping drilling fluid down behind it which meets the obstruction of the gyro and helps to pull the cable out. Then we can put the pumps off and recover the gyro back and we get a good in-run and out-run survey inside drill pipe and of course with that we can go all the way up to horizontal or even higher.

Slide 23 (4:46) Inertial survey tools

This is an Inertial Gyro. It’s most easily explained by looking at the cartoon on the left hand side. If you can imagine the grey platform is absolutely level and pointing at north and mounted on that platform are three gyros (N, E and vertical). The gyros are not there to measure anything they’re really just there to stabilise the platform inside that gimbal. Now no matter what you do with the outside housing the platform will stay orientated on north and absolutely flat and level. Mounted on the same platform are three accelerometers (N, E and vertical). With this unit, as you move it around, the accelerometers are accumulating acceleration with time to get velocity – and if you accumulate velocity with time you actually get distance and so you can type in your position as an x, y, z position, and then move this unit around and it simply tells you where you’ve moved to in x, y and z, where x is East, Y is North and z vertical.

It was originally developed as a navigation system for stealth aircraft like the Tornado and the Phantom jet, which were capable of flying at supersonic speeds and so the enemy wouldn’t her you coming – you would arrive before they heard you. Similarly, they didn’t want a navigation system that gave out any radio signals to potentially give away its position to the enemy. With this unit you could type in your latitude and longitude, your easting and northing position on the map and your altitude and then as you started up the engines and head down the runway, bank away as you take off – that platform remains pointing at north and accumulates your x, y position and your altitude for you to a wonderful degree of accuracy. It used to accumulate about 6” of error for every 1000’ that it travelled.

The actual unit can be seen on the right hand side there and you can see it’s quite a sizeable unit. It wouldn’t be able to go down the inside of a drill pipe but when this tool was available (it’s no longer available now) we used to run it inside a collar in 10.5” OD collar, right down to the bottom of the 30 3/8’s casing. And it gave us wonderful accuracy in the top-hole part of the well on busy platforms like the ones in the North Sea. That was a huge advantage because we’re very close to other wells there and we need high accuracy to avoid collision risk in top-hole. If we get too close to another well, such that the uncertainty envelopes have a danger of overlapping then we have to shut down and depressurise production on the other well while we drill past it. And of course at 5000 barrels a day at a $100 a barrel that can cost us about $0.5 million for a 24 hour shutdown just on one well. So this was a huge advantage at the time – very expensive, difficult to maintain, only 12 of them were made and Shell, BP, StatOil and Total used them in the North Sea but they soon wore out and we didn’t have them anymore.

So why am I telling you about them? Well, primarily because this technology will come back in, in a different form, ring lasers more than likely in the future as we require higher and higher accuracy again but also while we did have these nine test wells were drilled in Norway at what was then Rogaland Research in Stavanger and is now called Iris (International Research Institute of Stavanger). These test wells are all different shapes but they’ve all been very accurately measured using the Ferranti Inertial Navigation Deviation Surveyor. So we know these trajectories very accurately, so any new survey tool can be sent to Stavanger and run up and down the test bores and a scatter plot of their errors produced to calibrate the tools.

So although this tool is no longer available we have inherited its accuracy for its successors which have been run up and down these test wells in Stavanger.

Slide 24 (2:58) Ring laser inertial gyro surveyor

This is a ring laser inertial gyro – very high accuracy, very expensive but theoretically a simple principle (but very difficult to manufacture). A ring of mirrors is set up in a glass housing and a laser beam is passed clockwise and anti-clockwise round the ring of mirrors at the same time. And as long as the gyro is not rotating around its axis there will be constructive interference between the two laser beams when they arrive back at the start. If there is the slightest amount of rotation then one of the laser beams is chasing mirrors that are running away from it while the other one’s running into mirrors that are running towards it – so one signal path is longer than the other. Very very slightly of course but it’s enough to see a slight phase difference on the incoming light beam. And from that phase difference we can work out the rate of orientation to incredible degrees of accuracy and over a very very wide range.

Most of these ring laser gyros will measure their rate of rotation anything from 1000° a second to 1° in 1000 seconds which makes them extremely flexible in their applications.

Ring laser gyros need to have three separate gyros to be able to work out their rotation around any of their three axes. And they also need accelerometers in there as well. But again, held stationary they can measure the earth’s rate of rotation and they can work out where north is by themselves, and when they’re moving they can be used in an inertial mode.

The tool you see in the bottom part of the picture is Baker-Hughes’ answer to high accuracy surveying, it’s called the RIGS tool (ring laser inertial gyro surveyor) and it’s a 5 ¼” outside diameter tool. It has some limitations in that the ring lasers themselves can only go up to 70°C which is not particularly hot for oil wells. So there’s a temperature limitation on it. It’s also 5 ¼” in diameter, which makes it difficult to run in anything other than the larger casing sizes but nevertheless this is a tool that provided us with accuracy of about 1.5 feet per 1000 and currently would be considered the most accurate survey tool we have available. Unfortunately, because the market was asking Baker-Hughes to provide this accuracy, and then Baker spent a lot of money developing it (and folks didn’t want to pay the difference), as far as I know this tool is moth-balled for the time being but it’s time we went back to Baker and persuaded them to re-launch it.

Slide 25 (0:56) Measurement while drilling (MWD)

MWD is the equipment that we use probably 90% of the time offshore or in the land oilfields. MWD allows the driller to steer the bottomhole assembly to follow a planned trajectory. The instruments in the bottomhole assembly tell him direction, inclination and toolface (direction is your angle from north, inclination your angle from vertical but toolface is the roll angle of the equipment and that’s what they use for steering the well. The instruments are powered by batteries or a mud turbine, most frequently by battery these days, and the data is converted to binary and transmitted up-hole by shutting and opening a mud vale. The pressure shocks represent ones and zeros and are measured at surface for conversion to data, so there are no cables running down there.

Slide 26 (2:00) MWD tools cont.

Here’s another MWD tool, where it’s a slightly different arrangement for getting the data to surface. Instead of having a poppet valve that creates a constraint in the fluid flow this one opens small holes out to the annulus that allows the pressure to drop for a one and recover to normal for zero. With this MWD unit it’s a negative pulse instead of positive pulse telemetry system. Either way, the data comes up to surface as thee angles (north, vertical and roll angle). In this case we’re looking at a display on the right hand side there that says our roll angle or toolface (GTF = gravity toolface) is 48° to the right of high-side. So if this was connected to a mud motor with a bent housing and the bent housing was aimed at 48° to the right of high-side the directional driller is building angle and turning right at the same time.

Just be a little bit careful with the measurement specifications on tools like this. The accuracies that are quoted on azimuth, inclination and toolface are the accuracies of the instrumentation not the accuracies of the entire system. So if course if the MWD is sitting within a bottomhole assembly that’s a very floppy assembly, poorly supported and stabilised and centralised, then accuracy will be a lot poorer than just 0.5°. Similarly, if we are operating in an environment where we don’t know the earth’s magnetic field very accurately, then we inherit the inaccuracies of the magnetic declination. The declination is only known to an accuracy of a degree, then there’s no way that the MWD can deliver any better than that, even though the instrumentation might be half of that in terms of its uncertainty.

Slide 27 (1:02) MWD tools cont.

Here’s MWD itself and the first thing you should notice about MWD is that it should be shiny. If it’s not shiny then it’s not good quality non-magnetic stainless steel and of course to MWD sensors are magnetic sensors so they have to be well protected from the steelwork ahead and behind in the rest of the drill string. So we always have to make sure that there’s enough non-magnetic spacing between us and normal mild steelwork to ensure that the influence on the azimuth is within acceptable limits.

On the left here you can see the poppet valve and the little brown ring there is the tungsten carbide bottleneck where the fluid flow rushes through there. If it wasn’t Tungsten carbide it would wear out the steel in hours but the Tungsten carbide lasts a lot longer than that and it can be unscrewed, replaced and thrown away. And the pulser just pushes that javelin up into the constraint and creates a pressure pulse up to surface.

Slide 28 (2:21) The future

There’s a few developments that are either happening now or will be very shortly: a gyroscopic MWD going all the way up to 90° is perfectly possible now. And with high-speed rotary steerable systems we’ve got the best of both worlds: we’ve got high accuracy MWD with a rotary steerable system being able to drill probably twice or three times the penetration rate of a sliding mud motor system.

We’ve also got electro-magnetic high speed data telemetry now. That can either be boosted at various points up the drill string or in horizontal wells it can be radio pulsed to surface and then a repeater station on the surface sends it back to the rig.

A few options have been looked at for using lasers, possibly with a strain gauge, for doing drill pipe depth. The strain gauge would tell you when the top drive was loaded and when it was unloaded and the laser would measure the movement of the travelling block. When the block is moving up and down that laser would measure the distance and accumulate that, to give us a digital measured depth.

Another option that’s been looked at is running fibre-optic in the wireline so that if we then fire a laser down the fibre-optic we can get a very accurate measured depth from the wireline. That’s actually how lasers are calibrated – a certain known length of fibre-optic is measured out I a car park or something and a laser beam is fired down the fibre-optic so we can use it to calibrate lasers, and we can use lasers to calibrate the fibre-optics.

A lot of work has gone into looking at inertial measurement while tripping, where we could have ring laser gyros that would give us discreet north-seeking measurements as MWD when we’re on our way into the hole but then these same instruments could be used in inertial mode when we’re tripping out of the hole and give us a 3D trajectory all the way back to surface filling in all the gaps between the discreet surveys that we took at every connection – and that’s something to look out for in the near future.

Slide 29 (0:24) The technical challenges

This is an interesting one. Shell and BP were looking a few years ago for TVD accuracy better than 1 foot per 1000; they would like it to be a gyro survey with no rig time cost; capable of withstanding 400G of shock so the gyro didn’t have to be removed during the drilling operation; and they didn’t want to pay for it!

Slide 30 (0:52) The military challenge

A similar challenge was set to British Aerospace working for the military in the UK for operation Desert Storm. They wanted a system that would work in a variety of different military applications from aircraft to heavy artillery. They needed high accuracy inertial positioning, a wide velocity range, they didn’t want to pay for it either and they needed it to withstand up to 400G of shock. Now the reason they need 400G of shock is because they need gyros that will sit on the gun barrels of heavy artillery and they don’t want to take the time to remove the gyro before they move the gun to shoot the same target from a different location so that if the enemy calculates the incoming trajectory and fires back at the origin, they’ve moved before they’ve taken their second shot. So we need a gyro that will stay on the gun.

Slide 31 (0:20) LINAPS

This is it. It’s developed by British Aerospace in Edinburgh, it’s called LINAPS (laser inertial artillery pointing system). It’s three ring laser gyros mounted in a 6.5” cube that sits inside a very robust outer housing and the whole thing is mounted onto the gun barrel.

Slide 32 (0:12) A shockproof solution

Here’s the gyro sitting on the gun barrel and in the picture on the right you can see where the stops are, where the recoil comes back after firing a 120mm shell – so you can imagine the shock that goes through the gyro.

Slide 33 (0:13) 400G

It’s very hard to imagine what 400G actually feels like but that gyro continues to operate during that shock and then inertially positions the gun to its next firing position.

Slide 34 (1:02) Ring laser gyro (RLG)

Here’s the ring laser gyro. This is a remarkable piece of equipment made here in Scotland. There are three mirrors on the gyro. I asked if the signal path would change if the gyro was warmed up and they said no because we put a crystal behind the mirrors of exactly the right thermal co-efficient of expansion to push the mirrors towards each other so that the distance around the mirrors stays the same regardless of the temperature. They actually polish the mirrors to one molecule in an electro-microscope and then polish the glass to one molecule, put the two together in a vacuum and Van de Valt’s forces take over. This is an incredibly robust piece of equipment and extremely high accuracy. This will measure angles from true north to an accuracy of 20000’s of a degree and if we can ever get that into an MWD system we’ll have the perfect solution.

Slide 35 (0:29) RLG in a BHA

This is one possible way of running the tool, by having an aluminium heat sink. Again, ring laser gyros are temperature sensitive and even these more modern ones have a limit of about 100°c. So they would have to be flasked or there would have to be a heat sink and survey electronics assembly mounted all linearly along with the battery pack and possibly a heat sink above as well.

Slide 36 (0:13) First tests

We ran some tests here in Scotland by putting the ring laser gyros onto the funicular railway at Cairngorm and we ran the gyros in parallel on the train, up to the top of the mountain and back down again. That was a total of a 4km run.

Slide 37 (0:28) 2km stopping every 30m

And these British Aerospace gyros accumulated an error of about 1.4 metres in 4km. If we were able to achieve that sort of accuracy downhole a lot of our collision risk issues and target sizing issues would just disappear. So, watch this space. What was working on the slopes of Cairngorm this year may well be working down your oil well in another 4 or 5 years’ time.

Summary (0:46)

We’ve gone a long way. Discussing everything from plumb-bobs, acid bottles and film read compasses, all the way to ring laser gyros with space age accuracy. But it’s not necessarily the surveyor’s job to use the best tool. The surveyor’s job is to decide what is a fit-for-purpose tool. Well it’s an economic decision for the oil well depending on the targets that they have to achieve, the wells that they have to avoid, the geology that we have to drill through and we’ll look at another presentation about how we model the uncertainty on each of these tools to decide which is the most appropriate one for the job at hand.