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Simultaneous Prediction of Geological Surfaces and Well Paths

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SUMMARY

We present a novel model for the true vertical depth (TVD) positioning error in horizontal wells. The model utilizes a non-stationary Gaussian process known as the integrated Ornstein-Uhlenbeck process. This process is continuous and exhibits the known systematic accumulation of vertical errors with increasing measured depth. The well corrections produced are smooth and maintain the underlying shape of the well path. The smoothness can be adjusted through a correlation range parameter.

Using the geological constraints contained in the zonation, we can predict or simulate surface depths and well depths simultaneously. The size of the surface and well displacements are governed by the relative magnitude of the surface and well path TVD uncertainties. The resulting well paths and surfaces stay within their uncertainty envelopes and are consistent with the zonation.

The surface/well relationships can be expressed as a highly dimensional truncated multivariate Gaussian distribution. We draw samples from this distribution using an efficient rejection sampling strategy that allows fields with hundreds of horizontal wells to be handled.

Introduction

The first recorded true horizontal oil well was drilled in Texas in 1929, but little practical application occurred until the early 1980's, by which time advances in equipment, materials, and technologies, had given applications that were within the imaginable realm of commercial viability (King, 1993). By 1990, horizontal drilling had become fully commercialized, leading to a completion of more than a 1000 wells worldwide that year.

Since then the number of horizontal wells has increased dramatically. Despite major technological improvements, these wells often fail to hit the target reservoir or stay in the reservoir zone, resulting in economic losses. This is partly due to an incomplete description of the subsurface, and partly due to the positioning error inherited in the drilling process. This positioning error increases with increased deviation and with well length, and has both a vertical an a lateral component. In this paper, we focus on the vertical component, since vertical position control is more important to get a correct zonation.

The assumption is that both surfaces and well paths have uncertain depth values with known uncertainty envelopes. We aim at finding their expected vertical positions with the constraint that the surfaces need to match the zonation.

We present a continuous model for the true vertical depth (TVD) error. This model is based upon the so-called integrated Ornstein-Uhlenbeck process (Barndorff-Nielsen , 1998), a non-stationary Gaussian process that produces smooth well trajectories, and that exhibits the known systematic accumulation of vertical errors with increasing measured depth (MD). This continuous stochastic interpretation, gives analytic expressions for well covariances independent of the sampling resolution of the well path.

Our well repositioning is demonstrated with a synthetic case study that consists of two depth surfaces and a single well. In the modelling, the top and base surfaces and the well are all moved within their uncertainty envelopes to produce the correct zonation.

Surface uncertainty model

Surfaces are represented as a sum of a trend and a residual. The trend is assumed to contain all large scale features and may consist of several terms including depth trends and lateral trends. The residual captures unobservable deviations from the trend and is modelled by a stationary Gaussian random field determined by a variogram model.

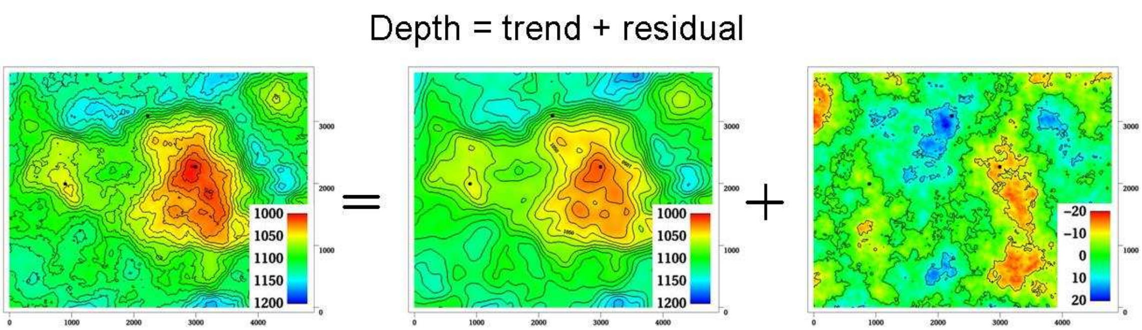

Figure 1 *Example of a surface represented as a sum of a deterministic trend and a simulated Gaussian random field with a spherical variogram.*

Well TVD uncertainty model

It it known that the vertical positioning error of long horizontal wells accumulates systematically along surveys (Brooks *et al.* , 2005). Let E_t be the difference between the true, unknown TVD and the measured TVD at location $t = \mathrm{MD}$. We propose the following model for the evolution of the TVD error

$$E_t = a_t S_t, \tag{1}$$

where S_t is the so-called integrated Ornstein-Uhlenbeck process

$$S_t = \varphi \int_0^t OU_s \, ds, \tag{2}$$

where OU_s is the Ornstein-Uhlenbeck process starting at the origin, with mean 0, standard deviation 1 and mean reverting parameter φ (Øksendal , 2003). This process is defined as a convolution

$$OU_s = \int_0^s e^{\varphi(\tau - s)} dW_\tau, \tag{3}$$

where W_τ is a standard Wiener process. The parameter φ may be thought of as determining the stiffness of the well TVD error. We express this stiffness as $R = 1/\varphi$, which has the dimension of length. R is referred to as the range. The function a_t is a variance adjustment needed to produce the known uncertainty of the well path, σ_t. With $\sigma_t^2 = \mathrm{Var}(E_t)$, a_t becomes

$$a_t = \sigma_t / \sqrt{\mathrm{Var}(S_t)}. \tag{4}$$

The covariance, $\mathrm{Cov}(S_t, S_u)$, is

$$\mathrm{Cov}(S_t, S_u) = t - \frac{1}{\varphi}\left[1 - e^{-\varphi t} - e^{-\varphi u} + e^{-\varphi(u-t)}\right] + \frac{1}{2\varphi}\left[e^{-\varphi(u-t)} - e^{-\varphi(u+t)}\right], \text{ for } t \leq u. \tag{5}$$

The Ornstein-Uhlenbeck process is a stationary Gaussian process, usually seen as the continuous analogue of the discrete autoregressive process of first order. Since the integrand of (2) is a continuous function, the fundamental theorem of calculus ensures that paths of the integrated Ornstein-Uhlenbeck process are differentiable and thereby smooth.

In Figure 2, we have illustrated how the expected TVD error is affected by an observation, and how simulated TVD errors depend on the range parameter.

Simultaneous prediction and simulation of surface depths and well depths

Predicted well paths must be consistent with an underlying stochastic subsurface model, where geological markers and interpreted zones are given as information. These surface/well relationships give rise to a large number of constraints that can be expressed as a highly dimensional truncated multivariate Gaussian distribution. In Abrahamsen and Benth (2001) and Abrahamsen *et al.* (2014), we have presented an efficient rejection sampling strategy that draws samples from this multivariate distribution. The essential idea is to exploit the nature of the constraints to set up a blocked variant of the Gibbs sampler, define an iteration that approximates the mean of the multivariate distribution and use this approximation as initial state to a fast implementation of the Gibbs sampler. This sampling strategy efficiently handles reservoirs with several hundred wells.

Example

In Figure 3, we demonstrate the well repositioning methodology by a simple, synthetic case where a horizontal well has been drilled through the top of an anticline and follow the structure down one of the flanks. The zone log interpretation tell us that the well path must stay between the top and the base surfaces, and this cannot be obtained by conditioning the top surface to the well intersection only (top figure). By conditioning the surfaces to the full well path, and the well path to the surfaces, a correct and consistent geometry is obtained.

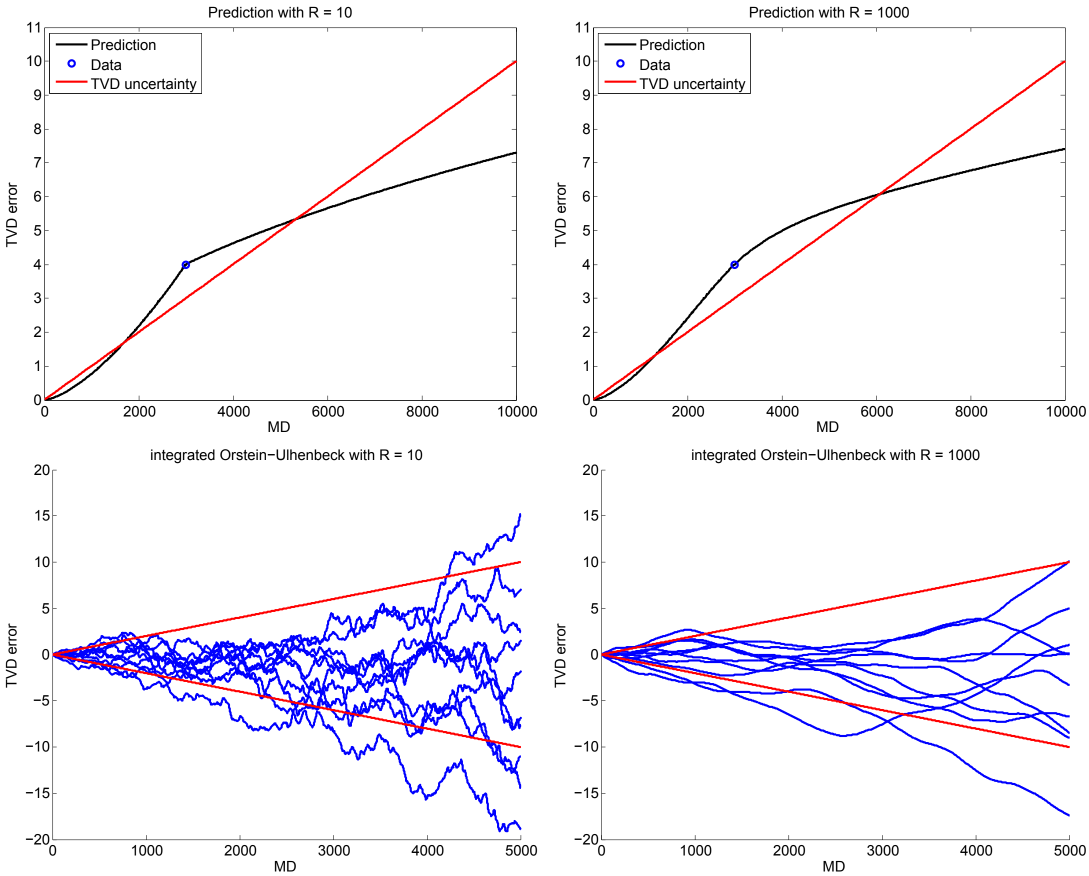

Figure 2 *In the upper row, we show the effect a single observation has on a well path when the range is set to 10 (left) and 1000 (right). The longer range produce the smoother correction. In the lower row, we give a set of simulated well paths made with ranges 10 (left) and 1000 (right). The shorter range gives an erratic path resembling a random walk, whereas the longer range gives a smooth path better suited for representing well corrections.*

Conclusions

We have presented a new model for well TVD error that allows surface depths and well depths to be predicted and simulated simultaneously. The magnitude of the surface and well adjustments are consistent with the magnitude of their respective uncertainties. The new well paths maintain their smoothness and stay within the uncertainty envelope. The TVD error model has also been extended to handle multilateral wells.

References

Abrahamsen, P., Dahle, P., Hauge, V. L., Almendral-Vazquez, A., Vigsnes, M. (2014) "Surface prediction using rejection sampling to handle non-linear relationships." *Advances in Applied Geomodeling for Hydrocarbon Reservoirs*. Banff: Canadian Society of Petroleum Geoscientists.

Abrahamsen, P., Benth, F. E. (2001) "Kriging with Inequality Constraints." *Math. Geol. Vol. 33 No. 6, pp. 719-744.*

Barndorff-Nielsen, O. E. (1998) "Processes of normal inverse Gaussian type." *Finance Stochast., 41-68.*

Brooks, A., Wilson, H., Jamieson, A., McRobbie, D. (2005) "Quantification of Depth Accuracy." *SPE Annual Technical Conference and Exhibition, 9-12 October, Dallas, Texas*. Society of Petroleum Engineers.

King, R. F. (April 1993) "Drilling Sideways – A Review of Horizontal Well Technology and Its Domestic Application" *Energy Information Administration Technical Report*. DOE/EIA-TR-0565.

Øksendal, B. (2003) "Stochastic Differential Equations: An Introduction with Applications", Berlin: Springer, 5th edition.

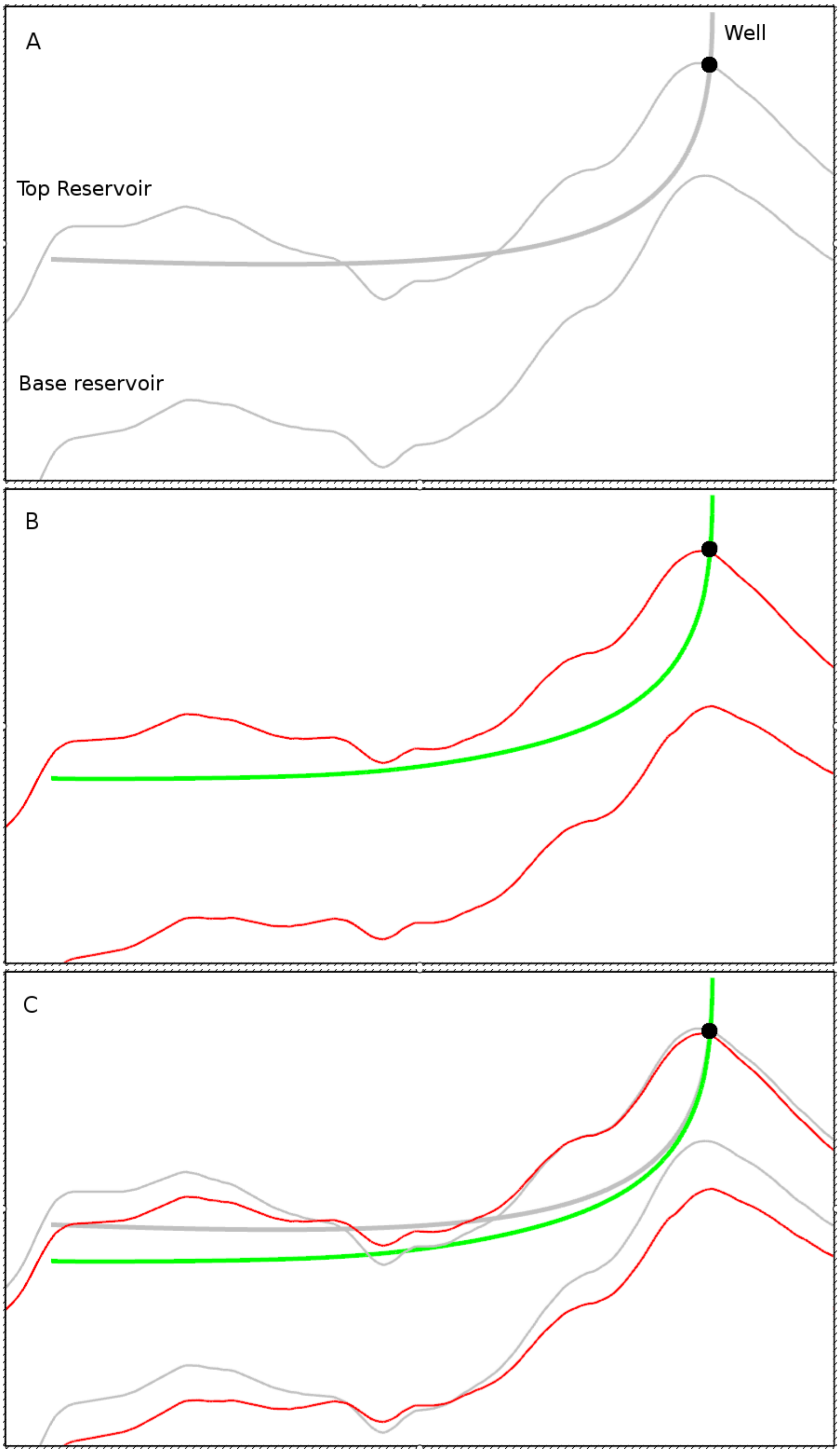

Figure 3 *In figure A, we show a cross section through two surfaces along a well path. The top surface has been conditioned to the well observation (black bullet). The well incorrectly crosses the top surface half way down the well. In figure B, the surfaces have been conditioned to the full well path, and the well path has been allowed to move ($R = 100$). This gives a correct zonation. For comparison, the two modelling results have been given simultaneously in figure C. Note that the base surface is also affected and is partly pushed down but mostly lifted up.*