

Borehole Positioning and Tortuosity Standard Calculation Methods

"Where we are now and where we are going"

Darren Aklestad

1



Speaker Information

- Darren Aklestad
- Principal Surveying Engineer
- **Schlumberger**
 - 25 yrs Drilling & Measurements experience
 - Specialized in: Well Planning, Anti-Collision, Error Modelling, Survey Corrections, Cartography, Drilling Automation (Software Solutions)

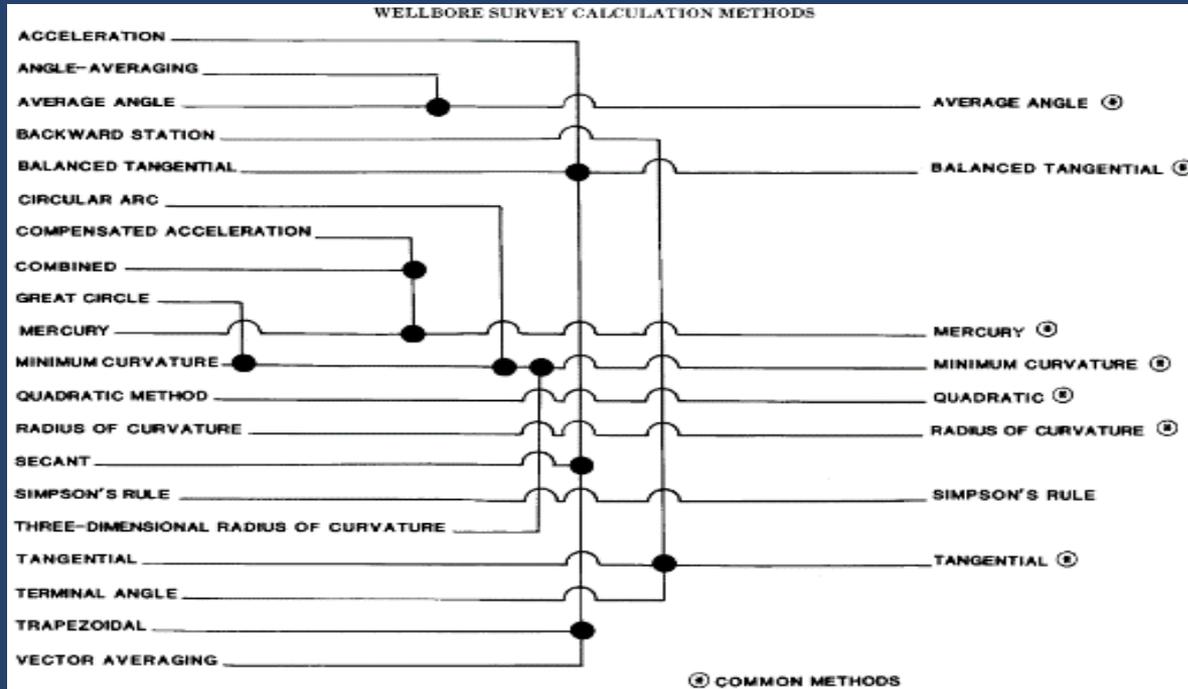
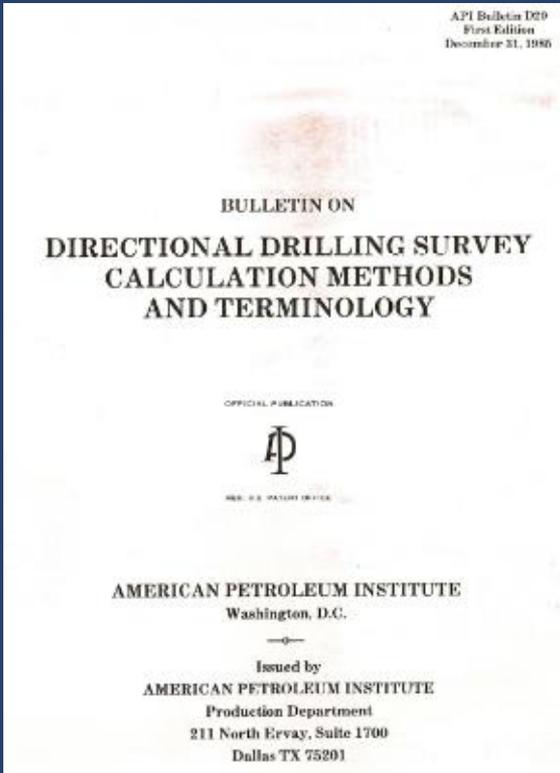


Presentation Agenda

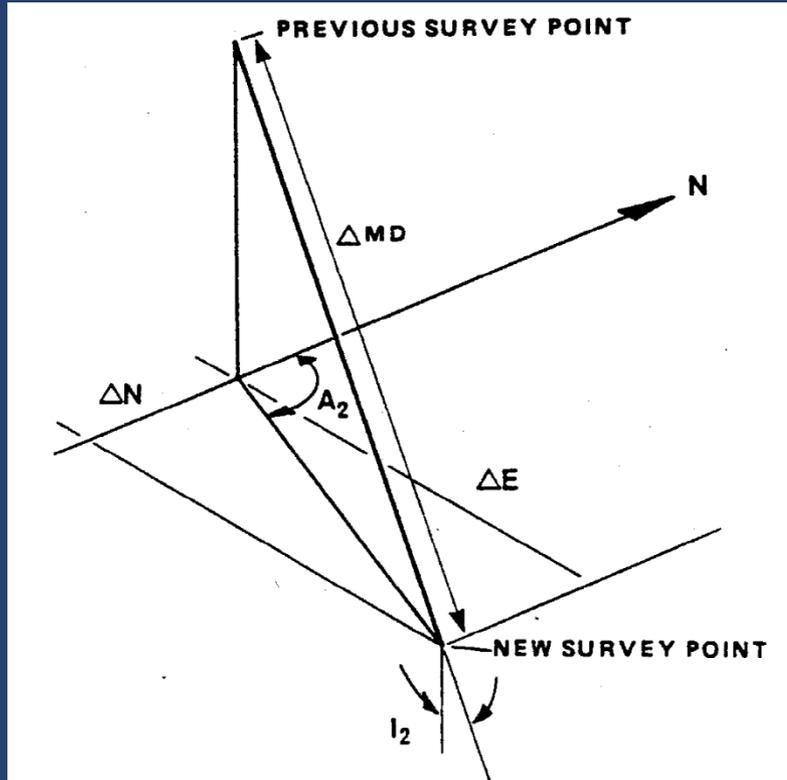
- **Borehole Position Calculation Methods – “Where We Are & Have Been”**
- **Hole Condition “Shape” Indicators**
 - Dogleg / Severity
 - Tortuosity
 - Rugosity
- **Borehole Position Calculation Methods – “Where We Are Going”**
 - High frequency surveys
 - Computation Problems
 - New Model Methods



Trajectory Calculation Models API Bulletin D20 (1985)

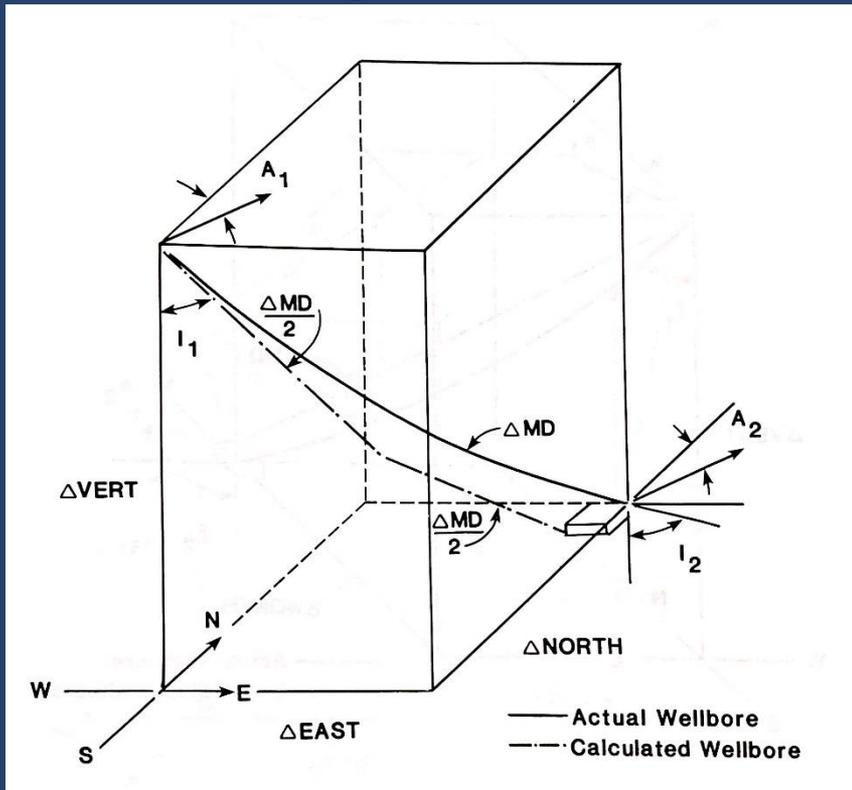


Tangential Method



$$\begin{aligned}\Delta \text{ North} &= \Delta \text{ MD} \cdot \sin I_2 \cdot \cos A_2 \\ \Delta \text{ East} &= \Delta \text{ MD} \cdot \sin I_2 \cdot \sin A_2 \\ \Delta \text{ Vertical} &= \Delta \text{ MD} \cdot \cos I_2 \\ \text{Depth} \\ \Delta \text{ Course displacement} &= \Delta \text{ MD} \cdot \sin I_2\end{aligned}$$

Balanced Tangential Method



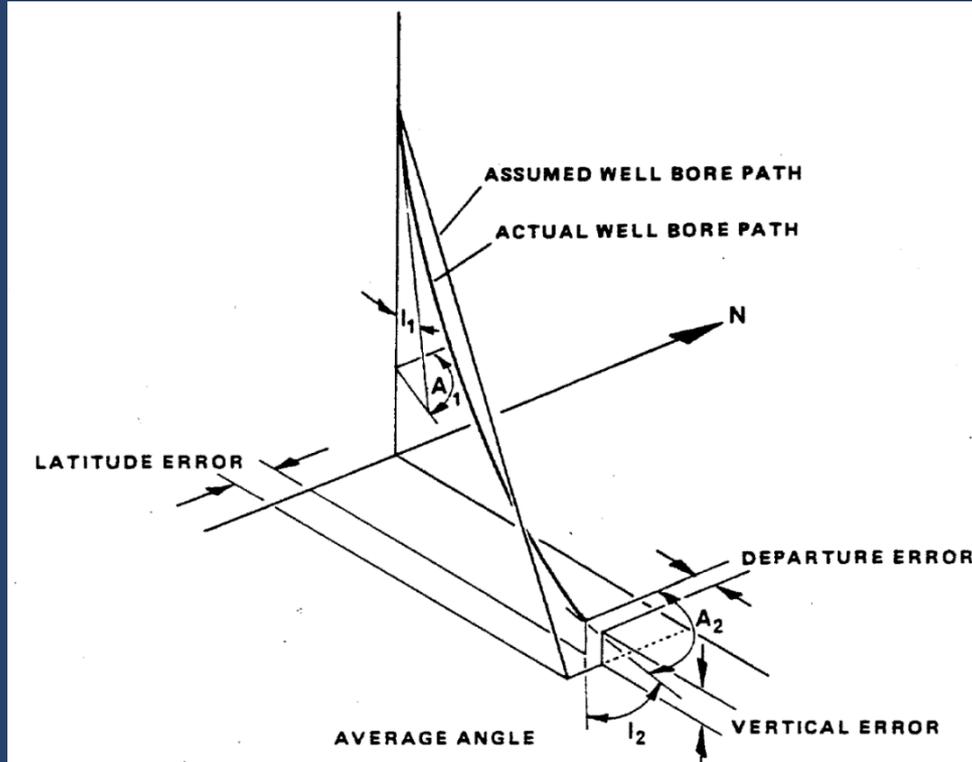
$$\Delta North = \frac{\Delta MD}{2} \left[\sin I_1 \cos A_1 + \sin I_2 \cos A_2 \right]$$

$$\Delta East = \frac{\Delta MD}{2} \left[\sin I_1 \sin A_1 + \sin I_2 \sin A_2 \right]$$

$$\Delta Vertical\ Depth = \frac{\Delta MD}{2} \left[\cos I_1 + \cos I_2 \right]$$

$$\Delta Course\ Displacement = \frac{\Delta MD}{2} \left[\sin I_1 + \sin I_2 \right]$$

Average Angle Method



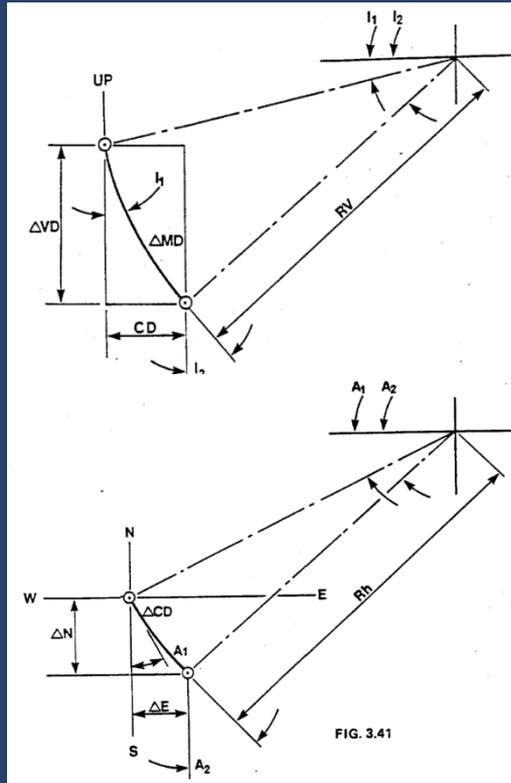
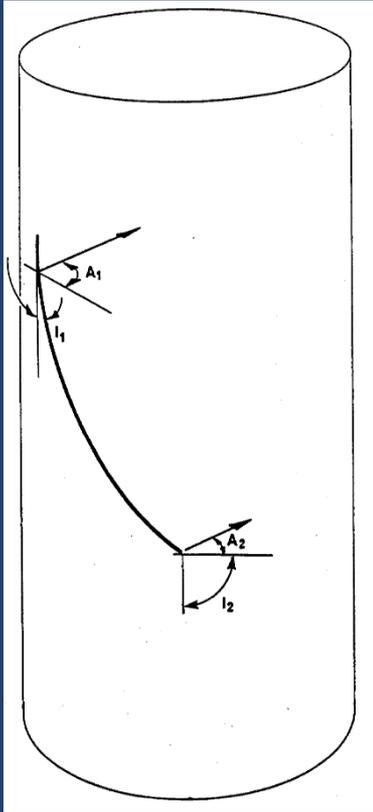
$$\Delta \text{ North} = \Delta \text{ MD} \cdot \sin \left[\frac{l_1 + l_2}{2} \right] \cdot \cos \left[\frac{A_1 + A_2}{2} \right]$$

$$\Delta \text{ East} = \Delta \text{ MD} \cdot \sin \left[\frac{l_1 + l_2}{2} \right] \cdot \sin \left[\frac{A_1 + A_2}{2} \right]$$

$$\Delta \text{ Vertical Depth} = \Delta \text{ MD} \cdot \cos \left[\frac{l_1 + l_2}{2} \right]$$

$$\text{Course Displacement} = \Delta \text{ MD} \cdot \sin \left[\frac{l_1 + l_2}{2} \right]$$

Radius Of Curvature



$$R_v = \frac{180 \cdot \Delta MD}{\pi (I_2 - I_1)}$$

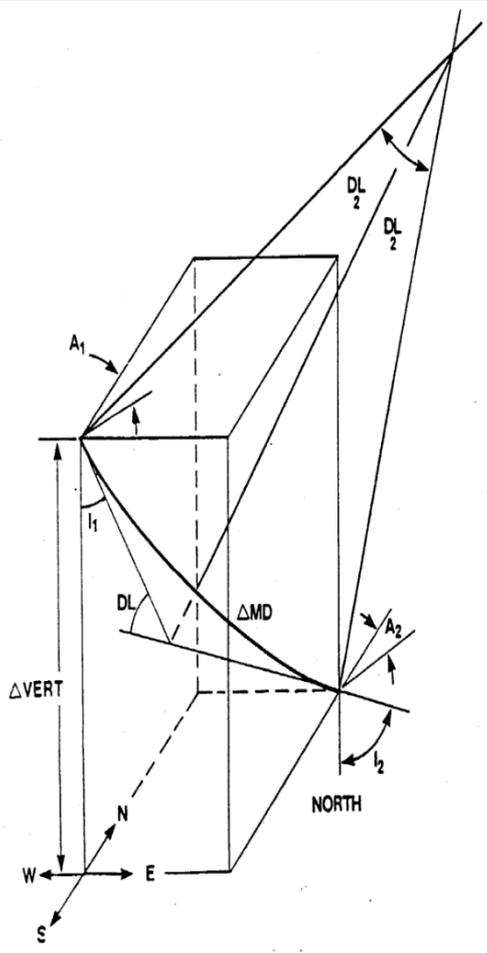
$$\begin{aligned} \Delta VD &= R_v \sin I_2 - R_v \sin I_1 \\ &= R_v (\sin I_2 - \sin I_1) \\ &= \frac{180 \cdot \Delta MD}{\pi} \frac{(\sin I_2 - \sin I_1)}{(I_2 - I_1)} \\ CD &= R_v \cos I_1 - R_v \cos I_2 \\ &= \frac{180 \cdot \Delta MD}{\pi} \frac{(\cos I_1 - \cos I_2)}{(I_2 - I_1)} \end{aligned}$$

$$R_h = \frac{180 \cdot \Delta CD}{\pi (A_2 - A_1)}$$

$$\begin{aligned} \Delta \text{North} &= R_h \sin A_2 - R_h \sin A_1 \\ &= \frac{180^2 \Delta MD}{\pi^2 (A_2 - A_1) (I_2 - I_1)} (\cos I_1 - \cos I_2) (\sin A_2 - \sin A_1) \\ \Delta \text{East} &= \frac{180^2 \Delta MD}{\pi^2 (A_2 - A_1) (I_2 - I_1)} (\cos I_1 - \cos I_2) (\cos A_1 - \cos A_2) \end{aligned}$$

Minimum Curvature

$$DL = \cos^{-1} \left[\cos(I_2 - I_1) - \sin I_1 \cdot \sin I_2 \left[1 - \cos(A_2 - A_1) \right] \right]$$



$$RF = \frac{360}{DL \cdot \pi} \cdot \frac{\tan \frac{DL}{2}}$$

or,

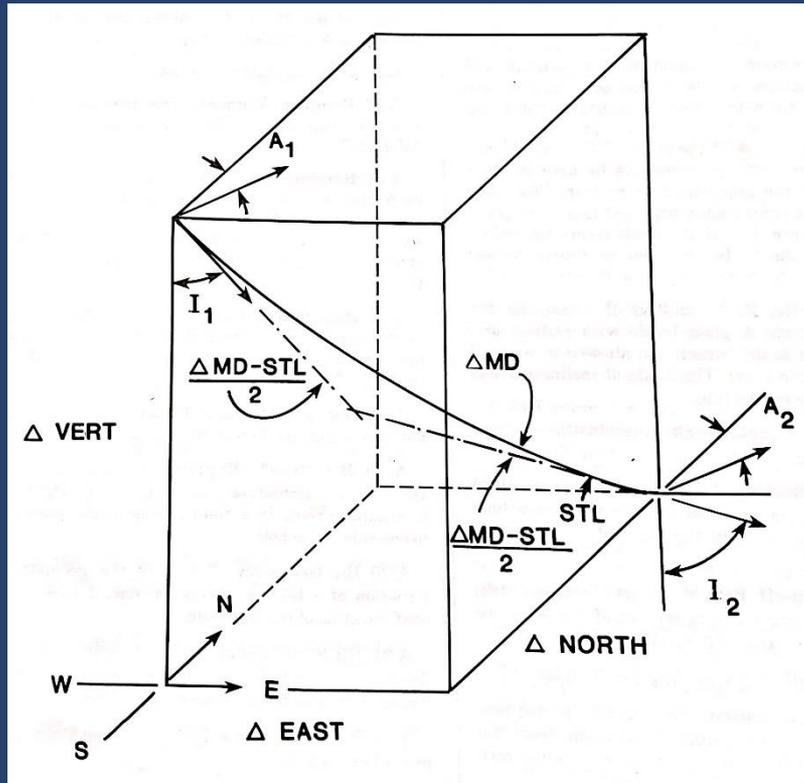
$$RF = \frac{360}{DL \cdot \pi} \cdot \frac{1 - \cos DL}{\sin DL}$$

$$\Delta VD = \frac{\Delta MD}{2} \cdot (\cos I_1 + \cos I_2) \cdot RF$$

$$\Delta N = \frac{\Delta MD}{2} \cdot (\sin I_1 \cos A_1 + \sin I_2 \cos A_2) \cdot RF$$

$$\Delta E = \frac{\Delta MD}{2} \cdot (\sin I_1 \sin A_1 + \sin I_2 \sin A_2) \cdot RF$$

Mercury Method



Mercury, Nevada Nuclear Test Site

$$\Delta N = \left[\frac{\Delta MD - STL}{2} \right] \left[\sin I_1 \cdot \cos A_1 + \sin I_2 \cdot \cos A_2 \right] + STL \cdot \sin I_2 \cdot \cos A_2$$

$$\Delta E = \left[\frac{\Delta MD - STL}{2} \right] \left[\sin I_1 \cdot \sin A_1 + \sin I_2 \cdot \sin A_2 \right] + STL \cdot \sin I_2 \cdot \sin A_2$$

$$\Delta VD = \left[\frac{\Delta MD - STL}{2} \right] \left[\cos A_2 + \cos A_1 \right] + STL \cdot \cos A_2$$

Where STL is the survey tool length.

Borehole Condition Indicators

- **Dogleg**
 - Lubinski – pipe bending
 - Wilson – Tangential Method / Radius of Curvature
 - Mason and Taylor – Minimum Curvature
- **Tortuosity – Cumulative Dogleg – can be normalized**
- **Rugosity – Wellbore diameter irregularity**



High Frequency Surveys

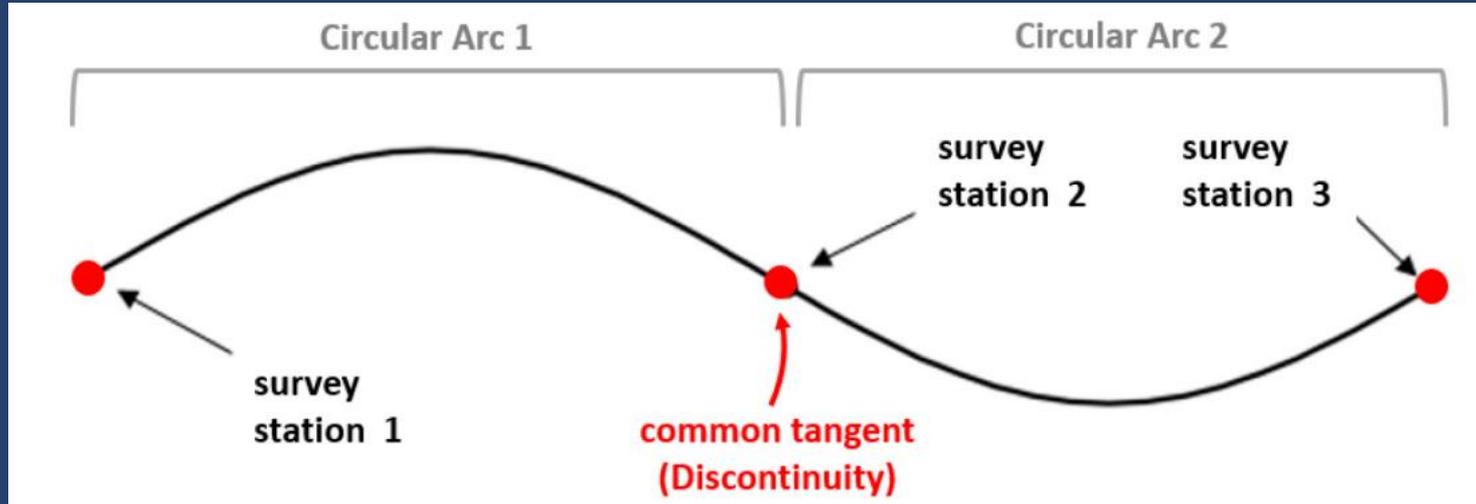
- **Continuous Surveys – Gyro & MWD**
 - Gives better indication of the “true” shape of the well path
 - Shows and corrects for “Stockhausen Effect”
 - Short intervals can magnify angular changes when shown as rates, e.g. large DLS values



Advanced Spline Curve (ASC) model

IADC/SPE-178796 • Advanced Trajectory Computational Model • Mahmoud F Abughaban

Borehole Positioning and Tortuosity
Standard Calculation Methods
Presented by
Darren Aklestad



Advanced Spline Curve (ASC) model

IADC/SPE-178796 • Advanced Trajectory Computational Model • Mahmoud F Abughaban

Borehole Positioning and Tortuosity
Standard Calculation Methods
Presented by
Darren Aklestad

- Current trajectory method has an invalid assumption (constant curvature arc) proven by high resolution surveys in slide/rotation pattern modes:
 - Causes artificially low tortuosity
 - Significant TVD error accumulation
 - Underestimates torque and drag output
- A robust three dimensional wellbore trajectory model (The ASC Model) has been developed:
 - Based on Cubic polynomial piece-wise continuous functions
 - Solving system of liner equations
 - Continuous at all survey stations up to the third derivative
 - Requires no assumptions / definite solution
- The ASC characteristics allow:
 - More accurate wellbore positioning, tortuosity and rugosity with less number of surveys taken than current trajectory methods while drilling and post-drilling

14



Advanced Trajectory Computational Model Improves Calculated Borehole Positioning, Tortuosity and Rugosity

MINES

IADC / SPE-178796-MS

Mahmoud Abughaban¹, Alfred Eustes², Bernard Bialecki³, John de Wardt⁴, Steve Mullin⁵

ISCWSA 43rd General Meeting, Ft. Worth, March 4 2016



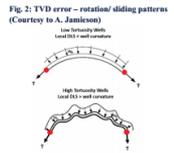
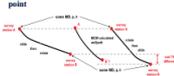
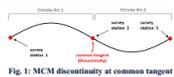
Borehole Positioning and Tortuosity Standard Calculation Methods Presented by Darren Aklestad

Abstract

Current three-dimensional well trajectory models represented by the minimum curvature method (MCM) tends to mathematically smoothen the wellpath between survey-stations creating an artificially low tortuosity expressed as dogleg severity (DLS). This can lead to the miscalculation of the actual true vertical depth (TVD) and underestimates the torque and drag (T&D) output. A robust three-dimensional trajectory model, the Advanced Spline-Curve (ASC) model, has been developed by the Colorado School of Mines to overcome these limitations. The ASC model provides realistic results and accurately calculate the spatial course of the wellpath. The principal method proposed using the ASC model is a step toward more accurate representation of wellbore trajectories, as compared to other methods using constant curvature, minimum curvature or tangential calculations. The calculated trajectory utilizing ASC model guarantees continuity along the entire wellpath with significant better accuracy. These findings allow better wellbore positioning, more realistic tortuosity and the introduction of a rugosity measurement. This helps to evaluate drilling equipment and procedures while drilling long-reach horizontal wells and deep verticals. ASC was validated for accuracy using two approaches: (1) 88 horizontal wells recorded using high resolution continuous gyroscopic (HRCG) surveys recorded at one survey per foot (2) a complex synthetic well example of a known wellbore trajectory. Results from both approaches favor ASC model to be the most accurate when compared to all traditional methods.

Background

- Wellbore tortuosity, defined as the degree of wellbore deviation from the smooth trajectory, and wellbore rugosity, defined as the degree of wellbore diameter irregularity, are critical elements in determining torque and drag (T&D) magnitudes in the drilling of long-reach horizontal wells and deep verticals.
- Minimum curvature method (MCM) assumes a constant curvature arc between survey stations (Fig. 1). The two arcs are sharing a common tangent at the middle survey station (station 2) causing discontinuity in the rate of curvature (second order). This assumption causes an artificially low tortuosity created from the constant radius of curvature represented by each circle's radius. This leads to significant TVD errors accumulating along the wellpath (Fig. 2) and underestimation of T&D output.
- The discontinuity is one of the main weaknesses of using the MCM to predict T&D parameters. This is due to the assumption that the bending part in the T&D equilibrium equation is discontinuous at the survey stations (Fig. 3).
- It is suggested that improved T&D models will require a robust, more advanced and continuous 3D trajectory model. The improved wellbore trajectory model can be used as an input to a T&D model which will help in evaluating drilling equipment, minimizing the bottom-hole assembly, analyzing the buckling of tubular, and improving the drilling procedures while minimizing non-productive time from T&D problems. This process is currently under investigation by the Colorado School of Mines.



Model Development - ASC Model

The Advanced Spline Curve T used in this research is a function that consists of cubic polynomial pieces, in which T_1 and T_2 are continuous at all survey stations. During the process of developing this robust 3D wellbore trajectory model, the following criteria were taken into account:

- The mathematical model must have the ability to compute the wellpath trajectory positions TVD, wellbore and Easting coordinates along the entire wellpath with higher accuracy.
- The computed curvature must be continuous at the first derivative (C1), the second derivative (C2) and the third derivative (C3) at any point along the entire wellpath. This continuity allows the measure of tortuosity and rugosity more accurately and better represent the real drill string configuration for T&D calculation.

ASC Model Formulation

The proposed Advanced Spline Curve T has the ability to compute wellpath trajectories with high accuracy while end post-drilling and continuous up to the third order derivative (C3) at any point along the entire wellpath. The mathematical steps to compute the wellbore positions (TV) and northing and easting coordinates, tortuosity and rugosity are outlined below:

- Compute the tangent vectors:

$$\lambda_i = \frac{dx_i}{ds} = \frac{dx_i/ds}{\sqrt{(dx_i/ds)^2 + (dy_i/ds)^2 + (dz_i/ds)^2}} = \frac{dx_i/ds}{\sqrt{1 + (dy_i/ds)^2 + (dz_i/ds)^2}}$$
 Where:

$$\lambda_i = \text{inclination } (^\circ), \lambda_i = \text{Azimuth } (^\circ)$$
- Set the boundary conditions:

$$T(s) = A_3 s^3 + A_2 s^2 + A_1 s + A_0 = \sqrt{C_1^2 + C_2^2 + C_3^2} + (s - s_0) \lambda_0$$
 There are 4n unknown coefficients:

$$A_1 = \lambda_0, \quad A_2 = \frac{3}{2} \lambda_0 \frac{d\lambda_0}{ds}, \quad A_3 = \frac{1}{2} \lambda_0 \frac{d^2\lambda_0}{ds^2}$$

$$C_1 = \frac{dx_i}{ds}, \quad C_2 = \frac{dy_i}{ds}, \quad C_3 = \frac{dz_i}{ds}$$
- Integrate $T(s)$ to compute the wellbore positioning:

$$Y(s) = \int T(s) ds = \int \sqrt{1 + (dy_i/ds)^2 + (dz_i/ds)^2} ds = \int \sqrt{1 + (dy_i/ds)^2 + (dz_i/ds)^2} ds$$
- Find the second derivative of $Y(s)$ to compute the tortuosity:

$$T''(s) = \frac{d^2Y}{ds^2} = \frac{d}{ds} \left(\frac{dY}{ds} \right) = \frac{d}{ds} \left(\sqrt{1 + (dy_i/ds)^2 + (dz_i/ds)^2} \right)$$
- Find the third derivative of $Y(s)$ to compute the wellbore rugosity:

$$R(s) = \frac{d^3Y}{ds^3} = \frac{d}{ds} \left(\frac{d^2Y}{ds^2} \right) = \frac{d}{ds} \left(\frac{d}{ds} \left(\sqrt{1 + (dy_i/ds)^2 + (dz_i/ds)^2} \right) \right)$$
 Where:

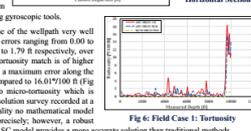
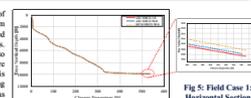
$$R(s) = \frac{d^3Y}{ds^3}$$



ASC Model Validation

During the validation process of ASC model, original data set from HRCG (1 ft resolution) is sampled to simulate typical drilling surveys. More data points was introduced to simulate the convergent to more accurate solution. According to this pre-processed data set, sag correction is not required at any point out by ISCWSA when predicting wellbore accuracy using gyroscopic tools.

ASC model preserves the baseline of the wellpath very well (Fig. 5), with TVD and departure errors ranging from 0.00 to 1.01 ft (0.00 to 0.30 m) and 0.00 to 1.79 ft respectively, over the entire wellpath. The overall tortuosity match is of higher accuracy compared to MCM with a maximum error along the entire wellpath of 8.337190 ft compared to 16.617100 ft (Fig. 6). The error is expected due to the fact that the model is only visible when using a high resolution survey recorded at a resolution of around 1 foot. In reality to mathematical model can predict the exact curvature precisely; however, a robust mathematical model such as the ASC model provides a more accurate solution than traditional methods.



Results Summary

In summary, the ASC model shows excellent precision and significant improvement in calculated position of a borehole and the calculation of tortuosity than currently used methods. Hence, increased borehole position accuracy from while drilling surveys is possible with the ASC calculation method. This provides the possibility for reduced borehole path uncertainty for comparison to the high resolution continuous surveys therefore increasing the confidence level in the definitive survey. In addition, the comparison of the data sets provides gross error detection with up to 50% improvement in complex wells compared to the MCM (Fig. 7).

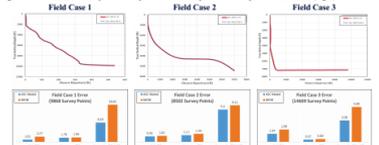


Fig. 7: Field Cases Summary Results

Conclusions

The drilling industry has for decades enjoyed the use of the minimum curvature method as the standard. With the current advancement of computer technology, the time needed to calculate a wellbore trajectory is minimal. The improvement in borehole accuracy and robustness of the computational method is the key to selecting the appropriate model. The following conclusions may be made based on the above analysis and field applications:

- The use of the Advanced Spline Curve (ASC) while drilling provides multiple advantages to drilling efficiency and borehole quality. In terms of drilling efficiency, it increases the calculated borehole position accuracy over current calculation methods without increasing the number of survey takes. In terms of borehole quality, it calculates true measures of tortuosity and rugosity than current methods using the borehole surveys recorded while drilling.
- The ASC provides significant improvement to the accuracy of the calculated position of a borehole and to the calculation of tortuosity and wellbore rugosity using HRCG surveys and the synthetic wellpath compared to currently used calculation methods. This improvement delivers value to both while drilling surveys and final surveys and for both low and high resolution.

Steps Forward

- The ASC model improved wellbore trajectory results can be used as an input for a torque and drag (T&D) model.
- Real-time forces that define torque and drag measured at surface and at the bottom of the wellbore and is required to evaluate / validate the results' accuracy.
- Software as a key component of current Automated Manual systems, which is used in aircraft controls.
- Using ASC model is not only an alternative approach to accurately approximate wellbore trajectories in the oil field, it can also serve as a step forward to drilling automation, too.
- Propose to the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) to evaluate ASC and revise the current trajectory calculation model.

Authors

- ¹Ph.D. Candidate, Petroleum Engineering Department, Colorado School of Mines, Golden, CO.
- ²Associate Professor, Petroleum Engineering Department, Colorado School of Mines, Golden, CO.
- ³Associate Professor, Department of Applied Mathematics & Statistics, Colorado School of Mines, Golden, CO.
- ⁴Consultant and President, DE WARDT & CO, Steamboat Springs, CO, dewardt@dewardt.com
- ⁵Director of Marketing, Gyrodine Incorporated, Houston, TX, smullin17745@gyrodine.com



Improved Wellbore Quality Using a Novel Real-Time Tortuosity Index

Borehole Positioning and Tortuosity
Standard Calculation Methods
Presented by
Darren Aklestad

IADC/SPE-178869 • Yang Zhou • Danden Zheng • Pradeepkumar Ashok • Eric van Oort

- Tortuosity Density Index



Documentation / Reference Updates

- Add borehole quality definitions to Lexicon
- Add new section to bibliography for hole condition and



THANK YOU

