METHOD OF ASSESSING POSITIONAL UNCERTAINTY IN DRILLING A WELL

VERFAHREN ZUM EINSCHÄTZEN VON POSITIONSUNSICHERHEITEN BEIM BOHREN EINES BOHRLOCHS

PROCEDE D'ÉVALUATION DU FACTEUR D'INCERTITUDE DE LA POSITION LORS DU FORAGE D'UN PUITS

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References cited:
WO-A-96/35859
US-A- 4 957 172

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Description

[0001] The present invention relates to a method of assessing positional uncertainty in drilling a well. Such a method may be used, for example, at the planning stage in order to direct the drilling operation and to assess whether it is worth while to drill a particular well. The method may also be used in real time to control the drilling of a well.

[0002] In order to drill a well, it is necessary to define a geological target for the placement of the well. The geological target is a surface which is bounded by geological factors such as the position of geological faults and the extension of an oil-water contact. The geological target is defined by a geophysicist and is based on data about geological structures. Such data may be obtained, for example, in the form of seismic data or as data from nearby existing wells.

[0003] Some geological target boundaries are more important than others in the sense that it is more important to be inside some boundaries than others. For example, if a drill bit misses an oil zone, it will never be possible to produce oil. The geophysicist thus defines a reduced geological target whose boundaries are judged to be sufficiently remote from the boundaries of the geological target to ensure that there is a very good chance that the wellbore will not stray outside the geological target.

[0004] Figure 1 of the accompanying drawings illustrates such a conventional geological target 1 in the form of a rectangular surface having boundaries 2 to 5. Each of the boundaries 2 to 5 is associated with a risk in the form of a percentage associated with the drill bore straying outside the boundary. Thus, the risk of straying outside the boundary 2 should be no greater than 1% whereas the risks of straying outside the boundaries 3 to 5 should be no greater than 2.5%.

[0005] Within the conventional geological target 1 shown in Figure 1, various geological structures are illustrated by way of example. A conventional reduced geological target 6 is also illustrated and this is defined by the geophysicist on the basis of experience.

[0006] Thus, the geophysicist judges how far the boundaries of the conventional reduced geological target 6 should be spaced from the boundaries of the conventional geological target 1. Because of the higher risk associated with the boundary 2, which corresponds to a geological fault, the corresponding boundary 7 of the conventional reduced geological target 6 is more remote than the boundary 8 with respect to the corresponding boundary 4.

[0007] The "risk values" shown in Figure 1 as percentages are effectively the inverse of the acceptable probabilities of straying outside the respective boundaries. These values are generally referred to as "hardline values" and risks or probabilities are conventionally only assigned to boundaries which must not be crossed.

[0008] The geological data about the nature and location of structures beneath the surface of the earth are not precise; if such data were precise, then there would be no need for the conventional reduced geological target. There is a degree of uncertainty in the actual position of geological structures compared with the positions indicated by seismic and other data. This results in the need for the reduced target, whose purpose is to set an actual target for a driller to aim for during drilling of the well. The actual uncertainty in position varies from situation to situation but it is possible to provide some measure of the inaccuracy of the geological data. The geophysicist uses judgement in deciding the size and location of the conventional reduced geological target 6 within the conventional geological target 1.

[0009] Drilling of a well is also not a precise process. The geophysicist supplies the conventional reduced geological target 6 to a drilling engineer who must then define a drillers target within the conventional reduced geological target 6. The actual position of a drill bit compared with the measured or estimated position is also subject to inaccuracies. Such inaccuracies depend, for example, on the well trajectory geometry and the accuracy of drill position measuring equipment located behind the drill bit. The position measuring equipment can provide measurements of different accuracies depending on the type of measuring equipment and, in particular, on the cost thereof. A typical drillers target is shown at 9.

[0010] The drilling engineer has to define the drillers target such that, if the position of the drill bit is measured to be inside the drillers target, there is a predetermined likelihood that the well will actually be within the conventional reduced geological target 6 and hence, allowing for the inaccuracies in the geological data, the actual positioning of the well will be acceptable. The drilling engineer must judge whether more money should be spent on the drill position measuring equipment in order to improve the chances of drilling the well in the correct place.

[0011] United States Patent No. 4,957,172 discloses a system for use in drilling a relief well to intersect a target blow out well. A probable location distribution is used to survey the location of the candidate relief wells and the blow out well. A relief well plan is designed to drill a relief well to intersect the target blow out well with a low probability of a collision.

[0012] PCT Publication No. WO 96/35859 discloses a method for determining positional uncertainty of directional bore holes. The method comprises taking measurements of the bore hole at intervals along it and adopting a statistical approach to obtain the probability that the bore hole lies within the specified radius of the point of interest.

[0013] According to a first aspect of the invention, there is provided a method of estimating positional uncertainty in drilling a well, comprising supplying a first set of values representing a first three-dimensional uncertainty of the actual
position of a drill bit with respect to the estimated position thereof, supplying a second set of values representing a second three-dimensional uncertainty of the actual position of a geological feature with respect to the estimated position thereof, combining the first and second sets of values to form a third set of values representing a third uncertainty of the position of the drill bit with respect to the geological feature, calculating from the third uncertainty the probability that the drill bit reaches a predetermined position relative to the geological feature, defining a geological target as a finite surface and selecting a desired point of intersection of the drill path with the geological target, characterised in defining a plurality of geological targets along an intended drill path, calculating the probability of the drill path intersecting each of the geological targets, and deriving from the calculated probabilities the probability of the drill path staying within a corridor defined by the geological targets.

At least one of the first, second and third sets of values may comprise parameters of an error ellipsoid with a predetermined confidence interval referred to a Cartesian coordinate system.

At least one of the first, second and third sets of values may comprise a covariance matrix referred to a Cartesian coordinate system.

The first and second sets of values may be referred to different coordinate systems and the combining step may comprise transforming the first and second sets of values to fourth and fifth sets of values, respectively, referred to a common coordinate system and summing the corresponding values of the fourth and fifth sets to form the third set of values.

The probability may be calculated as a normal distribution.

The method may comprise calculating the probability of the drill path intersecting the geological target. The geological target may be a polygon. The geological target may be rectangular. Each side of the polygon may be ascribed a maximum acceptable probability of the drill path missing the geological target on that side.

The method may comprise calculating the probability of the drill bit being at a predetermined distance from the geological target.

The method may comprise using information from a marker point whose relative position including positional uncertainty to the geological target is at least partly known to correct at least one of the first set of values. The marker point may be the position of the drill bit during drilling when the drill bit penetrates a seismic reflector whose distance from the geological target is at least partly known. The geological target may be selected to coincide with a predetermined geological structure, the marker point may be disposed at the predetermined geological structure, and the position of the predetermined geological structure may be derived from a pilot well. The marker point may be observed during drilling using means disposed at or adjacent the drill bit. Such means may, for example, comprise seismic, acoustic or electromagnetic means. The method may comprise defining a drill target as a sub-surface within the geological target and calculating the probability that the drill path directed at a point within the drill target will intersect the geological target. The method may comprise defining a drill target as a sub-surface within the geological target and calculating the lowest probability that the drill path directed within the drill target will intersect the geological target.

The method may comprise defining a drill target as a sub-surface within the geological target and calculating the total probability that the drill path directed within the drill target will intersect the geological target. The method may comprise deriving a drill target as a sub-surface within the geological target whose boundary is defined by a predetermined probability.

According to a second aspect of the invention, there is provided a method of assessing the value of a well, comprising supplying details of a hydrocarbon reservoir, selecting an optimum point of intersection of a drill path with the reservoir, calculating the probabilities of the drill path intersecting the reservoir at a plurality of points using a method according to the first aspect of the invention, and calculating the probability distribution of the value of recoverable hydrocarbons for each of the points of intersection and deriving from the calculated probabilities and the probability distribution a distribution of the value of the well.

The drill may be partially withdrawn and the direction of drilling may be changed if the probability of the drill path intersecting the geological target following correction of the first set of values is less than a predetermined value.

It is thus possible to provide a technique which allows the uncertainties in the drilling of a well to be quantified in terms of probability. For example, when planning the drilling of a well, a geological target may be determined in the usual way with the appropriate hardline values being selected for the boundaries. Uncertainties in the actual positions of geological features compared with estimated or measured positions and uncertainties in drill bit position compared with estimated or measured position are combined to allow probabilities to be given, for example as to whether a selected intersection point with a geological target will be achieved. This allows the drillers target to be defined more accurately so as to improve the probability of correctly positioning a well. Also, the degree of accuracy of measurement of the drill bit position can be selected so as to achieve an acceptable probability of correctly positioning a well.

When combined with details of a hydrocarbon reservoir, it is possible to assess the commercial viability of the well and the need for more accurate drill bit positioning equipment when drilling the well. For example, if the structure of the reservoir is known or estimated, for example from geological data, the profitability of the well can be plotted as a function of probability and vice versa. The profitability of the well can be measured as the value of the hydrocarbon
reserves which can be produced for a given position of the well head at the hydrocarbon reservoir minus the costs of production. The probability of the position of the well head can be assessed. This allows more informed decisions to be taken as to whether it is commercially worth while to extract the hydrocarbon reserves and what sort of measuring equipment should be used during drilling of the well.

[0026] These techniques may be used during the planning stage before beginning to drill a well. However, the present technique may also be used in real time during drilling. For example, the material withdrawn through the drill string during drilling can indicate when the drill bit has reached the position of a known type of rock. At that point, the position of the drill bit is known to greater accuracy and this can be used to correct the set of values representing inaccuracy of the position of the drill. Such information may be used to guide the drill so as to increase the probability of intersecting the geological target at a particular position. It may be determined that the drill is straying too far away from the desired trajectory, in which case the drill may be steered so as to return towards the desired trajectory. If the drill bit has strayed too far away from the desired trajectory for correction by steering to be possible, it is possible to withdraw the drill bit partially and then to recommence drilling in a different direction so as to return towards the desired trajectory.

[0027] The present invention will be further described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a diagrammatic plan view illustrating conventional geological and reduced geological targets;

Figure 2 is a cross-sectional diagram illustrating a vertical section with geological features representing a geological model;

Figure 3 is a view similar to Figure 2 illustrating a geological target and a drill path;

Figure 4 is a view similar to Figure 3 illustrating a driller’s coordinate system;

Figure 5 is a diagram illustrating the nature of a geological target;

Figure 6 is a diagram illustrating a specific example of a geological target;

Figure 7 is a contour map illustrating an example of an oil reservoir;

Figures 8A and 8B show histograms and graphs relating to the economics of producing oil from the reservoir illustrated in Figure 7;

Figures 9A and 9B are similar to Figures 8A and 8B but illustrate the effect of using more accurate drill positioning equipment; and

Figure 10 illustrates the use of a plurality of geological targets for a thin oil zone.

[0028] Like reference numerals refer to like parts throughout the drawings.
[0029] Figure 2 is a vertical cross-sectional view of a geological model of a region in which it is believed that an oil reservoir exists and in which the drilling of a well is to be considered. The reservoir is shown at 10 and is bounded by a cap formation 11, a fault 12, and an oil-water contact 13. The geological model is supplied, for example, from the result of a seismic survey of the region and includes two major reflectors 14 and 15 disposed above the reservoir 11. The reflectors 14 and 15 represent transitions from one type of rock to another so that intersection with each of the reflectors 14 and 15 can be detected during drilling from formation measurements and material removed from the drill string (“cuttings”).
[0030] Figure 3 shows the model of Figure 2 together with the desired drilling trajectory 16 and the main reference coordinate system NEV, where N is grid north, E is grid easting and V is vertical position downwards (also referred to as true vertical depth or TVD). The coordinate system NEV is a three dimensional cartesian orthogonal right-handed coordinate system and, for convenience, the origin of this coordinate system is assigned to the desired intersection point 17 of the well with the cap formation 11 which partially bounds the reservoir 10 from above.
[0031] A geological target for the well drilling operation is defined, for example in the form of a polygon, as illustrated at 20 in Figure 3. Although the geological target may be defined in the NEV coordinate system, it is generally more convenient to define the geological target 20 in its own coordinate system uvw, which is also a three dimensional cartesian orthogonal right-handed coordinate system. In this coordinate system, u is directed along the dip direction of the geological target 20, v is directed horizontally and w is perpendicular to the uv plane but is not used because the geological target 20 is contained within the uv plane. The orientation of the uvw coordinate system is described
with respect to the NEV coordinate system by the azimuth $\text{Az}_{uvw}$ for the $u$ and $w$ axes (the plane $uw$ is a vertical plane) and the inclination $\text{Incl}_{uvw}$ for the $w$ axis. For convenience, the origin of the $uvw$ coordinate system coincides with that of the NEV system and the desired point of intersection 17 of the well 16 with the geological target 20 at the cap formation 11.

[0032] A geophysist and a reservoir geologist define the optimal well intersection point 17 and the direction of the well in the reservoir as the azimuth (for example 33°) and the inclination (for example 40°) in the NEV coordinate system. As shown in Figure 4, the well has a coordinate system $xyz$ which is also a three dimensional cartesian orthogonal right-handed coordinate system. In this system, $x$ is directed upwardly (along the azimuth for a vertical well), $y$ is directed horizontally to the right and $z$ is directed downwardly along the well axis. The orientation of the $xyz$ coordinate system with respect to the NEV coordinate system is described by the azimuth $\text{Az}_{xyz}$ for the $x$ or $z$ axis (the plane $xz$ is a vertical plane) and the inclination $\text{Incl}_{xyz}$ of the $z$ axis. Again for convenience, the origin of the $xyz$ axis coincides with that of the $uvw$ axis.

[0033] The actual shape of the geological target is determined by the geological formation and may be of any form. Figure 5 illustrates a polygonal geological target 20 in the $uv$ plane of the $uvw$ coordinate system with the comers of the polygon being numbered in a clockwise direction. The position $\text{POS\_GEO}_{uvw}$ of the geological target is specified in the $uvw$ coordinate system by the positions of the comers and may be represented in matrix form as:

$$\text{POS\_GEO}_{uvw} = \begin{bmatrix} u_1 & u_2 & \ldots & u_n \\ v_1 & v_2 & \ldots & v_n \\ w_1 & w_2 & \ldots & w_n \end{bmatrix}$$

where the $w$ coordinates are all equal to zero.

[0034] By way of example, Figure 6 illustrates a rectangular geological target 20 which is disposed parallel to the well azimuth. The size of the geological target 20 is specified with tolerance distances to the boundaries #1-#2, #2-#3, #3-#4 and #4-#1 from the desired intersection point 17 with the well.

[0035] Each of the sides of the geological target 20 is associated with a "hardline value" representing the maximum acceptable probability (in percent) of the well intersecting outside the respective side of the geological target 20. For example, the lower side #2-#3 may represent a fault having a risk value of 1% whereas the other sides of the geological target boundary are less critical and are associated with risk values of 2.5%. The tolerance distances and hardline values for a typical example of the geological target 20 are as follows:

<table>
<thead>
<tr>
<th>Geological Target</th>
<th>Target Line</th>
<th>Tolerance Distance</th>
<th>User specified Hardline value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#1-#2</td>
<td>100.0</td>
<td>2.5%</td>
</tr>
<tr>
<td></td>
<td>#2-#3</td>
<td>30.0</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>#3-#4</td>
<td>100.0</td>
<td>2.5%</td>
</tr>
<tr>
<td></td>
<td>#4-#1</td>
<td>140.0</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

which may be represented in matrix form as:

$$\text{POS\_GEO}_{uvw} = \begin{bmatrix} -30 & 140.0 & -30.0 & 140.0 \\ 100.0 & 100.0 & -100.0 & -100.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

where all distances specified herein are in metres.

[0036] A drillers target is specified as the target which a directional driller has to hit. Any position measured during drilling inside the drillers target is allowed. The shape of the drillers target can be of any form and may be represented...
as a plane within the uvw coordinate system. The size of the drillers target is determined by various factors such as the rock drillability, the well trajectory geometry and the directional drilling equipment being used. However, the drillers target is not based on any uncertainties in the geological model. The size of the drillers target is specified with tolerance distances to the boundaries from the intersection point.

[0037] The drillers target may also be described in the xy plane as the area within a polygon. The target is represented by the comers of the polygon ordered clockwise, in the same way as the geological target.

[0038] In order to calculate drilling position uncertainties, it is necessary to refer to a common coordinate system. This involves performing various coordinate transformations but only rotations are necessary. For example, in order to transform the drill bit position POS_DRxyz in the xyz coordinate system to the position POS_DRNEV in the NEV coordinate system, the following matrix formula is used:

\[
\text{POS}_{\text{DRNEV}} = \text{ROT}_{\text{xyz}} \ast \text{POS}_{\text{DRxyz}}
\]

where the rotation matrix \(\text{ROT}_{\text{xyz}}\) is given by:

\[
\text{ROT}_{\text{xyz}} = \begin{pmatrix}
\cos A_{\text{xyz}} \ast \cos I_{\text{xyz}} & -\sin A_{\text{xyz}} & \cos A_{\text{xyz}} \ast \sin I_{\text{xyz}} \\
\sin A_{\text{xyz}} \ast \cos I_{\text{xyz}} & \cos A_{\text{xyz}} & \sin A_{\text{xyz}} \ast \sin I_{\text{xyz}} \\
-\sin I_{\text{xyz}} & 0 & \cos I_{\text{xyz}}
\end{pmatrix}
\]

[0039] The reverse transformation from the NEV coordinate system to the xyz coordinate system is given by:

\[
\text{POS}_{\text{DRxyz}} = \text{ROT}^T_{\text{xyz}} \ast \text{POS}_{\text{DRNEV}}
\]

because the rotation matrix is orthogonal and the inverse matrix is thus the transpose \(\text{ROT}^T_{\text{xyz}}\) of the rotation matrix \(\text{ROT}_{\text{xyz}}\).

[0040] Similar transformations may be performed between the uvw coordinate system and the NEV coordinate system.

[0041] Transformations between the uvw coordinate system and the xyz coordinate system can be simplified because all of the w and z values are equal to zero. Such transformations represent orthogonal projections. Transformations between these coordinate systems may be performed by setting all of the w and z values to zero and then performing the transformation in two steps via the NEV coordinate system.

[0042] In the following example, the geological target and drillers target are transformed to the xyz co-ordinate system. Rotation from the uvw coordinate system to the NEV co-ordinate system uses the rotation matrix:

\[
\text{ROT}_{\text{uvw}} = \begin{pmatrix}
\cos A_{\text{uvw}} \ast \cos I_{\text{uvw}} & -\sin A_{\text{uvw}} & \cos A_{\text{uvw}} \ast \sin I_{\text{uvw}} \\
\sin A_{\text{uvw}} \ast \cos I_{\text{uvw}} & \cos A_{\text{uvw}} & \sin A_{\text{uvw}} \ast \sin I_{\text{uvw}} \\
-\sin I_{\text{uvw}} & 0 & \cos I_{\text{uvw}}
\end{pmatrix}
\]

[0043] In the specific example of a maximum dip of 10° in an Azimuth of 33°, the rotation matrix is:

\[
\text{ROT}_{\text{uvw\rightarrow NEV}} = \begin{pmatrix}
0,826 & -0,545 & -0,146 \\
0,536 & 0,839 & -0,095 \\
0,174 & 0,000 & 0,985
\end{pmatrix}
\]

[0044] The rotation from the NEV coordinate system to the xyz co-ordinate system is treated as described hereinbefore. The wellbore intersects the target plane with an azimuth of 33° and an inclination of 40°. This gives the transformation matrix:
The resulting transformation from the uvw coordinate system to the xyz co-ordinate system is:

\[
\begin{bmatrix}
0,642 & -0,545 & 0,539 \\
0,417 & 0,839 & 0,350 \\
-0,643 & 0,000 & 0,766
\end{bmatrix}
\]

The geological target is transformed to the xyz co-ordinate system by:

\[
\text{POS}_\text{GEO}_\text{xyz} = \text{ROT}^\top_{\text{uvw}-\text{xyz}} \cdot \text{POS}_\text{GEO}_\text{uvw}
\]

so that:

\[
\begin{bmatrix}
90,0 & -19,3 & 19,3 & 90,0 \\
100,0 & 100,0 & -100,0 & -100,0 \\
- & - & - & -
\end{bmatrix}
\]

In order to calculate the drilling positional uncertainty, it is necessary to add drilling uncertainty values to geological uncertainty values. The drilling uncertainty values are specified, for example by a drilling engineer on the basis of the drilling equipment to be employed, the drilling geometry and the drillability of the rocks through which the well must pass. The drilling uncertainty values are estimated for the well at the target intersection point.

Similarly, the geological uncertainties are estimated at the target depth and are supplied, for example by the geologist and the geophysist. The geological uncertainties are derived, for example, from the quality of the seismic data and from the interpretation of the seismic data.

The present method bases calculations on variances and covariances. However, any type of accuracy measure may be used, such as covariance matrices, confidence ellipses or ellipsoids and standard deviations.

The standard way of representing the geological accuracy is by assuming that all boundaries are determined with the same accuracy characterised by the covariance matrix:

\[
\Sigma_{\text{pos} \_ \text{NEV}} = \begin{bmatrix}
\text{var}(N) & \text{cov}(N, E) & \text{cov}(N, V) \\
\text{cov}(N, E) & \text{var}(E) & \text{cov}(E, V) \\
\text{cov}(N, V) & \text{cov}(E, V) & \text{var}(V)
\end{bmatrix}
\]

So far, variables are assumed to be distributed in accordance with the normal or standard distribution. However, the calculations do not need to use the chi-square distribution (derived from normal distributed variables) and other distributions for the variables may be used.

The geological uncertainty is based on factors like seismic navigation and data quality, interpretation uncer-
tainty and well tie-ins/calibrations. The calculations in this example are based on the covariance accuracy representation, and the numbers used are lateral/horizontal (40.0) and vertical (15.0) error (δ) as a one-dimensional (1D) 95% confidence interval.

\[
\begin{align*}
\text{Var}(N) &= \text{Var}(E) = (\delta_{\text{LATERAL}}/k_{1D 95\%})^2; \quad k_{1D 95\%} = 1.96 \\
\text{Var}(V) &= (\delta_{\text{VERTICAL}}/k_{1D 95\%})^2;
\end{align*}
\]

\[
\Sigma_{\text{POS \_ GEOwnc}} = \begin{pmatrix}
\text{var}(N) & 0 & 0 \\
0 & \text{var}(E) & 0 \\
0 & 0 & \text{var}(V)
\end{pmatrix}
\]

\[
\Sigma_{\text{BOORDER \_ GEOwnc}} = \begin{pmatrix}
413.4 & 0.0 & 0.0 \\
0.0 & 413.4 & 0.0 \\
0.0 & 0.0 & 58.1
\end{pmatrix}
\]

[0053] In some situations, some of the target boundaries may have different accuracy: e.g. a fault is determined with a higher precision than the other boundaries and thus contributes to the calculation of hitting probabilities in a different way from the others. The actual form of representing the accuracy thus becomes:

\[
\Sigma_{\text{BOORDER \_ GEOwnc}}
\]

[0054] This way of utilising this information is not shown here.

[0055] It is important to apply the "while drilling" position uncertainty values based on the planned combination of gyro and magnetic MWD survey tool runs prior to hitting the target, as well as to provide some distance prior to target intersection to allow for well trajectory adjustments.

[0056] The drilling error can be represented by a three dimensional (3D) error ellipsoid or as a horizontal ellipse and a vertical error with a specified confidence level:

<table>
<thead>
<tr>
<th>Drilling Uncertainty</th>
<th>Error</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Error Ellipse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major Half-axis</td>
<td>25.0</td>
<td>2D 95%</td>
</tr>
<tr>
<td>Minor Half-axis</td>
<td>12.0</td>
<td>2D 95%</td>
</tr>
<tr>
<td>Direction of Minor Axis</td>
<td>20.0°</td>
<td></td>
</tr>
<tr>
<td>Vertical Error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TVD Error</td>
<td>12.0</td>
<td>1D 95%</td>
</tr>
</tbody>
</table>

[0057] In this example, all uncertainty parameters are assumed to have a normal distribution. The variables can be scaled according to confidence interval and dimension. The scaling values can be picked from a chi squared distribution.
The 3D Error Ellipsoid can be transformed to the Covariance using the expressions:

\[
\begin{align*}
\text{var}(N) &= \cos^2(Az_{\text{MAJOR}}) \cdot \text{Var}_{\text{MAJOR}} + \sin^2(Az_{\text{MAJOR}}) \cdot \text{Var}_{\text{MINOR}} \\
\text{var}(E) &= \sin^2(Az_{\text{MAJOR}}) \cdot \text{Var}_{\text{MAJOR}} + \cos^2(Az_{\text{MAJOR}}) \cdot \text{Var}_{\text{MINOR}} \\
\text{var}(V) &= \text{Var}_{\text{TVD}} \\
\text{cov}(N,E) &= -\sin(Az_{\text{MAJOR}}) \cdot \cos(Az_{\text{MAJOR}}) \cdot (\text{Var}_{\text{MAJOR}} - \text{Var}_{\text{MINOR}}) \\
\text{cov}(N,V) &= \text{cov}(E,V) = 0
\end{align*}
\]

\[\Sigma_{\text{POS \_ DRNVP}} = \begin{bmatrix}
\text{var}(N) & \text{cov}(N,E) & \text{cov}(N,V) \\
\text{cov}(N,E) & \text{var}(E) & \text{cov}(E,V) \\
\text{cov}(N,V) & \text{cov}(E,V) & \text{var}(V)
\end{bmatrix}\]

The drilling survey covariance matrix is thus:

\[\Sigma_{\text{POS \_ DRNVP}} = \begin{bmatrix}
33.4 & -25.8 & 0.0 \\
-25.8 & 894.7 & 0.0 \\
0.0 & 0.0 & 37.2
\end{bmatrix}\]

Utilising the assumption that the drilling and the geological positions are independent variables, the compound accuracy becomes:

\[\Sigma_{\text{POS\_TOTAL}} = \Sigma_{\text{POS\_GEO}} + \Sigma_{\text{POS\_DR}}\]

when the covariances are given in the same co-ordinate system.

Geological markers identified while drilling or pilot well information may provide stratigraphic control and improve the tie between the well and the surface seismic and geological model. As a result, a more favourable TVD uncertainty number at the target can be achieved.

A tie to a geological marker improves the accuracy in a direction normal to the marker plane. The covariance matrix must be transformed (ROT\_NEV\_MARKER\_PLANE) to the plane before the error budget can be updated with the relative uncertainty:
Then the matrix has to be transformed back to the NEV-plane.

The relative TVD error (ID 95% confidence interval) represents the estimated relative uncertainty from the geological marker to the target. The relative TVD error must include both the drilling and geological uncertainty (Square-Root-Sum of the uncertainties) at the target calculated from the reference point.

In this example, a relative TVD error from the marker of 4.0 (ID 95% confidence interval) is anticipated. The geological marker plane is also horizontal. The "new" total (relative) covariance for this example is:

\[
\Sigma_{POS \_TOTAL \_NEV} = \begin{pmatrix}
446.8 & -25.8 & 0.0 \\
-25.8 & 508.2 & 0.0 \\
0.0 & 0.0 & 4.1
\end{pmatrix}
\]

Because of the linear relationship between co-ordinates in the different systems, the covariance propagates as:

\[
\Sigma_{POS \_TOTAL \_xyz} = \text{ROT}^T_{xyz\_NEV} \Sigma_{POS \_TOTAL \_NEV} \text{ROT} \_xyz\_NEV
\]

The variance for a point along the axis \(t\) with a constrained direction \(a\) is given by:

\[
\text{var}(t) = (\cos \alpha \ \sin \alpha \ 0) \cdot \Sigma_{POS \_TOTAL \_xyz} \cdot (\cos \alpha \ \sin \alpha \ 0)
\]

where \(t\) is a linear transform of the normal distributed \(x, y\) and \(z\) and thus becomes normal distributed itself. The complete distribution function is evident.

The following covariance matrix is used:
To obtain effective calculation formulae, the standard error ellipse parameter is found and the searching direction which gives maximum standard deviation is given by:

\[ \theta_\eta = \arctan(2 \cdot \text{cov}(x,y)/(\text{var}(x)-\text{var}(y))) \]

Maximum and minimum variances are given by:

\[ q = ((\text{var}(x) - \text{var}(y))^2 + (2 \cdot \text{cov}(x,y))^2)^{1/2} \]
\[ \text{var}(\zeta) = 0.5 \cdot (\text{var}(x) + \text{var}(y) + q) \]
\[ \text{var}(\eta) = 0.5 \cdot (\text{var}(x) + \text{var}(y) - q) \]

A point with co-ordinates \( xy \) is now transformed into the \( \zeta\eta \) system which is characterised by no statistical correlation between its axes.

\[ \zeta = x \cdot \cos(\theta) + y \cdot \sin(\theta) \]
\[ \eta = x \cdot \sin(\theta) + y \cdot \cos(\theta) \]

The probability density, \( f() \), for a point is now:

\[ f() = r \cdot e^{-0.5(\zeta^2/\text{var}(\zeta) + \eta^2/\text{var}(\eta))} \]
\[ r = 1/(2 \cdot \pi \cdot \sqrt{\text{var}(\zeta) \cdot \text{var}(\eta)}) \]

In order to calculate the probability of intersection on the right side of a geological boundary, the standard deviation along the direction orthogonal to the actual border line is calculated. Further the distance from the point of interest to the border line is calculated. These two values are the input to a straightforward calculation of probability.

The \( \text{var}(t) \) can be scaled according to confidence interval and dimension. The scaling values \( (k_{1D}^{95\%}) \) to a given confidence interval can be picked from a normal distribution.

The "Hardline Value" is the one-sided distribution of the confidence interval:

"Confidence Interval" = 100% - \( P_{\text{HARDLINE}} \cdot 2 \)

For example, for Target Line #1-#2:
\[ P_{\text{HARDLINE}} = 2.5\% \]
"Confidence Interval" = 100% - (2.5\% \cdot 2) = 95\%; \Rightarrow \text{var}(95\%) = 1.96
Minimum distance = \( \sqrt{\text{var}(\text{target line}) \cdot k_{1D}^{95\%}} \)

In this example, this formula is used to calculate the minimum distance from the geological boundaries to the drillers target, using the total uncertainty and the "Hardline Values".
This gives the drillers target co-ordinates

\[
\text{POS\_DR}_{uvw} = \begin{pmatrix} 58.2 & 18.3 & 18.3 & 58.2 \\ 55.4 & 55.4 & 55.4 & 55.4 \end{pmatrix}
\]

which can be transformed to the uvw coordinate system by:

\[
\text{POS\_DR}_{uvw} = \text{ROT}_{uvw-xyz} \cdot \text{POS\_DR}_{xyz}
\]

to give:

\[
\text{POS\_DR}_{uvw} = \begin{pmatrix} 90.6 & 28.4 & 28.4 & 90.6 \\ 55.4 & 55.4 & 55.4 & 55.4 \\ 0 & 0 & 0 & 0 \end{pmatrix}
\]

In this case, it is preferred to aim the wellbore to interest in the centre of the drillers target. This results a new coordinate for the wellbore with an offset with the new tolerance distances for the chillers target:

\[
\text{POS\_WELL\_OFFSET}_{uvw} = \begin{pmatrix} 49.2 \\ 31.9 \\ 10.3 \end{pmatrix}
\]

One method of computing the probability (\(P_{\text{HIT}}()\)) of hitting the geological target is to divide the geological target into cells (e.g. an orthogonal grid covering the geological target with 100 cells in both x and y direction) and to do a numerical integration.
The steps in probability calculation for a given location in the xy plane comprise:

Temporarily translating the origin for the distribution function to be in the actual point. Calculating the probability density for all cells within the target; and

Calculating the hitting probability by summing the probability densities multiplied with the cell size (area).

This method gives the hitting probability from one realisation of the planned drillbit coordinate. However, the hitting probability is changed by moving around in the drillers target. The hitting probability can be calculated for all points inside the drillers target and gives:

\[ P_{\text{HIT}}(\text{Minimum}) = 95.1\% \]

\[ P_{\text{HIT}}(\text{Target Centre}) = 99.91\% \]

This technique may be used to assess the value of a potential oil well before drilling begins so as to assess whether the cost of the well is likely to be justified by the profit and whether improved positional accuracy in drilling is likely to be justified by the likely increased profit.

Figure 7 is a horizontal contour map illustrating, from above, the measured position of an oil reserve. A contour 25 represents the horizontal edge of the reservoir i.e. corresponding to an oil layer thickness of zero. Contours 26 and 27 represent increasing constant thicknesses of the oil layer and a point 28 represents the top of the oil layer. In order to achieve maximum production from an oil well, it would be necessary for the drill path to intersect the reservoir at the point 28. Intersection at any other point within the boundary of the reservoir illustrated by the contour 25 would result in less than maximum oil production.

The technique described hereinbefore may be used to assess the probability of the drill path intersecting the reservoir at various points. Intersection at each point is associated with an expected value corresponding to the amount of oil likely to be produced. A probability distribution of the value of recoverable hydrocarbons for each of the points is thus calculated and this allows the distribution of the value of the well to be calculated.

This analysis may be performed before drilling commences so as to assess whether the well is likely to be commercially worthwhile.

The analysis may be repeated under different conditions. For example, by using more accurate positioning equipment in the drill bit, drilling inaccuracies can be reduced so as to improve the probability of achieving larger production from the well. Figures 9A and 9B illustrate the effect of using more accurate positioning equipment. The initial cost 37 of the more expensive equipment is higher but the likelihood of greater production 38 from the well is substantially increased. The new integrated NPV is illustrated at 39 with the other uncertainty levels illustrated at 40 and 41 (corresponding to 32 and 33 in Figure 8A). This is also illustrated in Figure 9B where the expected value 42 is higher than that of Figure 8B with the other uncertainties 43 and 44 corresponding to 35 and 36 in Figure 8B. For comparison, the distribution of Figure 8B is illustrated in broken lines at 45 in Figure 9B.

Figure 10 illustrates an extension of this technique such that a plurality of geological targets 20a to 20k are defined along a planned drill path 16a. The use of such a technique is desirable, for example, in the case of relatively thin oil zones where a horizontal well is drilled into the reservoir 10. It is important for the well to stay within the oil zone and not, for example, to enter a water zone which would result in the oil production rate being reduced or lost. The geological targets 20d to 20k are defined in the oil zone. A positive economic value is assigned to points inside the geological targets 20d to 20k with a large negative value being assigned to points outside these targets. Information can be obtained about the distribution of oil production which is likely to be achieved and this can be assessed against the cost of reducing the drilling or geological uncertainty by further investment. For example, the technique described with reference to Figures 7 to 9 may be used in this assessment.

The same type of analysis may be performed in real time. The NPV can be estimated during drilling and evaluated against planned values. A drilled well bore is illustrated at 16b. The path is very close to the oil/water contact and the expected NPV would be low. The need for and benefits of a new side-track may be evaluated and executed at an early stage.
The completion of the well may also be changed based on the drilled well bore, uncertainties and the estimated risk of water coning.

Claims

1. A method of estimating positional uncertainty in drilling a well, comprising supplying a first set of values representing a first three-dimensional uncertainty of the actual position of a drill bit with respect to the estimated position thereof, supplying a second set of values representing a second three-dimensional uncertainty of the actual position of a geological feature with respect to the estimated position thereof, combining the first and second sets of values to form a third set of values representing a third uncertainty of the position of the drill bit with respect to the geological feature, calculating from the third uncertainty the probability that the drill bit reaches a predetermined position relative to the geological feature, defining a geological target (20) as a finite surface and selecting a desired point of intersection of the drill path with the geological target, and characterised in defining a plurality of geological targets along an intended drill path, calculating the probability of the drill path intersecting each of the geological targets, and deriving from the calculated probabilities the probability of the drill path staying within a corridor defined by the geological targets.

2. A method as claimed in claim 1, in which at least one of the first, second and third sets of values comprises parameters of an error ellipsoid with a predetermined confidence interval referred to a Cartesian coordinate system.

3. A method as claimed in claim 1 or 2, in which at least one of the first, second and third sets of values comprises a covariance matrix referred to a Cartesian coordinate system.

4. A method as claimed in any one of the preceding claims, in which the first and second sets of values are referred to different coordinate systems and the combining step comprises transforming the first and second sets of values to fourth and fifth sets of values, respectively, referred to a common coordinate system and summing corresponding values of the fourth and fifth sets to form the third set of values.

5. A method as claimed in any one of the preceding claims, in which the probability is calculated as a normal distribution.

6. A method as claimed in any preceding claim, comprising calculating the probability of the drill path intersecting the geological target.

7. A method as claimed in claim 6, in which the geological target (20) is a polygon.

8. A method as claimed in claim 7, in which the geological target (20) is rectangular.

9. A method as claimed in claim 7 or 8, in which each side of the polygon is ascribed a maximum acceptable probability of the drill path missing the geological target on that side.

10. A method as claimed in any preceding claim, comprising calculating the probability of the drill bit being at a predetermined distance from the geological target (20).

11. A method as claimed in any preceding claim, comprising using information from a marker point whose relative position including positional uncertainty to the geological target (20) is at least partly known to correct at least one of the first set of values.

12. A method as claimed in claim 11, in which the marker point is the position of the drill bit during drilling when the drill bit penetrates a seismic reflector whose distance from the geological target (20) is at least partly known.

13. A method as claimed in claim 11, in which the geological target (20) is selected to coincide with a predetermined geological structure, the marker point is disposed at the predetermined geological structure, and the position of the predetermined geological structure is derived from a pilot well.

14. A method as claimed in claim 13, in which the drill is partially withdrawn and the direction of drilling is changed if the probability of the drill path intersecting the geological target following correction of the first set of values is less
than a predetermined value.

15. A method as claimed in claim 12, in which the marker point is observed during drilling using means disposed at or adjacent the drill bit.

16. A method as claimed in any one of claims 6 to 15, comprising defining a drill target as a sub-surface within the geological target and calculating the probability that the drill path directed at a point within the drill-target will intersect the geological target.

17. A method as claimed in any one of claims 6 to 15, comprising defining a drill target as a sub-surface within the geological target and calculating the lowest probability that the drill path directed within the drill target will intersect the geological target.

18. A method as claimed in any one of claims 6 to 15, comprising defining a drill target as a sub-surface within the geological target and calculating the total probability that the drill path directed within the drill target will intersect the geological target.

19. A method as claimed in any one of claims 1 to 15, comprising deriving a drill target as a sub-surface within the geological target (20) whose boundary is defined by a predetermined probability.

20. A method of assessing the value of a well, characterised in comprising supplying details of a hydrocarbon reservoir, selecting an optimum point of intersection of a drill path with the reservoir, calculating the probabilities of the drill path intersecting the reservoir at a plurality of points using a method as claimed in any one of claims 1 to 19, calculating the probability distribution of the value of recoverable hydrocarbons for each of the points of intersection and deriving from the calculated probabilities and the probability distribution a distribution of the value of the well.

Patentansprüche


5. Verfahren nach einem der vorherigen Ansprüche, bei dem die Wahrscheinlichkeit als normale Verteilung berechnet.
wird.


7. Verfahren nach Anspruch 6, bei dem das geologische Ziel (20) ein Polygon ist.

8. Verfahren nach Anspruch 7, bei dem das geologische Ziel (20) rechteckig ist.

9. Verfahren nach Anspruch 7 oder 8, bei dem jeder Seite des Polygons eine maximale akzeptable Wahrscheinlichkeit zugeschrieben wird, dass der Bohrweg das geologische Ziel auf dieser Seite verpasst.


15. Verfahren nach Anspruch 12, bei dem der Markierungspunkt während des Bohrens mit Mitteln beobachtet wird, die an oder neben dem Bohrmeißel angeordnet sind.


19. Verfahren nach einem der Ansprüche 1 bis 15, umfassend das Ableiten eines Bohrziels als eine Subfläche innerhalb des geologischen Ziels (20), deren Grenze durch eine vorbestimmte Wahrscheinlichkeit definiert wird.

Revendications

1. Procédé d'estimation d'une incertitude de position au niveau du forage d'un puits, comprenant l'application d'un premier jeu de valeurs représentant une première incertitude en trois dimensions de la position réelle d'un outil de forage par rapport à sa position estimée, l'application d'un second jeu de valeurs représentant une seconde incertitude en trois dimensions de la position réelle d'une caractéristique géologique par rapport à sa position estimée, la combinaison des premier et second jeux de valeurs afin de former un troisième jeu de valeurs représentant une troisième incertitude de la position de l'outil de forage par rapport à la caractéristique géologique, le calcul, à partir de la troisième incertitude, de la probabilité que l'outil de forage atteigne une position prédéterminée par rapport à la caractéristique géologique, la définition d'une cible géologique (20) en tant que surface finie et la sélection d'un point d'intersection souhaité de la voie de forage avec la cible géologique, et caractérisé par la définition d'une pluralité de cibles géologiques le long d'une voie de forage visée, par le calcul de la probabilité que la voie de forage intersecte chacune des cibles géologiques et par la dérivation, à partir des probabilités calculées, de la probabilité que la voie de forage reste à l'intérieur d'un corridor qui est défini par les cibles géologiques.

2. Procédé selon la revendication 1, dans lequel au moins l'un des premier, second et troisième jeux de valeurs comprend des paramètres d'un ellipsoïde d'erreurs moyennant un intervalle de confiance prédéterminé rapporté à un système de coordonnées cartésiennes.

3. Procédé selon la revendication 1 ou 2, dans lequel au moins l'un des premier, second et troisième jeux de valeurs comprend une matrice de covariance rapportée à un système de coordonnées cartésiennes.

4. Procédé selon l'une quelconque des revendications précédentes, dans lequel les premiers et second jeux de valeurs sont rapportés à des systèmes de coordonnées différents et l'étape de combinaison comprend la transformation des premier et second jeux de valeurs selon des quatrième et cinquième jeux de valeurs, de façon respective, rapportés à un système de coordonnées commun et la sommation de valeurs correspondantes des quatrième et cinquième jeux pour former le troisième jeu de valeurs.

5. Procédé selon l'une quelconque des revendications précédentes, dans lequel la probabilité est calculée en tant que distribution normale.

6. Procédé selon l'une quelconque des revendications précédentes, comprenant le calcul de la probabilité que la voie de forage intersecte la cible géologique.

7. Procédé selon la revendication 6, dans lequel la cible géologique (20) est un polygone.

8. Procédé selon la revendication 7, dans lequel la cible géologique (20) est rectangulaire.

9. Procédé selon la revendication 7 ou 8, dans lequel chaque côté du polygone se voit attribuer une probabilité acceptable maximum que la voie de forage manque la cible géologique sur ce côté.

10. Procédé selon l'une quelconque des revendications précédentes, comprenant le calcul de la probabilité que l'outil de forage soit à une distance prédéterminée de la cible géologique (20).

11. Procédé selon l'une quelconque des revendications précédentes, comprenant l'utilisation d'une information en provenance d'un point de marqueur dont une position relative incluant une incertitude de position par rapport à la cible géologique (20) est au moins partiellement connue pour corriger au moins une valeur du premier jeu de valeurs.

12. Procédé selon la revendication 11, dans lequel le point de marqueur est la position de l'outil de forage pendant le forage lorsque l'outil de forage pénètre un réflecteur sismique dont la distance par rapport à la cible géologique (20) est au moins partiellement connue.

13. Procédé selon la revendication 11, dans lequel la cible géologique (20) est sélectionnée de manière à coïncider avec une structure géologique prédéterminée, le point de marqueur est disposé au niveau de la structure géologique prédéterminée et la position de la structure géologique prédéterminée est dérivée à partir d'un puits de pilote.
14. Procédé selon la revendication 13, dans lequel l'outil de forage est partiellement retiré et la direction de forage est modifiée si la probabilité que la voie de forage intersecte la cible géologique à la suite d'une correction du premier jeu de valeurs est inférieure à une valeur prédéterminée.

15. Procédé selon la revendication 12, dans lequel le point de marqueur est observé pendant le forage en utilisant un moyen qui est disposé au niveau de l'outil de forage ou en une position adjacente à l'outil de forage.

16. Procédé selon l'une quelconque des revendications 6 à 15, comprenant la définition d'une cible de forage en tant que sous-surface à l'intérieur de la cible géologique et le calcul de la probabilité que la voie de forage qui est dirigée en un point à l'intérieur de la cible de forage intersecte la cible géologique.

17. Procédé selon l'une quelconque des revendications 6 à 15, comprenant la définition d'une cible de forage en tant que sous-surface à l'intérieur de la cible géologique et le calcul de la probabilité la plus faible que la voie de forage qui est dirigée à l'intérieur de la cible de forage intersecte la cible géologique.

18. Procédé selon l'une quelconque des revendications 6 à 15, comprenant la définition d'une cible de forage en tant que sous-surface à l'intérieur de la cible géologique et le calcul de la probabilité totale que la voie de forage qui est dirigée à l'intérieur de la cible de forage intersecte la cible géologique.

19. Procédé selon l'une quelconque des revendications 1 à 15, comprenant la dérivation d'une cible de forage en tant que sous-surface à l'intérieur de la cible géologique (20) dont une frontière est définie par une probabilité prédéterminée.

20. Procédé d'évaluation de la valeur d'un puits, caractérisé en ce qu'il comprend l'application de détails d'un réservoir d'hydrocarbure, la sélection d'un point d'intersection optimum d'une voie de forage avec le réservoir, le calcul des probabilités que la voie de forage intersecte le réservoir en une pluralité de points en utilisant un procédé selon l'une quelconque des revendications 1 à 19, le calcul de la distribution de probabilités de la valorisation d'hydrocarbures récupérables pour chacun des points d'intersection et la dérivation à partir des probabilités calculées et de la distribution de probabilités d'une distribution de la valeur du puits.