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Achieving Efficient Well Spacing Using Advanced MWD Correction Techniques

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Abstract

This paper will discuss the implementation of advanced Measurement While Drilling (MWD) survey correction techniques that are being deployed in unconventional drilling operations for the purpose of tightening up on well spacing. Proximity management for nearby wells or multi-well pad drilling requires all of the available survey accuracy and validation techniques that should be part of the factory drilling package. The growth in the use of infield referencing (IFR) and multistation analysis (MSA) to enable this process has been prolific, but is not always understood. This paper will also discuss the pros and cons of these techniques and how they can be applied in a practical and effective way to deliver what may, or may not, have been promised.

Case studies will be used to show the effects of these techniques on the accuracy of the well position and, more importantly, how the driller can use these techniques to place the well on plan in real time, and how the MWD service company can verify that the tools are performing within specification and to the required survey standard. This is especially important where entire wells are being drilled in single, two or only three runs, with no further opportunity or time available for additional well surveying. This paper will then conclude with a recommended flowchart and process for selecting the best survey solution for the minimum survey cost and time.

Introduction

This paper is intended as an aid for the Drilling Engineer and Well Planner to optimize magnetic MWD survey selection for unconventional wells from an efficiency and practicality standpoint.

There are two main types of wellbore surveying instruments in use in the oilfield today: gyroscopes and magnetic MWD tools. Magnetic MWD surveying has become the de-facto standard for defining the position of most unconventional wells. An MWD survey consists of a set of downhole measurements obtained during a connection or other short break in the drilling process. Under ideal conditions, the acquisition of these measurements should not add any additional delay to the drilling phase of the well, and they provide continuous 'near-real-time' feedback to the driller that ensures that the well is being drilled along the desired trajectory. In contrast, gyroscopic surveys typically require the use of additional rig time during the well construction process.

The measurements obtained by the MWD tool consist of a magnetic azimuth, or direction reading, relative to the direction of magnetic north, and an inclination, or gravity reading which provides the angle of the well relative to the Earth's gravity field. Magnetometers within the MWD tool detect the magnetic field present in the vicinity around the tool, and the inclination is measured by accelerometers that detect the Earth's gravity field in the vicinity of the tool. Considering that the drilling environment is energetic and dynamic, MWD tools have been engineered to be very robust, with very high reliability rates. The MWD sensors are also highly accurate calibrated instruments. While it was once generally accepted that MWD surveying methods were not as accurate as gyroscopic surveying methods, advancements in magnetic surveying[1] have narrowed the gap in accuracy to the point where practicality and the emphasis on drilling efficiency has superseded the additional time and costs required for gyroscopic surveys.

In the meantime, the unconventional drilling process has been industrialized to the point of factory-like repeatability. Horizontal wells that that five years ago were taking 30 days to drill are not only drilled in a matter of days today but also drilled to significantly greater depths. The well surveying process has had to adapt to these step changes in the operating rhythm of the drilling process, and this has prompted improved techniques for managing well position assurance in this new 'single-survey-run-per-section' environment.

Well Spacing Challenges

Spacing units for the development of unconventional oil and gas wells have commonly been set at 640 acres. With the advent of improved horizontal well technologies, there is a growing prevalence of 1280-acre section units. This means that horizontal laterals now extend to at least 4,000 ft., and more commonly may extend out past 10,000 ft. of lateral displacement.

Since the objective of longer horizontal wells is to increase the recovery rate and volume from each well, then this has also led towards a need for longer narrower section units or, alternatively, the need to drill multiple wells per section so that the optimum drainage per section can be achieved by the fewest number of wells drilled. When these needs are coupled with the desire by the operators to minimize the environmental footprint and surface disruption, this has resulted in multiple wells being drilled from the same 'drilling pad' or surface location. These 'multi-well' pads also provide the opportunity to approach the business of oil and gas well drilling in a factory-like manner. There is the opportunity to achieve economies of scale in terms of minimizing rig move delays, lowering the cost of land preparation, and the lowering number of well locations that need to be serviced per section unit.

Some regulatory bodies set the number of wells allowed per spacing unit, but this approach has become outdated with drilling technology advances. In many cases where geologic and engineering evidence can show that additional wells per unit will improve resource recovery (without damaging correlative rights), regulatory bodies are providing for increased well density, infill wells, or multiple laterals, especially in larger voluntarily pooled units.

These still evolving efficiencies have resulted in multi-well pads containing from three to four wells, up to and including some 22 well pads that have become, in effect, the equivalent of drilling an 'offshore' style of installation with many of the same or similar technical and logistical challenges. Wellhead spacing of 7 ft. to 10 ft. at surface is commonplace, and the wellheads are typically laid out in long single or double rows so that the drilling rig can be easily and quickly moved from 'slot' to 'slot'.

Boundary Setbacks and Well-to-Well Spacing

The drainage pattern that extends from horizontal wells producing from unconventional formations is driven by the shape of the fracture invasion as it extends out from the wellbore. In terms of wellbore positioning accuracy, there are two objectives that should be satisfied to ensure that the desired drainage pattern is achieved. First, the well must be placed in the correct position within the reservoir rock and second, the distance between lateral horizontal wellbores must be at the desired spacing.

In addition, specific rules about the distances from unit boundaries must be observed. These boundary setback requirements are usually prescribed based on regulatory requirements, and the MWD surveys therefore also ensure that unit boundary setbacks are not crossed, and that all other drilling application requirements relating to the proposed well position are observed. This includes the observance of good surveying practice, and the filing of well-position information with the relevant regulatory authority upon completion.

Though fracturing and completion practices for unconventional wells continues to evolve, the requirements to ensure that the surveying objectives and deliverables based on position, and on wellbore position accuracy, must continue to be met.

Surveying Challenges for Well Spacing

These two wellbore positioning objectives give rise to requirements relating to the control of the wellbore trajectory. Placement of the well in the optimal position in the rock is primarily concerned with vertical depth management, whereas ensuring the correct lateral well spacing requires control of the azimuth of the wellbore.

The surveying challenges for well spacing can be categorized into two main groups; managing the proximity risk of a well-to-well collision in vertical and low angle hole when wells are physically spaced very close together, and managing the observance of unit boundaries and maximization of drainage through optimal lateral horizontal positioning and placement within the unit.

Unconventional Drilling and Surveying

It is well known that the two main reasons for the success in exploiting unconventional reservoirs are horizontal drilling and fracturing. What is perhaps less well known is that this success has been further built upon with cost and time reductions brought about by drilling increasingly longer horizontal wells with fewer hole sections, and with fewer drilling 'runs'. This means that an unconventional well that is in excess of 18,000 ft. in length and which extends out more than 10,000 ft. across multiple units, can be drilled in a matter of a few days.

The need to be able to survey and place today's unconventional wells while drilling faster and farther has also increased surveying complexity. The requirement is to drill the well in the right place in real time in only two or three sections, and therefore with only two or three MWD runs if possible. The opportunity to take multiple overlapping survey runs for comparison, and the time needed to provide extensive quality control analysis that represents the current 'industry standards' in surveying[2] are being found to be inefficient and costly at best, and impractical and in danger of being ignored at worst.

MWD Survey References

The best method for validating MWD surveys continues to be the use of an overlapping high accuracy north-seeking gyroscopic survey, typically run after each hole section is complete. When this is not possible or practical, the MWD survey must be validated using another method. In cases where there has been more than one MWD tool run in the same hole section of the well, then the surveys can be validated through the use of a series of overlapping comparison checkshots to confirm the integrity of the well position. Where only a single MWD run has been performed in a single hole section, then further reliance needs to be placed on indirect methods for validating that the surveys are correct.

MWD tools measure the Earth's magnetic field as a direction reference, and the Earth's gravity field as a reference against verticality. The third leg of the survey triangle is provided by the drillers depth, obtained from the pipe tally where each joint of drillpipe is 'strapped' with a measuring tape and the individual lengths measured 'into the hole' as the well is drilled.

The Earth's magnetic field is a good reference for direction because it is always present, and the expected value for the magnetic field is well known for any location. It is less convenient because the value of the magnetic field in any one location is constantly changing, and the direction of magnetic north changes with location in a way that is not aligned to conventional mapping systems. In addition, the possibility exists for the magnetic field measured by the MWD tool to be interfered with due to the presence of nearby steel-cased wells, or from drillstring magnetic interference caused by steel components that are adjacent to the non-magnetic MWD collar in the drilling assembly or bottom hole assembly (BHA)[3].

The Earth's gravity field is also a good survey reference because it too is always present, and it is relatively easy to measure. However, this generally means that the MWD tool must be 'held still' in one position for a good measurement of the gravity field to be obtained, otherwise the results are easily perturbed and the angle of the well cannot be accurately measured. Operationally, this is not usually a problem because the BHA is held still in the hole as each new pipe connection is made up, and the MWD survey can be easily obtained in this way as drilling progresses.

Drillpipe depth is a straightforward tape measurement of the length of the drillpipe that has been run in hole. This is the measurement of the pipe at ambient surface temperature in a mechanically neutral state. There are numerous drillpipe length related error sources documented elsewhere[4] and of these, mechanical stretch and thermal expansion are usually the two factors that can contribute any appreciable depth measurement error[5] to the overall survey measurement.

Magnetic Reference Validation

A reference model of the Earth's magnetic field is used to convert the MWD magnetic north measurements into map north referenced measurements that can be used to plot the well position. The use of these models therefore affects only the accuracy of the direction of the well. These models also provide independent knowledge of the expected magnetic field measurements for the drilling location that the MWD tool should have measured. These expected values can therefore be used to qualify the validity of the MWD surveys, based on the comparison of the expected magnetic field readings to the actual readings made by the tool[6]. The declination correction, or conversion of magnetic north referenced measurements into map north based measurements is one of the largest sources of error in the well position, depending on the type of reference model used.

There are numerous magnetic reference models typically used to reference and correct MWD surveys today. The IGRF[7] model and the WMM[8] model are the least accurate of these models, but are typically free to use. The BGGM[9] and HDGM[10] models are more accurate and represent current industry standards, but come at a cost to the user. Each of these models are global models that provide an increasingly more accurate definition of the expected Earth's magnetic field for a given location. By far the most accurate method of obtaining magnetic reference values that can be used for MWD drilling applications is to deploy high accuracy magnetic field mapping instruments at the wellsite, and use these to measure the reference values directly instead of obtaining them from a model. These direct measurement methods to obtain the local magnetic field at the wellsite are collectively known as infield referencing models, or IFR models[11]. Obtaining an IFR model for a specific drilling location can be costly, although there is an increasingly competitive market of companies who can provide these types of models.

When each MWD survey is obtained, the measured magnetic field should be compared to the reference value and should meet an expected tolerance level based on the capabilities of the specific MWD tool in use, and the expected accuracy of the magnetic reference model in use.

Gravity Reference Validation

The gravity measurements from the MWD tool are used to obtain the inclination, or angle of the well at the measurement point relative to vertical. An independent Earth's gravity reference model is used to check the MWD surveys for two simultaneous purposes; first, to provide an indication that the MWD tool has measured the Earth's total gravity field for a given location correctly, and second, to indicate that the MWD tool is being held relatively stationary so that the best possible survey measurements can be obtained during the short time that the next pipe connection is being made.

Gravity reference models are mathematical models of the Earth's gravity field, and the formulation of the most commonly used models can be found in the public domain. They range in levels of complexity from simple elliptical models that require only the latitude of the wellsite as an input to obtain the gravity reference for the well, up to and including sophisticated models that use estimates for Earth shape, and rock and water density above and below the current well position along the wellpath for a given depth below ground level.

When each MWD survey is obtained, the measured gravity field should be compared to the reference value and should meet an expected tolerance level, based on the capabilities of the specific MWD tool in use and the expected accuracy of the gravity reference model in use.

Drillpipe Depth Measurement Validation

The depth measurement used to calculate the well survey is obtained from the driller's tally of the lengths of each joint of pipe, measured manually using a tape measure. Although the depth measurement forms one of the three main inputs used to calculate the wellpath, it is often the most overlooked and least regarded from an accuracy perspective. This is not to say that the measurements of drillpipe length are inaccurate, and most rig operators have developed rigorous procedures for 'strapping' the pipe into and out of the hole to ensure that the tally is correct, and to prevent against unintended errors when combinations of singles, doubles, stands, and BHA components are all made up together during the drilling process.

The two largest sources of depth error measurement in the surveying process are thermal expansion of the drillpipe and mechanical stretch caused by the frictional forces incurred on the drillstring (which is caused by the shape of the well and the types of formations being drilled). With the advent of much longer unconventional wells being drilled, or in cases where the downhole temperatures are high, these errors may result in well position errors of many tens of feet. Today, these effects are largely uncorrected for in unconventional well drilling, although the increasingly complex reservoir models being developed will likely drive a future need for better treatment of these error sources.

Surveyed Position and Survey Accuracy

The wellpath, created by joining together all of the survey points recorded in the well as it is drilled, forms the best estimate of the 'notional' position of the wellbore in space. The last time that the absolute position of the drilling bit is known is when it is run in through the top of the well to begin drilling. From that point onwards, an estimation of the position of the wellbore is derived indirectly from the MWD measurements. The errors that are present in the surveying system (both instrument and environment) are estimated using an appropriate Instrument Performance Model, or IPM[12]. For modern day survey tools, the sensor errors are relatively small, and it is the much larger environmental errors that tend to drive positional uncertainty in the wellbore. Each time a survey measurement is recorded, a resulting volume of uncertainty based on the summation of these errors is calculated. This uncertainty in position increases downwards along the wellpath in the approximate shape of a cone and is sometimes referred to as a cone of uncertainty. In this manner a long horizontal unconventional well may have accumulated hundreds of feet of position uncertainty to the left or right of the wellpath by the time it has been drilled. Statistically, this would mean that there is a 95% probability that the well is located in a position somewhere within the cone of uncertainty defined by the volume generated using the IPM.

At each survey point, the 3D positional uncertainty associated with that survey is represented as an ellipsoid, although the term "ellipse of uncertainty" or EOU is more generally used, as the well trajectory is typically viewed as 2D projection (in which case one axis of the ellipsoid is not visible).

Instrument Performance Models

The IPM is a set of statistical coefficients that are used by directional drilling software applications to generate the requisite cone of uncertainty around the well trajectory. It is the clearance calculated between cones of uncertainty and to and from boundaries of interest that determines whether the spacing and positioning requirements for each well have been met. Statistically, if two cones of uncertainty between adjacent wells are touching at any point, then there is a possibility that a well-to-well collision can occur. And, if the cone of uncertainty for a given well trajectory extends beyond a property boundary at any point, then there is a possibility that a boundary or lease line has been violated. Both of these scenarios can have significant consequences for the operator from both an environmental and a legal standpoint.

There are a multitude of different IPMs available, and these arise from the fact that different sets of the statistical coefficients that drive the uncertainty measurement can be generated, depending on the type of surveying tool and magnetic reference validation being used. For example, there is a term in the coefficient set that relates to the uncertainty in the numeric value for the accuracy of the magnetic declination that is used to convert magnetic north reference measurements to map north reference measurements. For some magnetic reference models, this uncertainty is greater than others and so, all else being equal, an IPM that applies to a model with a greater magnetic declination uncertainty will generate an EOU of larger size than an IPM that applies to a model with a smaller magnetic declination uncertainty (see Case Study #1).

Underlying Assumptions for IPM Use

All well spacing clearance factors and calculations rely on the assumptions made about the accuracy of the wellpath defined by the surveys, and the applicability of the IPM code used to define the 'uncertainty envelope' and hence the minimum allowable well separation. The main underlying assumption of the standard MWD IPM code is that all of the MWD survey measurements meet or exceed certain quality criteria based on tool calibration and performance, the accuracy of the reference models in use, and the checks made to constrain environmental sources of position error. In practice, adequate time and effort is not always taken to ensure that these assumptions have been met. In the past, this was because of a lack of appreciation of the validation process required to ensure well position integrity. More recently, the validation challenge exists due to a lack of time, the speed of operations, and a lack of adequate industry experience with the well positioning integrity process.

One of the most common problems with the IPM integrity process is the presence of unmodeled levels of magnetic interference on the MWD tool measurements. This can be caused by a variety of external sources, but most commonly comes from the presence of adjacent nearby cased wells, or from the drillstring itself. In the latter case this is because the MWD tool collar has been inadequately isolated from the steel components of the adjacent parts of the drilling assembly. However desirable, taking the approach of removing the source of the interference through increased nonmagnetic well spacing and more expensive BHA configurations quickly becomes costly and impractical.

The presence of gravity reference errors in the MWD survey data is more easily dealt with by spending more time at each connection to ensure that the MWD tool is stationary before a measurement is made. Again, taking this approach comes at a cost (in rig time) that is contrary to the mission of factory drilling, and so should also be challenged by technology and process improvements.

Drillpipe depth errors are perhaps the most difficult to detect because in this case there is no independent reference against which to measure the length of the drillstring. Good tripping practices and comparison inclination surveys in the build sections are really the only methods to ensure that the well stays on 'pipe depth'. The presence of mechanical stretch and thermal expansion based depth errors have yet to be consistently tackled in the unconventional drilling space but will become more important in time. Long laterals may be tens of feet longer than believed in some cases due to these error sources and may exceed the boundary standoff as a result.

Advanced MWD Correction Techniques

Advanced MWD correction techniques have been designed to compensate for many of these error sources, and their rigorous application in the unconventional space is becoming more important as the well positioning challenges have increased. These techniques must also be aimed at improving the efficiency of the drilling cycle in some way or must support the factory drilling and regulatory setting and include the following:

- Rethinking the well surveying process so that the overall position based objectives can be met within the current operating envelope
- The need for real time solutions that place the well in the correct position as it is drilled
- Widespread use of IFR magnetic reference models that have resulted in a reduction in the need for gyro surveys
- Correction techniques that compensate for drillstring interference
- The use of advanced IPM models and improved operating procedures to reduce well spacing
- Improved records management and reporting in a changing regulatory environment

Real Time Services

Real time services refer to the ability to provide support to the wellsite drilling operation from the office or another location that is remote from the wellsite. Real time drilling centers, operations centers, and centralized advisory services have become commonplace for this purpose. Three main practical applications for these services have evolved over time as more and more rigs have become connected to the internet. First, they facilitate the ability to provide reduced crews at the wellsite by having MWD operators located in the remote centers. Second, they allow for additional surveillance and support to be called upon as required to facilitate more efficient data-based decision making and to better identify and act upon the drilling information in real time when changes to the plan or to the operational activity might be required. Third, they provide access to surveying, drilling, geological, and formation evaluation expertise and knowledge resources to several rigs through the surveillance of multiple rigs' data, simultaneously. Overall, these real time services form an intrinsic part of the factory drilling process through the efficiencies that they can afford.

Infield Referencing (IFR)

Infield referencing is the general term used to refer to the use of a more accurate local magnetic reference map for a specific drilling area. Where the global geomagnetic models provide a large scale magnetic reference map that can be used to see features of the Earth's magnetic field of the order of tens of kilometers in extent, a local magnetic model used for IFR purposes may capture the magnetic features of the local magnetic field in a drilling area with a resolution down to tens of meters. This in turn leads to an increase in accuracy of the magnetic reference used to map the well position to the geographical mapping system (which is independent of the type of MWD tool in use) and, therefore, allows the application of an IPM that will generate a smaller EOU.

Multistation Analysis (MSA)

It is important for the MWD tool to be as magnetically isolated as practicable from the remainder of the drillstring. The nonmagnetic drill collar that houses the MWD sensor is invariably placed between adjacent steel BHA components that cause some level of magnetic interference to the MWD measurements. Even when the adjacent steel components of the drillstring are magnetically clean, they can still affect the MWD sensor, especially as they can also become magnetized simply from the effects of the vigorous act of drilling. Multistation analysis (MSA) is a method for correcting for the magnetic interference to MWD surveys that is caused by the magnetized drillstring components. While MSA may further improve the accuracy of the MWD surveys[13], the main function of this process is to prevent uncontrolled or unknown drillstring magnetic interference errors from invalidating the well position. Experience has shown that this can be a significant problem in unconventional drilling if magnetic interference levels that affect the MWD surveys go unmonitored. A secondary but equally useful outcome of the MSA correction technique being applied to MWD surveys is that the additional data processing forms a 'second' more detailed look at the MWD survey quality, and this serves as additional level of assurance; especially in an environment where a second overlapping survey is not routinely carried out. It is therefore recommended that the MSA techniques be applied routinely in all 'single-survey-run' MWD scenarios (see Case Study #2).

Use of Optimized Surveying Procedures

A robust set of IPMs has been developed and maintained by the ISCWSA wellbore positioning technical section within the SPE[14]. These IPM codes describe a set of position error calculation parameters based on accepted standards of survey sensor accuracy and survey environment conditions and on the validation of industry standard surveying procedures. However, it is not always practical or possible to fully observe all of the requirements expected to be met for the use of these models. This is mainly due to the reduced time available for surveying and the reduced number of survey runs being used to drill the well. This in turn has resulted in the continuing development of optimized surveying procedures across the industry which are at least aimed at satisfying the principles of good surveying set out by the ISCWSA group.

MWD surveying requires that the drilling assembly be held still to allow the MWD sensors to obtain the best possible quality measurements of the Earths' gravitational and magnetic fields. These measurements are usually taken during a drilling connection, and require the MWD tool to be able to 'sense' that the pumps have stopped and that the string is no longer rotating. In general, this process works well and with a high degree of efficiency. However, this is still a dynamic environment where the MWD tool may not always sense that it is time to take a survey because mud may still be flowing around the tool even when the pumps have stopped, and vibration may still be transmitted to the tool through the drillpipe moving in the hole even when hung off in slips. The result is that there are times when the MWD tool is not able to automatically obtain a good survey during a connection. In order to try to satisfy industry standard survey quality requirements, the driller is often forced to delay drilling ahead until the MWD tool has cycled through the surveying sequence again until a 'good' MWD survey has been pumped up to surface and confirmed. Experience has shown that the need for multiple MWD surveys occurs in less than 5% of survey positions in a 10,000 ft. run, but in some cases this can rise to 20% of the survey stations depending on the rig and the drilling speed and conditions. If an MWD survey requires an average of two minutes to obtain a survey while 'in-slips' and there are up to twenty out of every hundred survey points where an additional survey cycle is needed to obtain the survey, then this can result in an additional forty minutes of invisible 'lost' drilling time being spent per run to obtain the full density of standard MWD surveys. Observations have also shown that up to 40% of survey stations can often be removed from long surveyed intervals of the wellpath without significantly changing the overall position of the well itself. This is not recommended, nor is it always the case, especially when the well is changing orientation very quickly, such as in a build or turn section. In this case more frequent MWD surveys may be required to ensure that the fidelity of the wellpath description is not compromised from inadequate survey sampling. This survey frequency efficiency - versus fidelity quality problem has not been effectively addressed in practice or with IPM's, and the default condition continues to be that MWD surveys are expected to be taken at least every stand (approximately every 30 m. or 96 ft.).

Two MWD surveying techniques that have been developed to eliminate these problems of invisible lost time are continuous MWD surveys and post-drilling MWD surveying while tripping out of hole.

Continuous MWD surveys have been developed by MWD survey vendors[15] to allow the MWD tool to record survey measurements while drilling is ongoing. This is not an ideal surveying environment for a conventional MWD survey that aims for a single high quality measurement to be obtained. However, by very large frequent samples of continuous MWD measurements in the 'noisier' drilling environment, a statistically averaged MWD survey can be produced to augment the small percentage of 'missing' standard MWD surveys that could not be obtained in time during each drilling connection. The result in this case is that the driller can continue to focus on drilling efficiency, with the MWD surveying activity being removed from the critical path without penalty.

A second method to compensate for missing MWD surveys that could not be acquired in time during the drilling process is to obtain them later when tripping the drilling assembly out of the hole after drilling. Provided that the missing surveys occur in parts of the well where reduced survey frequency is unlikely to affect the overall well position, an MWD tool that has been programmed to record surveys into tool memory when tripping out of hole could be used to augment the missing data points. Some MWD vendors are able to easily switch the MWD tool into memory survey mode after the drilling run has been completed. And in any case, even without the need to augment any missing data points, the MWD memory survey while tripping out of hole fulfills a useful integrity check on the existing MWD drilling surveys. This additional memory survey makes for a second level check and good surveying practice where overlapping surveys can allow for more robust survey quality checks between inrun (while drilling), and outrun (while tripping) surveys. This practice also allows for a more robust independent check on the drillers' depth measurement, especially if pipe is strapped on the way out of hole at the same time, since drillers' depth errors can be notoriously difficult to spot after the fact by examining the survey records alone.

Close Proximity Drilling Processes

The ideal unconventional well would be to start the borehole at one edge of the spacing unit, and then to drill straight down vertically until reaching the reservoir rock, before quickly turning the well horizontal to drill the entire length of the reservoir rock from one boundary to another. Multi-well pad drilling has resulted in exactly this type of well shape, with the added complexity that the vertical portion of the adjacent well sets must be spread out in the vertical plane to allow for the series of horizontal laterals to be laid out in rows across the lease from one boundary to another in the horizontal plane. In cases where the multi-well pad at surface cannot be located right at the edge of the lease boundary, then these wells are often drilled backwards, away from the desired horizontal spread before being 'dropped' back to vertical, and then laid out horizontally as described above. In either case the result is that multi-well pad unconventionals are drilled straight down for several thousand feet in very close physical proximity to each other until they can finally be spread out and laid out horizontally across the lease.

This poses a unique problem with regard to survey quality because the MWD surveys invariably become subject to external magnetic interference once the second, and then subsequent wells on the pad are drilled and cased from surface. Excessive external interference can invalidate a standard MWD survey, making it unusable with the standard MWD IPM survey accuracy code. This does not necessarily mean that the position of the well being drilled in a poor quality magnetic environment is unknown, only that the azimuth reference may no longer be the Earths' magnetic field. Physically, the separation at surface is known since it is the slot separation of the pad. Also, the inclination measurements or angle in the hole is known, and since these are based on the Earth's gravity field they are not affected by magnetic interference from nearby cased wells. When a well is drilled vertically, the direction of the well is undetermined, and when the angle in the hole is small, then the direction can be difficult to ascertain. Similarly, in this situation any uncertainty in the position of the well is driven more by the inclination and alignment error sources than by the direction related error sources. This means that even in an environment where direction is less accurate than normal and the hole angle is small, it is possible to assess the absolute change in position of the well from the vertical, even when the direction itself is less certain. Experience with passive magnetic ranging between nearby wells[16] has shown that the magnetic interference caused by a nearby well does not have a constant magnitude based on proximity only, and that the tendency is for the middle of the offset well casing joints to be magnetically neutral. The interference that a nearby MWD tool would see would be maximum when adjacent to a nearby casing joint just as if each separate casing joint were in effect a large bar magnet. These effects can be modeled using the interference information and the proximity to the nearby well can be managed effectively using a bespoke close drilling technique.

The reason that this technique is important is because the conventional response to this problem has been to run gyro surveys in the low angle part of the well. Experience with this has shown that the result (in the well position and not necessarily the accuracy of that position) is invariably the same as was obtained using the MWD to drill the section in the first place. Over time the use and practice of gyro surveying has been curtailed for this reason and because of the time taken to obtain the gyro surveys during the drilling phase of the well.

Modern anticollision management practices rely on industry standard quality MWD surveys. The basis for these techniques is the application of rules based on the separation between the combined survey uncertainties of the subject and offset wells. These separation ratios or 'separation factors' are based on statistical distributions of the errors that have accumulated along both wells. The close drilling process described here does not invalidate any of these requirements to adequately manage the risk of a well-to-well collision, but it does raise the question of the need for a complimentary approach that deals more effectively with what is known about the physical separation between wellpaths, and the clearance between their respective cones of uncertainty.

Case Study Data

Data from over 350 wells covering multiple U.S. unconventional basins was analyzed and used to develop the case studies presented here. Figure. 1 shows the displacement of these wells in terms of the projected compass azimuth and horizontal displacement based on the distance from the center of the compass rose. This 'experience diagram' shows that these wells extended horizontally as far out as 12,000 ft. in some cases, with a large number within the 5,000 ft. to 12,000 ft. range.

Each of these wells utilized at least one of the techniques that are described within the case studies, and in many instances, all of these techniques were delivered as part of an integrated package of advanced MWD correction techniques designed for efficient well spacing.

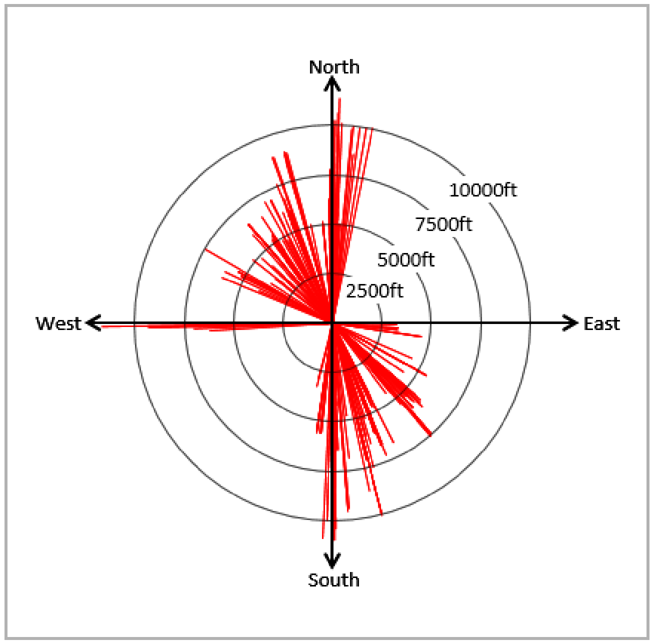

Figure 1. Advanced MWD Surveying Experience

Advanced MWD Surveying Case Studies

Case Study 1 – Efficacy of IFR Magnetic Models

This case study considers a pair of unconventional parallel lateral wells constructed using a standard profile consisting of surface hole, intermediate reverse build, and curve building towards the target azimuth with a horizontal lateral section to TD. The first well (Well A) has already been drilled and the second well (Well B) is being planned.

Figure 2 shows Well A (green wellbore) and the attached EOUs (green ellipses) represent the Well A wellpath with the standard MWD IPM code applied. The red wellbore and attached EOUs (red ellipses) represent the Well B wellpath with the same standard MWD IPM code applied. The smaller blue EOU ellipses associated with Well B represent the uncertainty in the position of the Well B wellpath with the MWD+IFR IPM code applied. Table 1 (below) shows the separation factor (SF) for these cases. These are a measure of the overlap of the EOUs: a value greater than one indicates the ellipses do not overlap, a value less than one means there is an overlap.

IPM for Well A	IPM for Well B	Minimum SF
MWD	MWD	0.934
MWD	MWD+IFR	1.063

Table 1: Case Study #1: Separation Factors

The key feature of Figure 2 is that it shows an overlap in the EOUs of the two wells towards the end of the laterals; meaning that even if Well B is drilled on plan, then using only standard MWD surveys to position Well B shows that there is a risk of a well-to-well collision occurring as Well B is being drilled. To mitigate the problem well B must either be drilled further away from Well A than planned, or the MWD survey uncertainties that exist in one or both wells must be reduced somehow (so that the EOUs can consequently be reduced and do not overlap).

In this case, the operator has a local magnetic IFR model for the lease and so can use a more accurate magnetic declination measurement than that offered by a standard magnetic reference model. This, in turn, allows for a more accurate IPM code to be applied to the well plan for Well B, which results in a smaller EOU being generated and thereby avoids the problem of overlapping EOUs. This reduces the possibility of a well-to-well collision taking place without compromising the desired well spacing between wells A and B.

IFR models typically cover the totality of the lease and in many instances the operator will obtain the IFR model for all of their leases in a given field. Therefore, in the situation described here, the IFR magnetic declination should also be applied to the Well A surveys, thereby also allowing for the use of the MWD+IFR IPM code for Well A. The application of the IFR declination can be done retrospectively provided that the original value of declination used to drill Well A can be backed out, and replaced by the more accurate IFR declination value (this technique is referred to as 'Level 1 IFR'). Obtaining the IFR magnetic model for entire lease can therefore also allow for previously drilled legacy wells to have their positional uncertainty improved, which may even result in the potential for additional wells to be drilled in an area that was previously thought to be fully spaced out but yet may still contain areas of the reservoir that might not have been accessed.

The results from the IFR sample data showed that as a result of using the IFR correction, the average shift in the bottom hole location was 10 ft. and the average reduction in the EOU size was 49%.

Case Study 2 – Efficacy of MSA Processing

This case considers a 4-well pad having horizontal laterals sections that are 7,000 ft. in length on a target azimuth of approximately 340 degrees. As can be seen in Figure. 3, there is a clear overlap in the positional uncertainties of the proposed wellbores shown by the overlapping ellipses (shown by the dashed ellipses), even with the MWD+IFR IPM code being used. This means that there are well spacing issues with this plan, and suggests that the separation of the lateral wellbores is inadequate.

In this case, to avoid having to space the wells further apart, an alternative IPM code that creates a smaller ellipse than can be generated by using the MWD+IFR IPM code is needed. The uncertainty in modeled magnetic declination is smallest when using IFR models, and so further improvement to the position accuracy through the use of an MSA correction is needed.

The MSA correction method for magnetic azimuth surveys is used to correct for the effects of drillstring magnetic interference. The MSA algorithm uses the information from multiple surveys acquired with the same drilling BHA to determine a set of scale factors and biases for the MWD magnetometers that are corrected for the effects of the interfering drillstring magnetic vector. The MWD survey is then recalculated with the new magnetometer values, which generates a corrected azimuth.

By utilizing MSA corrections the positional uncertainty in the wellbores is further reduced as shown by the revised solid line ellipses, thereby ensuring that sufficient lateral spacing exists to place the wellbores in the optimum position for production recovery. In addition, MSA corrections can be offered in real-time, so that the final position of the wellbore can be assured as the drilling process proceeds.

The results from the MSA sample data showed that as a result of using the MSA corrections, the average shift in the bottom hole location was 54 ft. and the average reduction in the EOU size was a further 43% (after the EOU reduction produced by the IFR correction only).

Case Study 3 – Improved Surveying Procedures

One of the wellbore positioning objectives for surveying unconventionals is to place the wellbore in the correct position within the reservoir rock. The use of gamma ray measurements help to identify the formation being drilled through; however, sometimes, there are discrepancies between the calculated wellbore position based on the surveys and the correlated position of the wellbore based on the gamma ray log.

While infill drilling in a developed field, gamma ray data referenced to MWD surveys was not correlating with existing data from offset wells and pre-drill models. Further investigation revealed that standard MWD surveying procedures were not mapping the true path of the lateral wellbores: doglegs from short sliding intervals were not being properly measured by the 95ft. survey intervals used, and the end result was a TVD error in excess of 15ft. over the length of a 4,500ft. lateral. This TVD uncertainty presented challenges for both geosteering current wells and for geological reservoir mapping for future wells. Stopping for additional surveys during the drilling process was undesirable, as it would lead to a significant increase in rig time when considered across the entire drilling campaign. The challenge was to find a solution which delivered an accurate final position of the wellbore without compromising drilling efficiency.

MWD memory data was therefore leveraged to reduce the effective course length of the surveys (thereby increasing the survey sample density) and to generate an improved well profile. The MWD tool was programmed to act as a 'multishot' tool while tripping out of hole so that additional MWD surveys could be obtained. These memory surveys were then combined with the real time MWD survey data to create a new higher definition survey profile. Upon analyzing the well logs using the corrected TVDs, the logging data was found to correlate with the offset wells and with pre-drill expectations. This allowed the operator to model and plan current and future prospects more effectively. Figure. 4 illustrates this, with the initial 95ft. while-drilling surveys being represented on the TVD versus VS plot by the red line, and the 'combined multishot' mode surveys being represented by the blue line.

Case Study 4 – Close Proximity Drilling Application

On an unconventional multi-well pad when drilling the initial surface holes, the MWD surveys were failing the magnetic component of the field acceptance criteria. Once each well in each 'row' of the pad had been cased the next subsequent well in the row would be affected by external magnetic interference caused by the previously drilled well, until it had been drilled far enough for the separation clearance to mitigate the problem. Running multiple gyroscopic surveys as the surface holes were drilled resulted in additional rig time and cost. Experience had also shown that in these situations the gyro surveys and the previously obtained MWD surveys overlapped to a high degree in this scenario. The challenge was to find a solution that would allow drilling to continue with MWD only while having a robust positive indicator that a well-to-well collision would not occur.

A bespoke application and set of operating procedures were developed that allowed the raw MWD data to be analyzed in real time to determine the impact of any observed magnetic interference on the accuracy of the position of the subject well being drilled. The results of this analysis, coupled with the operating workflow and knowledge of the surveyed position of the interfering well meant that the decision to drill ahead could be made with no interruption to the drilling process. Furthermore, no additional surveying was required after the section was drilled to TD.

In order to accurately describe the positional uncertainty associated with the interfered with surveys, custom IPM codes based on the levels of observed interference were created - one to be applied over the interval where interference was present, and another to be applied to all surveys taken with the same BHA after the MWD tool was clear of interference. The effect of applying these codes can be seen in Figure. 5; the surface holes were drilled from south to north (Well 1, Well 2…etc.), so for the second and subsequent surface holes there was in effect a single interfering offset well. The EOUs prescribed by these IPM codes demonstrate the clearance between wells, thereby ensuring that there was no violation of separation factor rules.

One key point that is worth mentioning in this case is that it is well known in the industry that separation factors may not give an adequate indication of well-to-well collision risk when the EOUs are small and the wells are in close physical proximity to each other. This is exactly the situation in this case study and the close proximity drilling application described here would be complimentary to, and could be integrated with, a separation factor based anticollision policy.

A Surveying Process for Unconventional Drilling

The case studies presented here have shown that advanced MWD surveying techniques could be designed that would be sympathetic to the challenges presented by unconventional drilling. Namely, ensuring the validity of the surveyed well position when very few survey 'runs' are available, managing potential well spacing and boundary management issues through the active use of the correct IPM codes, and the mitigation of well proximity risk in a fast paced dynamic drilling environment.

As stated, this paper is intended as an aid for the Drilling Engineer and Well Planner to optimize survey selection for unconventional wells from an efficiency and practicality standpoint. The primary objectives of this process are to allow for the selection of an optimized surveying program for unconventional wells based on surface layout and slot spacing and to design well spacing between adjacent wells and proximity to lease boundaries. It is also an objective of this process to respect the tenets of good survey quality practices within the constraints of a minimum number of survey runs while drilling and the time and resources available to ensure the integrity of the well positioning results. Figure 6. shows an initial version of a process flowchart that can be used and further elaborated as required, to take into account the specific challenges of each unconventional drilling project.

Advantages

The advantages of using advanced MWD surveying techniques for unconventional drilling are as follows:

1. Selection of surveying requirements is based on operational reality.
2. Industry standard survey practices can be met with more rigorous MWD surveying processes in a single survey run environment.
3. Provides a descriptive justification for MWD survey technique selection based on a holistic approach.
4. Clarifies the value of MWD surveying practices to aid in better risk management for unconventional wells.

Disadvantages

The disadvantages of using advanced MWD surveying techniques for unconventional drilling are as follows:

1. An increased level of oversight and expertise is required to be able to actively manage MWD service delivery.
2. Additional effort in well planning and survey quality assurance is required if the time savings described are to be validated.
3. Not all MWD survey vendors are capable of providing all of the techniques described.
4. Failure to apply a robust MWD surveying process in unconventional drilling usually results in inefficiency (there is a risk of excessive surveying costs) or a failure to recognize the attendant risks (the need for technical integrity is not recognized or is ignored).

Underlying Assumptions

There are several key underlying assumptions that underpin the successful application of the surveying process for unconventional drilling. These are:

1. Since MWD surveys are the predominant well positioning technology used to place unconventional wells, a very large part of the overall accuracy of the well position is related to the quality of the magnetic reference model used in the specific drilling location. This is completely independent of the MWD vendor selected or the type of instruments used
2. All MWD surveys suffer from some form of magnetic interference that degrades the quality of the attempt by

the MWD sensors to measure the Earth's magnetic field. This interference may come from the drilling assembly itself or from other nearby cased wells

3. Many MWD tool runs are still programmed to only send up the survey without any of the raw sensor data. To be able to recognize magnetic interference to the MWD, to analyze the nature and scale of the problem, and to proactively act accordingly requires that at some stage during the drilling process the raw magnetic sensor measurements are obtained in time for appropriate decisions and actions to be taken
4. Drilling in close physical proximity to other cased wells is inherently high risk and requires the highest degree of vigilance, especially in the unconventional multi-well drilling scenario
5. The risks of not following a robust surveying process are well-to-well collisions that may result in lost slots or worse, and the risk of violating a property boundary or failing to obtain the expected reserves recovery
6. In any situation where the status or condition of the MWD surveys cannot be positively ascertained either independently, or by running a second overlapping or replacement MWD tool then the use of calibrated, high accuracy gyro surveys is the preferred and most robust response

Conclusions

The following conclusions were developed from the material presented in this paper:

1. Well spacing challenges that are unique to the unconventional drilling space require a holistic MWD surveying approach
2. Conventional surveying methods, while robust, are not always practical or effective when drilling unconventional wells
3. Advanced MWD surveying techniques applied to unconventional drilling include the use of IFR models, MSA corrections, alternative MWD surveying methods, and alternative close drilling procedures
4. Case studies have shown that these techniques can be effective in delivering cost effective and efficient surveying solutions for unconventional drilling
5. The value delivered using these techniques is compatible with existing surveying quality principles
6. Continued work by concerned industry bodies is required to further develop surveying techniques and surveying best practices for unconventionals

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Nomenclature

BHA = *Bottom Hole Assembly*
MWD = *Measurement While Drilling*
IGRF = *International Geomagnetic Reference Field*
WMM = *World Magnetic Model*
BGS = *British Geological Survey*
BGGM = *BGS Global Geomagnetic Model*
HDGM = *High Definition Geomagnetic Model*
IFR = *Infield Referencing*
IPM = *Instrument Performance Model*
MSA = *Multistation Analysis*
ISCWSA = *Industry Steering Committee on Wellbore Survey Accuracy*
EOU = *Ellipse of Uncertainty*
TD = *Terminal Depth*
SF = *Separation Factor*
TVD = *True Vertical Depth*
VS = *Vertical Section*

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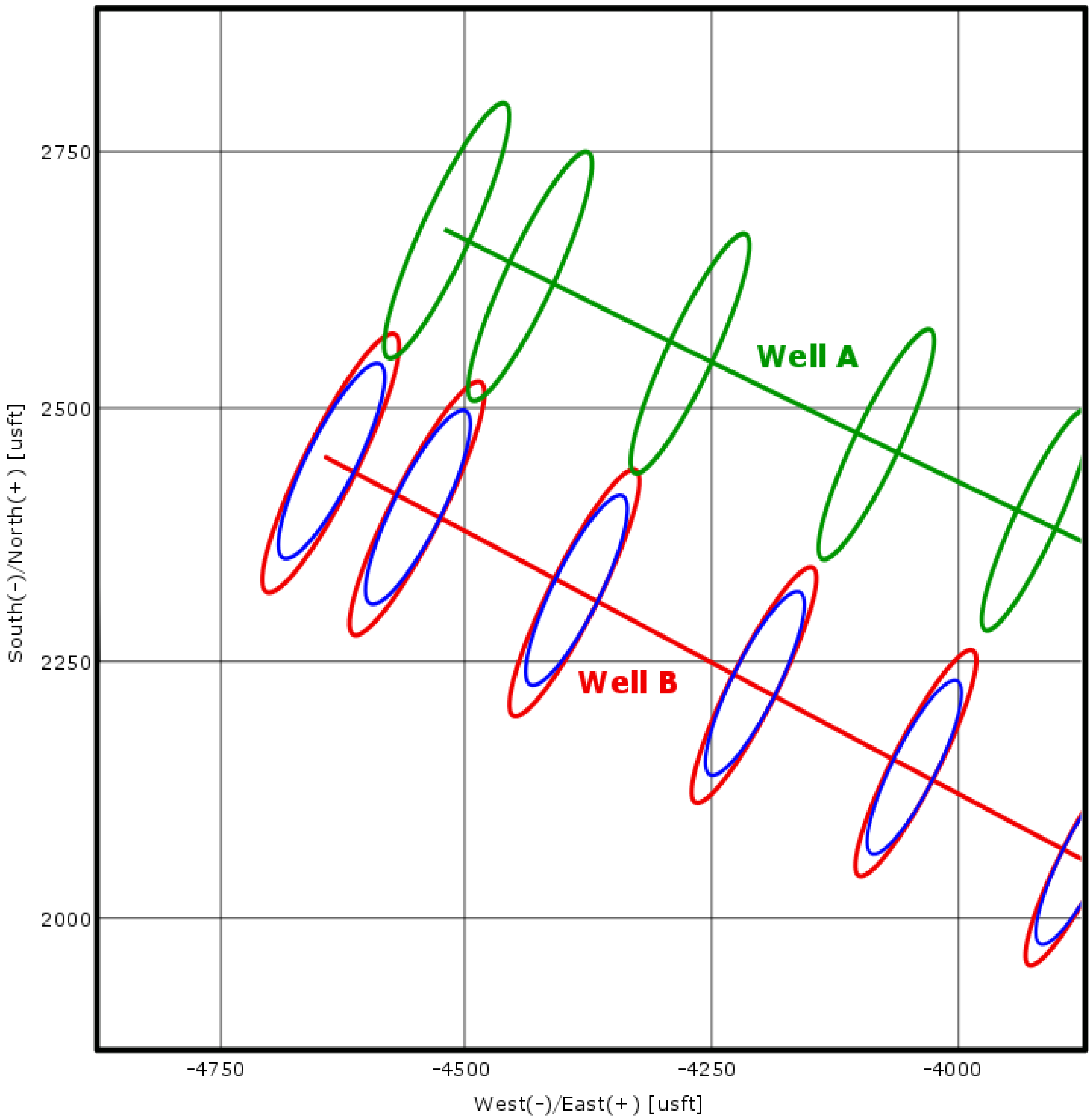
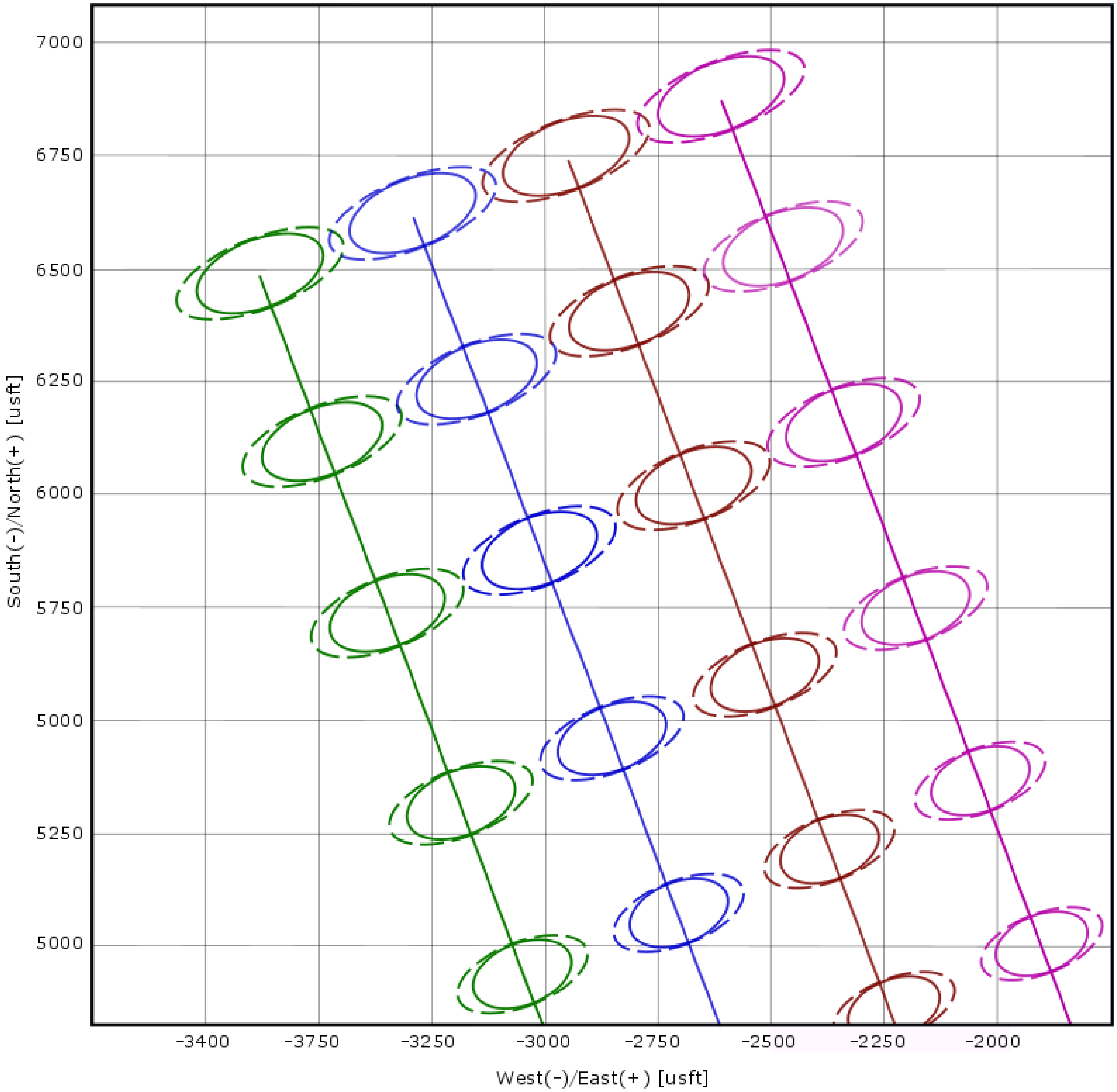
Figures



Legend:
- Ellipse of Uncertainty using the Standard MWD IPM Code (offset well drilled first)
- Ellipse of Uncertainty using the Standard MWD IPM Code (subject well drilled second)
- Ellipse of Uncertainty using the MWD+IFR IPM Code (subject well drilled second)

Figure 2. Case Study #1: Efficacy of IFR Reference Models



Legend:
– – – Dashed Line Ellipses of Uncertainty: the MWD+IFR IPM Code
—— Solid Line Ellipses of Uncertainty: the MWD+IFR+MSA IPM Code

Figure 3. Case Study #2: Efficacy of MSA Processing

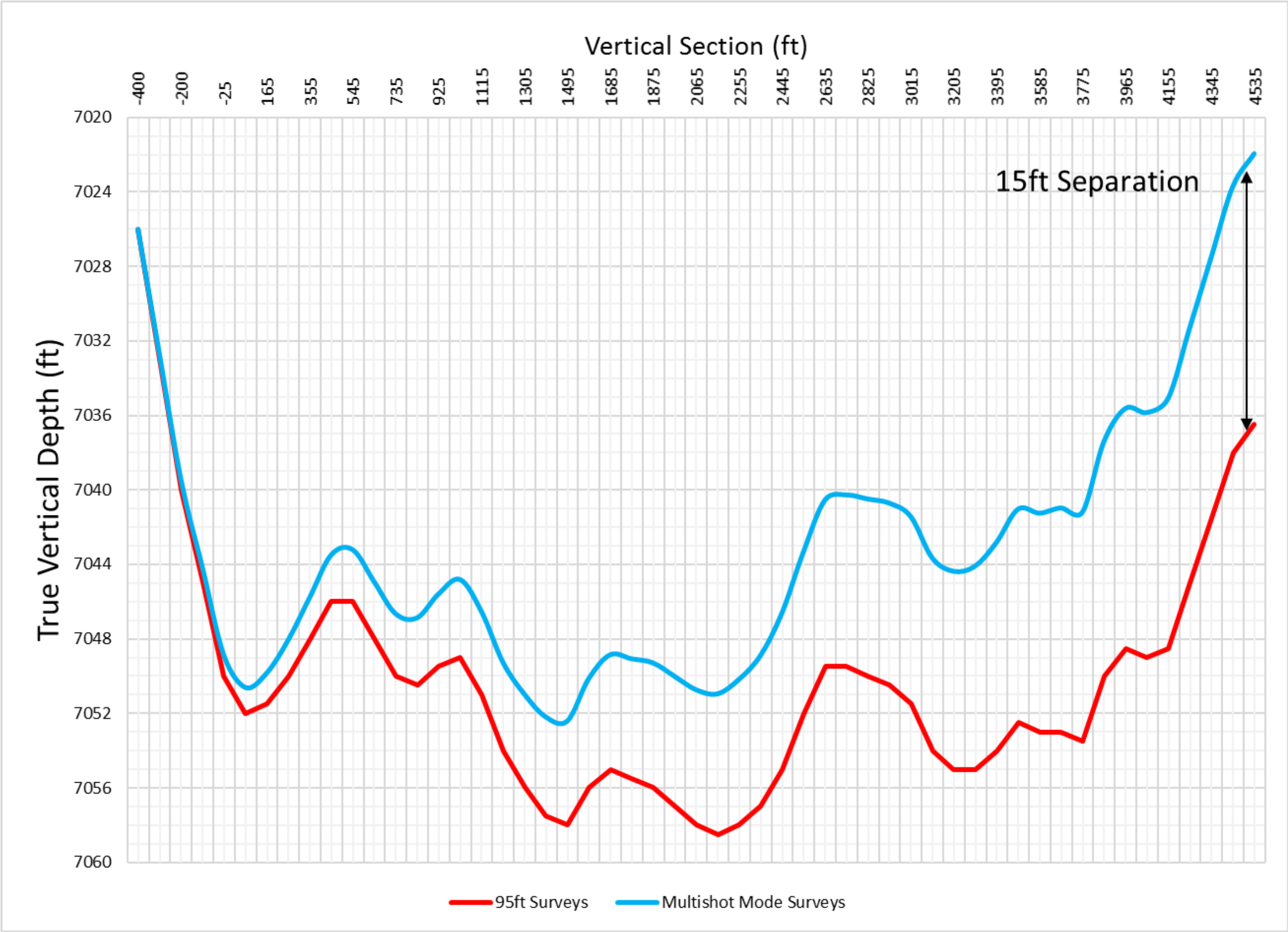


Figure 4. Case Study #3: Improved Surveying Procedures Reduce TVD Errors

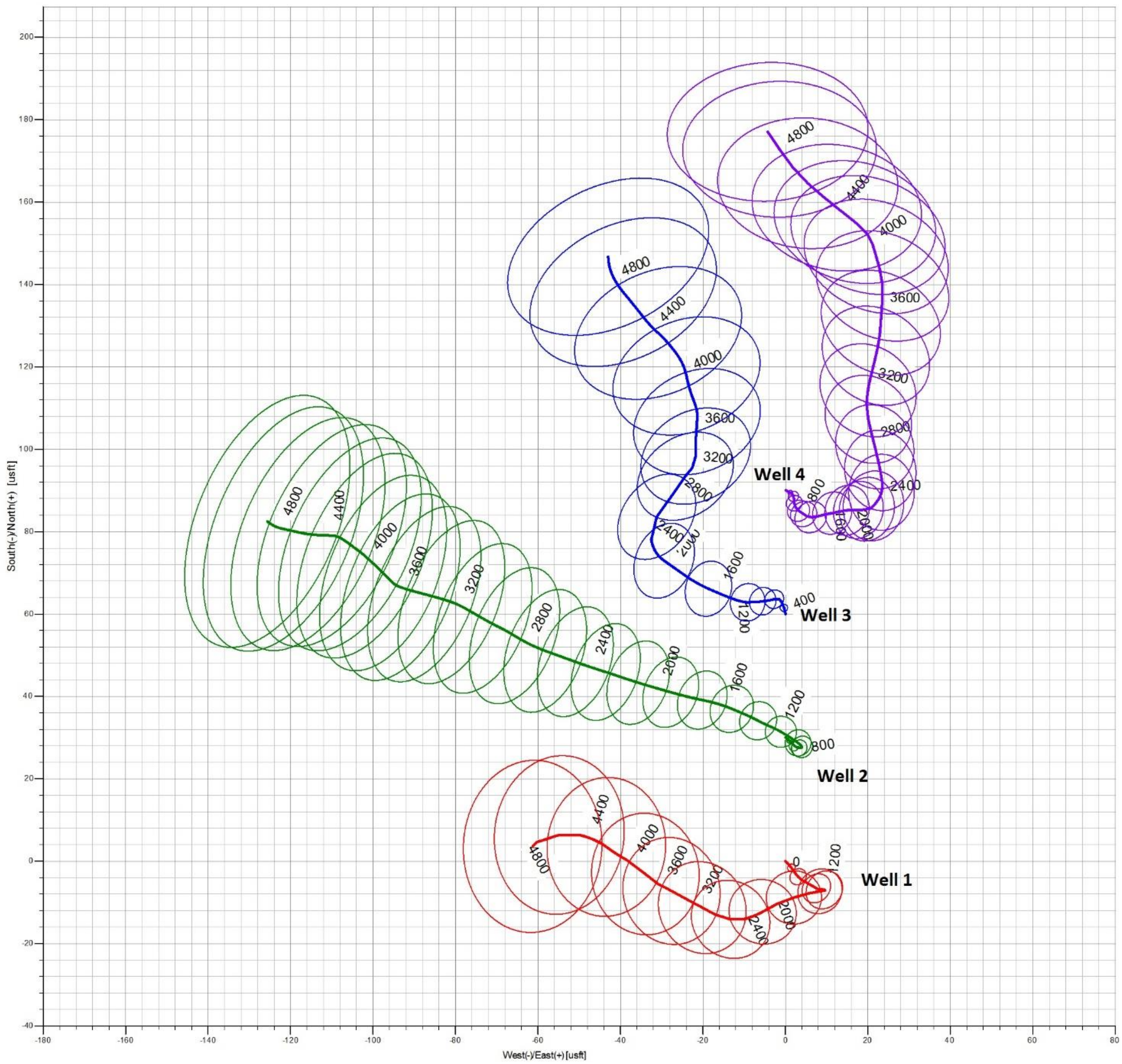


Figure 5. Case Study #4: Close Proximity Drilling Application

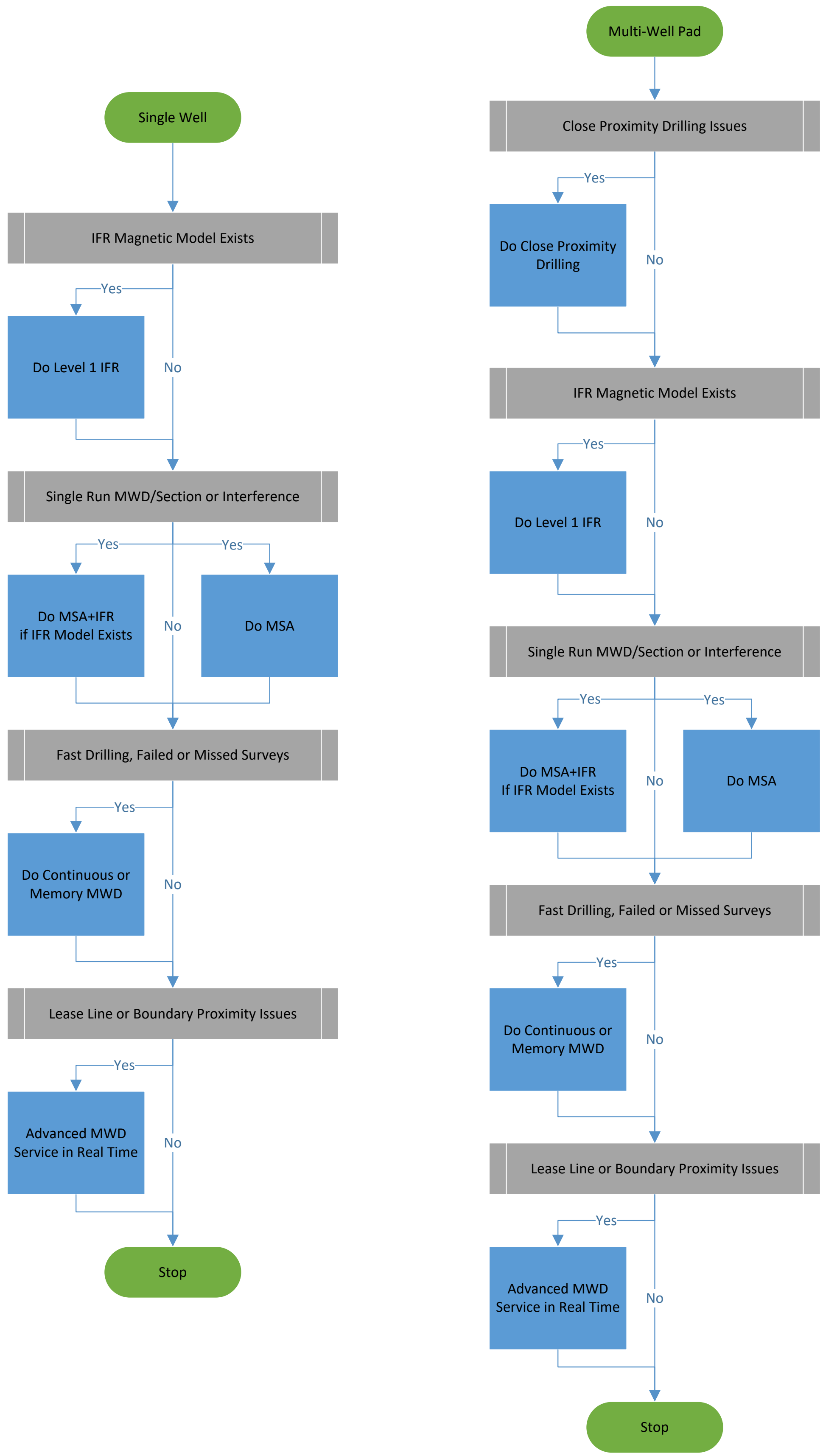


Figure 6. Advanced MWD Surveying Process Flowchart for Unconventional Wells