SPE-217744

An Analysis Of Drilling Projection Uncertainty And Implications For Collision Avoidance Management Systems

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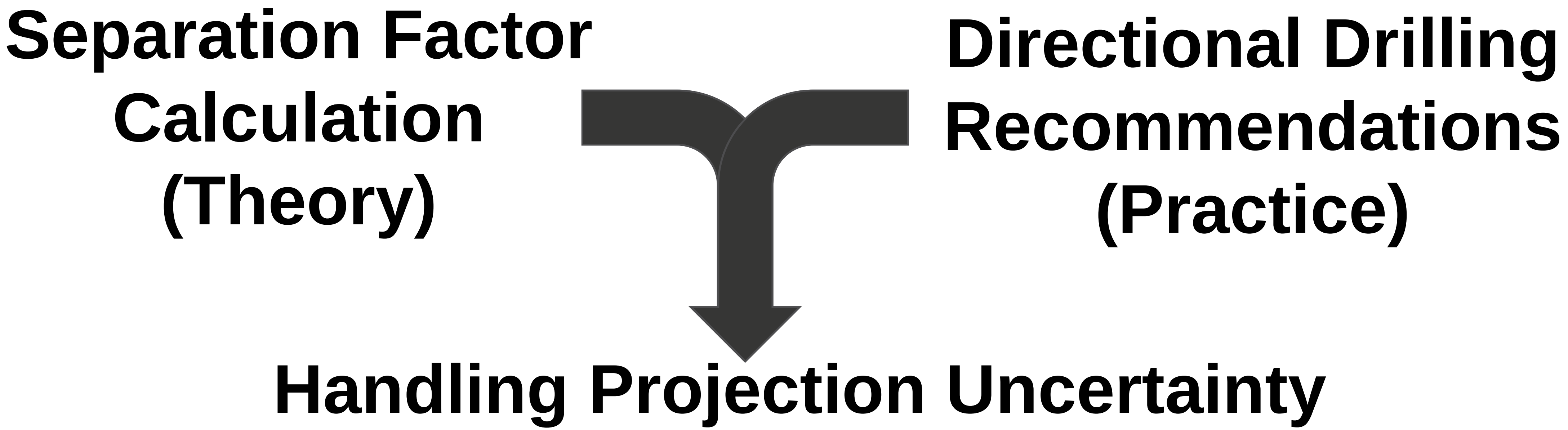
Context for this work – Massive Industry Efforts to Standardize

- Error Model Libraries, Guidance on Management and Principles, Standard Separation Rule, API Recommended Practice on Surveying (RP 78)

At the center of these efforts is one major gap:



Separation Factor Calculation (Theory)

Directional Drilling Recommendations (Practice)

Handling Projection Uncertainty

Handling Projection Uncertainty, In Theory

Separation Factor Equation from SPE-187073-PA:

$$SF = \frac{D - R_r - R_o - S_m}{k\sqrt{\sigma_s^2 + \sigma_{pa}^2}}$$

Handling Projection Uncertainty, In Theory

<u>Separation Factor Equation from SPE-187073-PA:</u>

$$SF = \frac{D - R_r - R_o - S_m}{k\sqrt{\sigma_s^2 + \sigma_{pa}^2}}$$

Typical uncertainty between wellbores from surveying

New extra uncertainty for projecting ahead…because We <u>haven’t surveyed yet!</u>

Handling Projection Uncertainty, In Practice

Projection Uncertainty is formally introduced in SPE-187073 with caveats

> ***"Its value is partially correlated with projection distance…the actual uncertainty also depends on planned curvature and on the BHA performance…The project ahead uncertainty is only an approximation…"***

…but a number was needed, so we get a back-of-envelope σ_{pa} value: **0.5m (1.6ft)**

Its impact is also implied in API RP 78 via course length recommendations:

Maximum Survey Interval (ft)		DLS (deg/ 100ft MD)		
		DLS < 2	2 < DLS < 6	DLS > 6
SF[-]	>4	200	100	100
	1.5-4	140	100	100
	<1.5	140	100	45

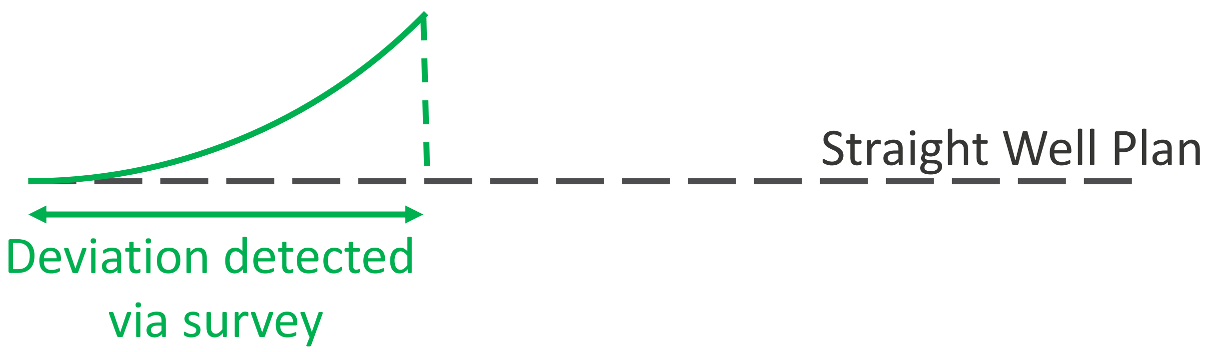
How Can We Estimate a Better σ_{pa}?

Simple Scenario

- Planned for straight rotary drilling,

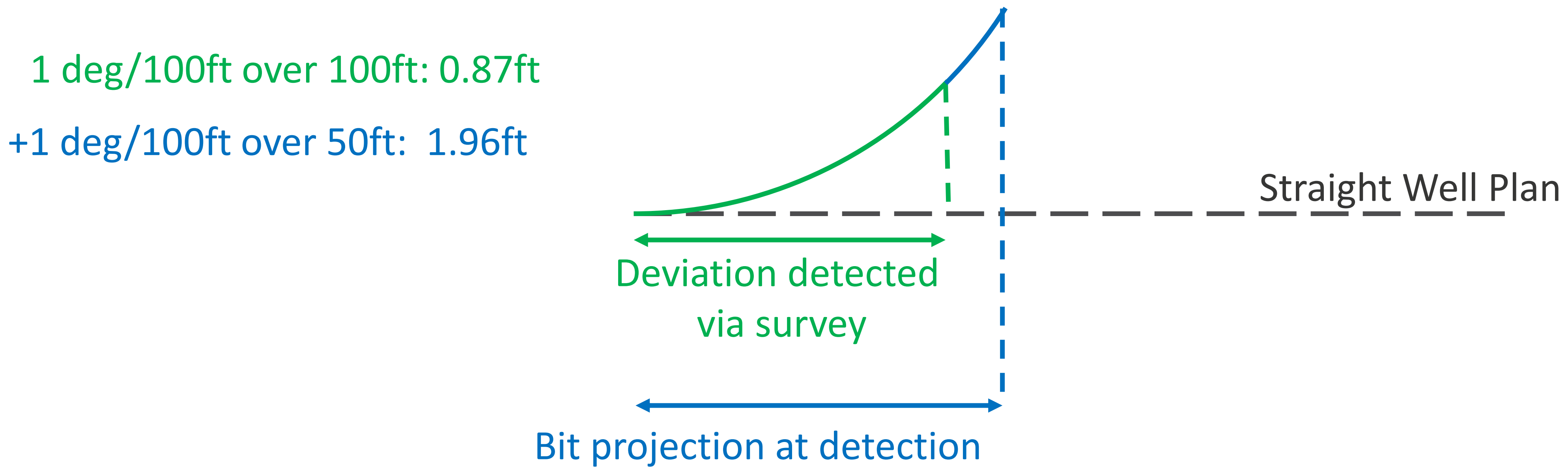
Simple Scenario

- Planned for straight rotary drilling, well path does not go straight (per our survey)


1 deg/100ft over 100ft: 0.87ft

Simple Scenario

- Planned for straight rotary drilling, well path does not go straight (per our survey)
- Must account for additional deviation already ahead of us to the bit



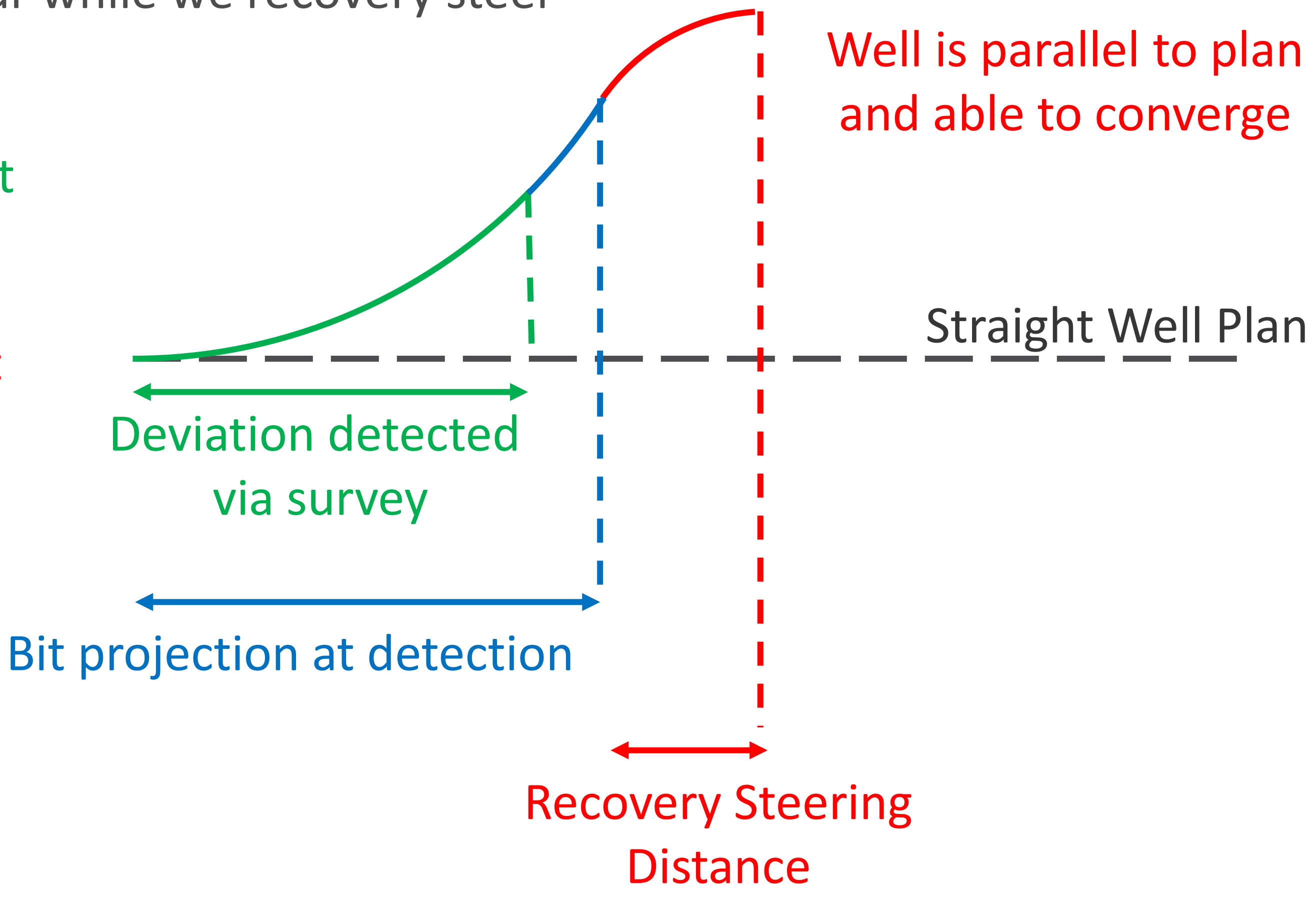
Simple Scenario

- Planned for straight rotary drilling, well path does not go straight (per our survey)
- Must account for additional deviation already ahead of us to the bit
- Even more deviation will occur while we recovery steer

1 deg/100ft over 100ft: 0.87ft

+1 deg/100ft over 50ft: 1.96ft

+3 deg/100ft over 50ft: 2.62ft



Well is parallel to plan and able to converge

Straight Well Plan

Deviation detected via survey

Bit projection at detection

Recovery Steering Distance

Generalized Model for a Minimum Curvature Segment (Curvature Uncertainty)

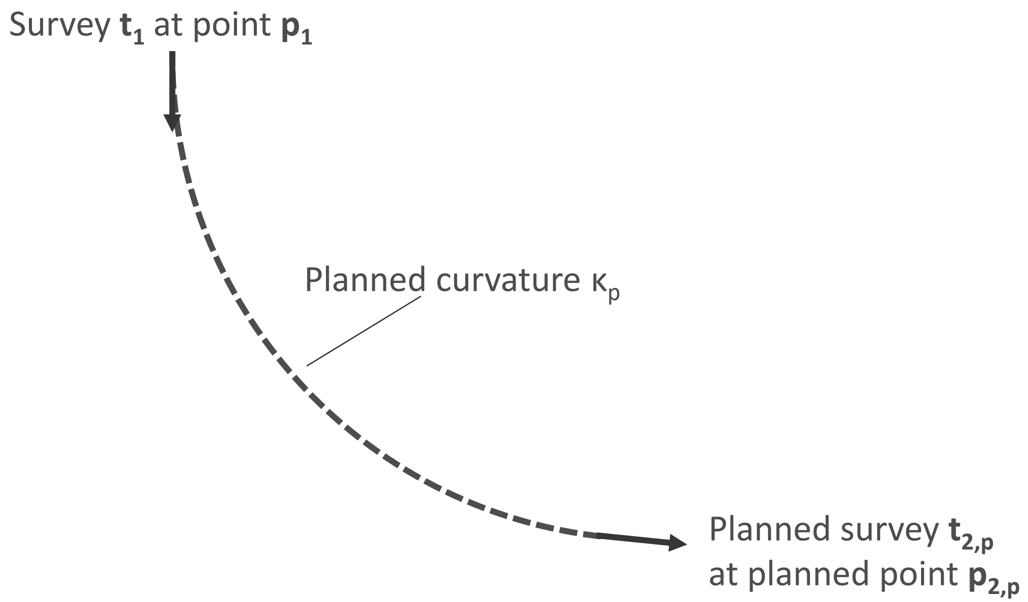
Key Parameters

Lengths

- Course Length: D_{cl}
- Sensor Offset: D_o
- Recovery Distance: D_r

Curvatures

- Planned Curvature: κ_p
- Observed Curvature: κ_o
- Recovery Curvature: κ_r



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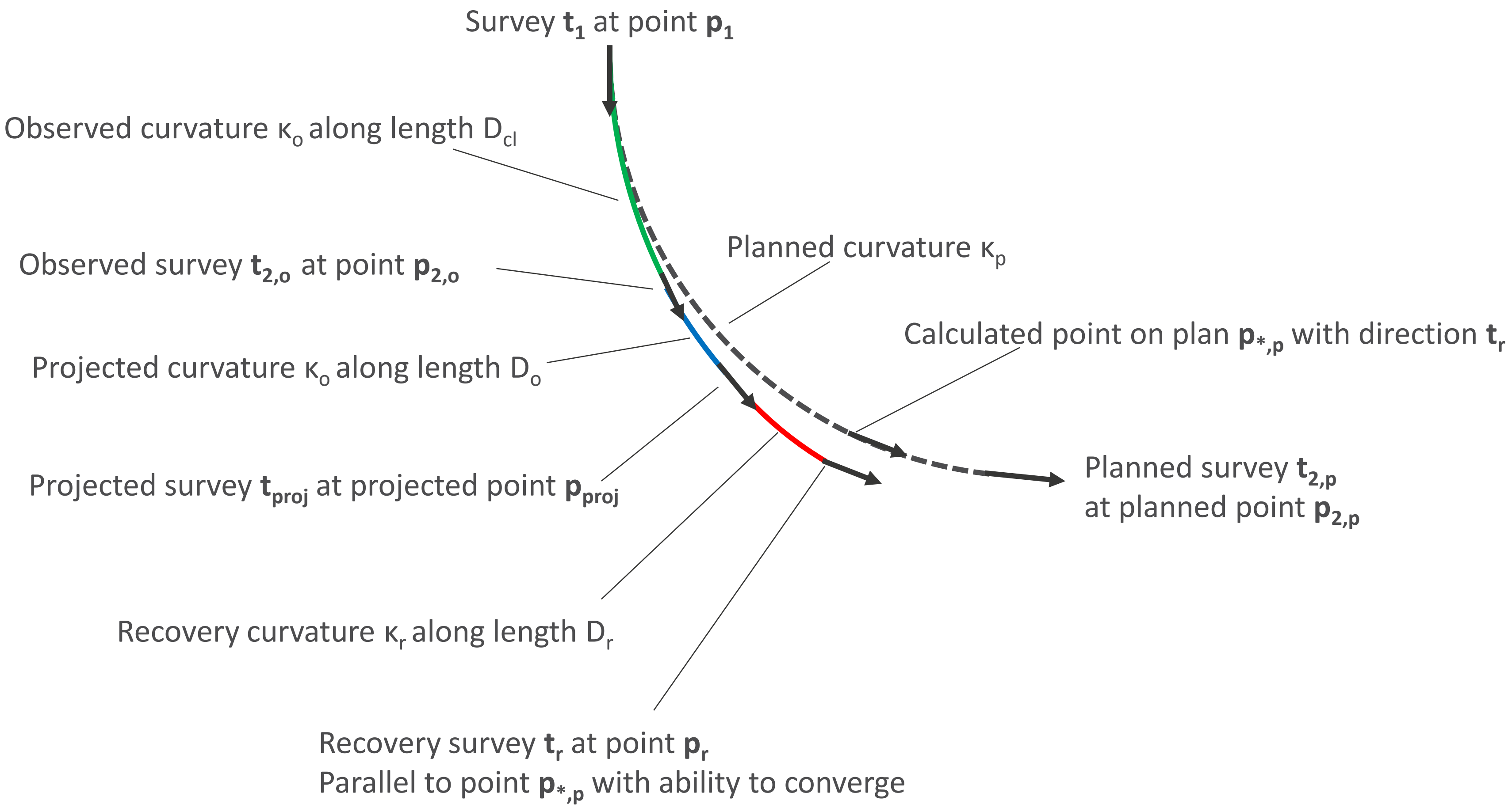


Survey $\mathbf{t_1}$ at point $\mathbf{p_1}$

Observed curvature κ_o along length D_{cl}

Planned curvature κ_p

Observed survey $\mathbf{t_{2,o}}$ at point $\mathbf{p_{2,o}}$

Calculated point on plan $\mathbf{p_{*,p}}$ with direction $\mathbf{t_r}$

Projected curvature κ_o along length D_o

Planned survey $\mathbf{t_{2,p}}$
at planned point $\mathbf{p_{2,p}}$

Projected survey $\mathbf{t_{proj}}$ at projected point $\mathbf{p_{proj}}$

Recovery curvature κ_r along length D_r

Recovery survey $\mathbf{t_r}$ at point $\mathbf{p_r}$
Parallel to point $\mathbf{p_{*,p}}$ with ability to converge

Same as our simple scenario, just twisted around a curve

Generalized Model for a Minimum Curvature Segment (Curvature Uncertainty)

Key Parameters

Lengths

- Course Length: D_{cl}
- Sensor Offset: D_o
- Recovery Distance: D_r

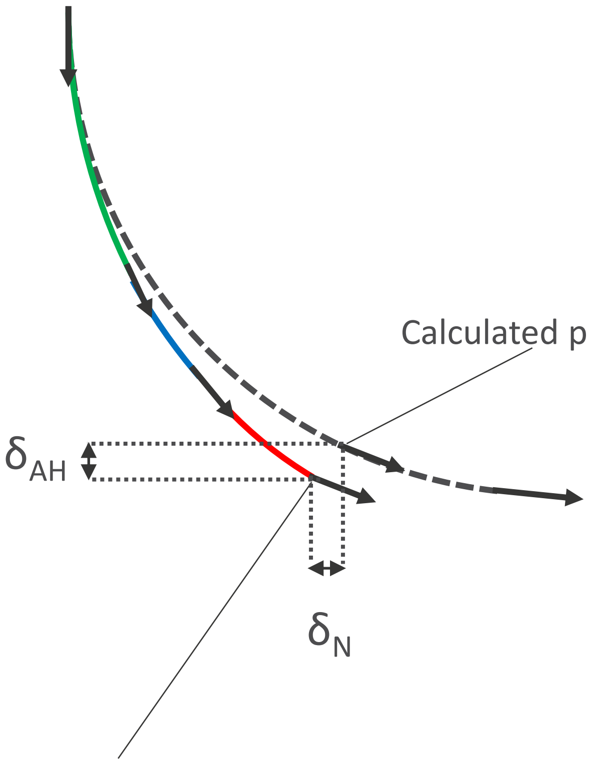
Curvatures

- Planned Curvature: κ_p
- Observed Curvature: κ_o
- Recovery Curvature: κ_r

Deviations (aligned to survey $\mathbf{t}_1$)

- Along-hole Error: δ_{AH}
- Normal plane Error: δ_N
- Upper bound on Error: $|\mathbf{p}_r-\mathbf{p}_{*,p}| = (\delta_{AH}{}^2+\delta_N{}^2)^{1/2}$

Survey $\mathbf{t}_1$ at point $\mathbf{p}_1$



Calculated point on plan $\mathbf{p}_{*,p}$ with direction $\mathbf{t}_r$

Planned survey $\mathbf{t}_{2,p}$
at planned point $\mathbf{p}_{2,p}$

Recovery survey $\mathbf{t}_r$ at point $\mathbf{p}_r$
Parallel to point $\mathbf{p}_{*,p}$ with ability to converge

Generalized Model for a Minimum Curvature Segment (Tool Face Uncertainty)

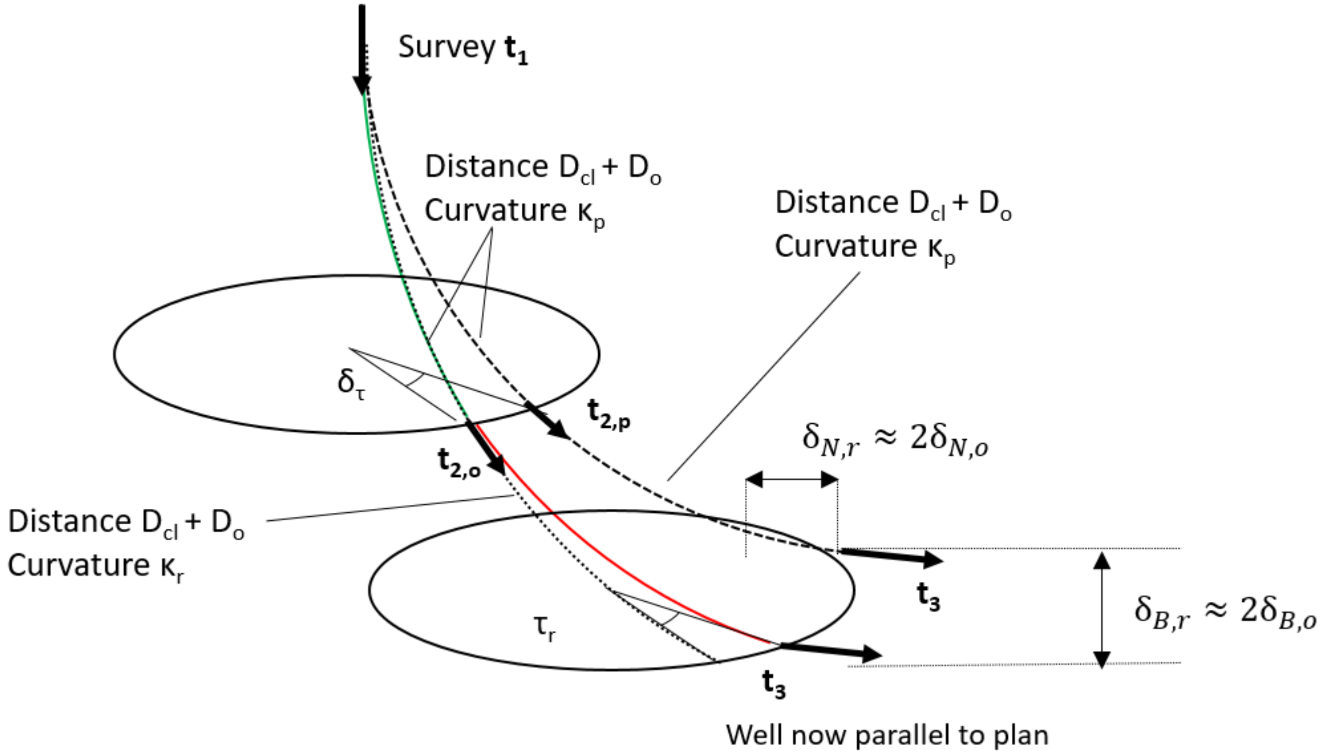
Additional Parameters

Tool Face Error

Planned Tool Face:	τ
Tool Face Offset:	δ_τ
Recovery Tool Face:	$\tau_r = \tau - \delta_\tau$

Deviations

Normal plane Error:	δ_N
Binormal plane Error:	δ_B



Note, this assumes a "mirrored" recovery, which implies a κ_r

Example Equation for Curvature Uncertainty

$$\delta_{AH} = \frac{(D_{cl} + D_o + D_r)}{2}\left(\cos[(D_{cl} + D_o)\kappa_o] - \cos\left[(D_{cl} + D_o)\kappa_p\right]\right) \ldots (2)$$

$$\delta_N = \frac{(D_{cl}+D_o+D_r)}{2}\left(\sin[(D_{cl} + D_o)\kappa_o] - \sin\left[(D_{cl} + D_o)\kappa_p\right]\right) \ldots (3)$$

$$D_r = \frac{(D_{cl} + D_o)\left(\kappa_o - \kappa_p\right)}{\left(\kappa_p - \kappa_r\right)} \ldots (4)$$

$$\delta_{total} = \sqrt{\delta_{AH}^2 + \delta_N^2} \ldots (5)$$

Example Equation for Curvature Uncertainty

Planned curvature is a design decision

$$\delta_{AH} = \frac{(D_{cl} + D_o + D_r)}{2}\left(\cos[(D_{cl} + D_o)\kappa_o] - \cos[(D_{cl} + D_o)\kappa_p]\right) \ldots (2)$$

$$\delta_N = \frac{(D_{cl}+D_o+D_r)}{2}\left(\sin[(D_{cl} + D_o)\kappa_o] - \sin[(D_{cl} + D_o)\kappa_p]\right) \ldots (3)$$

$$D_r = \frac{(D_{cl} + D_o)(\kappa_o - \kappa_p)}{(\kappa_p + \kappa_r)} \ldots (4)$$

$$\delta_{total} = \sqrt{\delta_{AH}^2 + \delta_N^2} \ldots (5)$$

Course Length and Sensor offset are known and/or design decisions

Observed curvature depends on directional uncertainty

Recovery curvature is a design decision and/or operational constraint

δ_{Total} relates to σ_{pa} via modelled uncertainty level in observed curvature (e.g. at 1-sigma curvature error they are equal)

Implications of σ_{pa} Estimation on Prior Guidance

Bottom Line Up Front

Recall: Specifying a σ_{pa} implies a specification on directional performance

- We are expected to stay within $k*\sigma_{pa}$ of the plan (3.5 * 0.5m) when we get our next survey
- The chart from API RP 78 includes some relevant design parameters (course length vs. DLS)

Maximum Survey Interval (ft)		DLS (deg/ 100ft MD)		
		DLS < 2	2 < DLS < 6	DLS > 6
SF[-]	>4	200	100	100
	1.5-4	140	100	100
	<1.5	140	100	45

σ_{pa} is likely being underestimated for many drilling scenarios

- For moderate to high steering (>5deg/100ft), a spec of <5.7ft deviation from plan is optimistic
- Similarly for cases with standard to long Course-Length-plus-Sensor-Offset values (150ft or more)

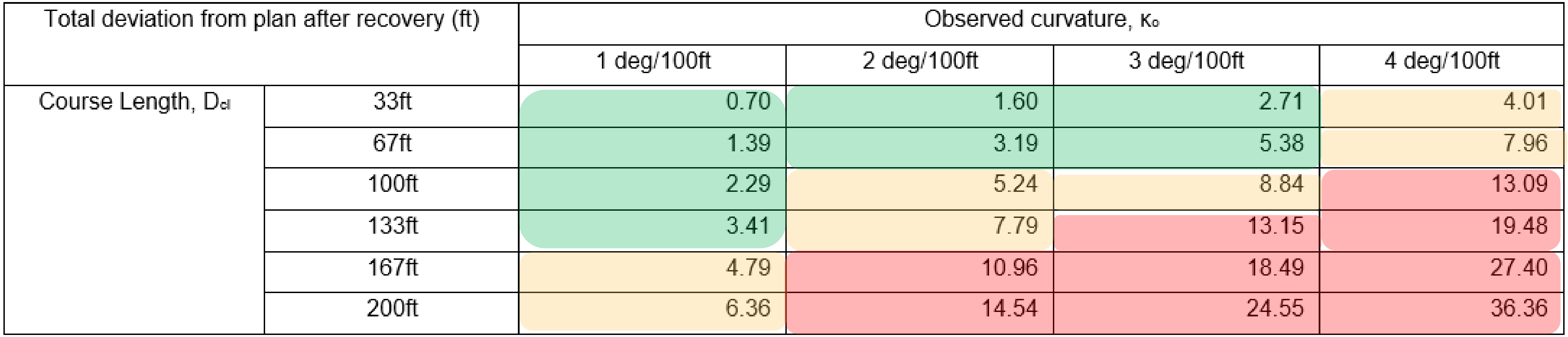
The suggested value of $k*\sigma_{pa}$ is not always congruent with survey course lengths and planned curvatures

Example 1 – Straight Drilling with a Steerable Assembly

- Planned DLS = 0, Maximum DLS = 6, Bit-to-Senor = 50ft
- **To stay within 5.7ft of plan at a 140ft course length implies 1-σ rotary uncertainty <0.6 deg / 100ft**

Maximum Survey Interval (ft)		DLS (deg/ 100ft MD)		
		DLS < 2	2 < DLS < 6	DLS > 6
SF[-]	>4	200	100	100
	1.5-4	140	100	100
	<1.5	140	100	45

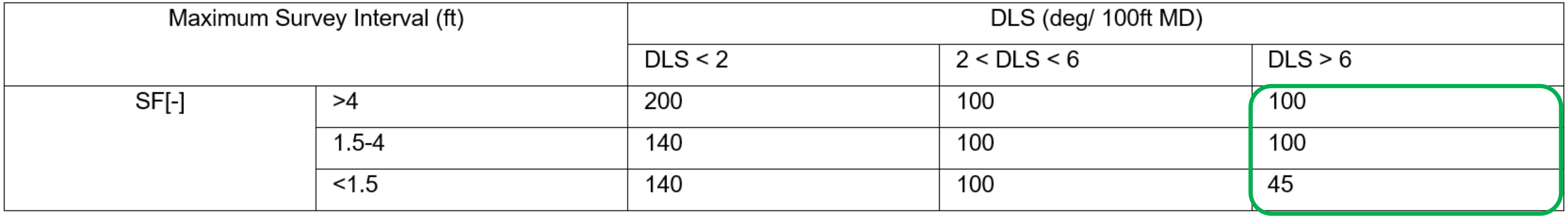
Table 4—Modelled maximum deviation from plan when D_o = 50ft, κ_p=0 deg/100ft, κ_r=6 deg/100ft



Total deviation from plan after recovery (ft)		Observed curvature, κ_o			
		1 deg/100ft	2 deg/100ft	3 deg/100ft	4 deg/100ft
Course Length, D_{cl}	33ft	0.70	1.60	2.71	4.01
	67ft	1.39	3.19	5.38	7.96
	100ft	2.29	5.24	8.84	13.09
	133ft	3.41	7.79	13.15	19.48
	167ft	4.79	10.96	18.49	27.40
	200ft	6.36	14.54	24.55	36.36

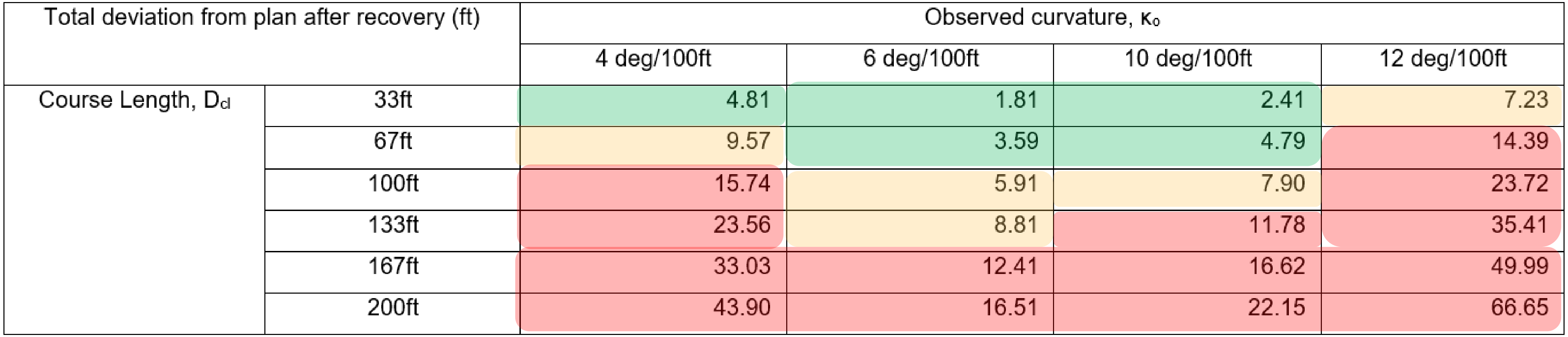
Example 2 – Medium Radius Curve Drilled with a Motor

- Planned DLS = 8, Maximum DLS = 12, Bit-to-Senor = 50ft
- **To stay within 5.7ft of plan at a 45ft course length implies 1-σ motor yield uncertainty <1.2 deg / 100ft**



Maximum Survey Interval (ft)		DLS (deg/ 100ft MD)		
		DLS < 2	2 < DLS < 6	DLS > 6
SF[-]	>4	200	100	100
	1.5-4	140	100	100
	<1.5	140	100	45

Table 5—Modelled maximum deviation from plan when D_o = 50ft, κ_p=8 deg/100ft, κ_r=12 deg/100ft (if $\kappa_o < \kappa_p$) or κ_r= 6 deg/100ft (if $\kappa_o > \kappa_p$)



Total deviation from plan after recovery (ft)		Observed curvature, κ_o			
		4 deg/100ft	6 deg/100ft	10 deg/100ft	12 deg/100ft
Course Length, D_{cl}	33ft	4.81	1.81	2.41	7.23
	67ft	9.57	3.59	4.79	14.39
	100ft	15.74	5.91	7.90	23.72
	133ft	23.56	8.81	11.78	35.41
	167ft	33.03	12.41	16.62	49.99
	200ft	43.90	16.51	22.15	66.65

Is This Concerning?

This underestimation has little practical impact on the recommended guidance

- σ_{pa} is often small relative to survey uncertainty (σ_s), impact on SF is similarly small
- **Exception**: Shallow kick-offs with narrow slot spacings
  - Special guidance may be needed for this, topic for future work!

Prior recommendations overlook the practical realities of Drilling Engineering

- Minimum guidance on safe separation is an achievement, but only a starting point

"How likely am I to have an unintentional crossing by my next survey?"

-- a very low bar to set

- What a drilling engineer really wants to know:

"How likely is it that I can safely drill to TD without a stop drilling condition?"

Practical Implications of σ_{pa} Estimation

The Real Problem with Projection Uncertainty

Recall the Separation Factor Equation from SPE-187073-PA:

$$SF = \frac{D - R_r - R_o - S_m}{k\sqrt{\boxed{\sigma_s^2} + \boxed{\sigma_{pa}^2}}}$$

Typical uncertainty between wellbores from surveying

DIRECTIONAL DRILLING TIME BOMB!!

What Happens When You Take a Survey?

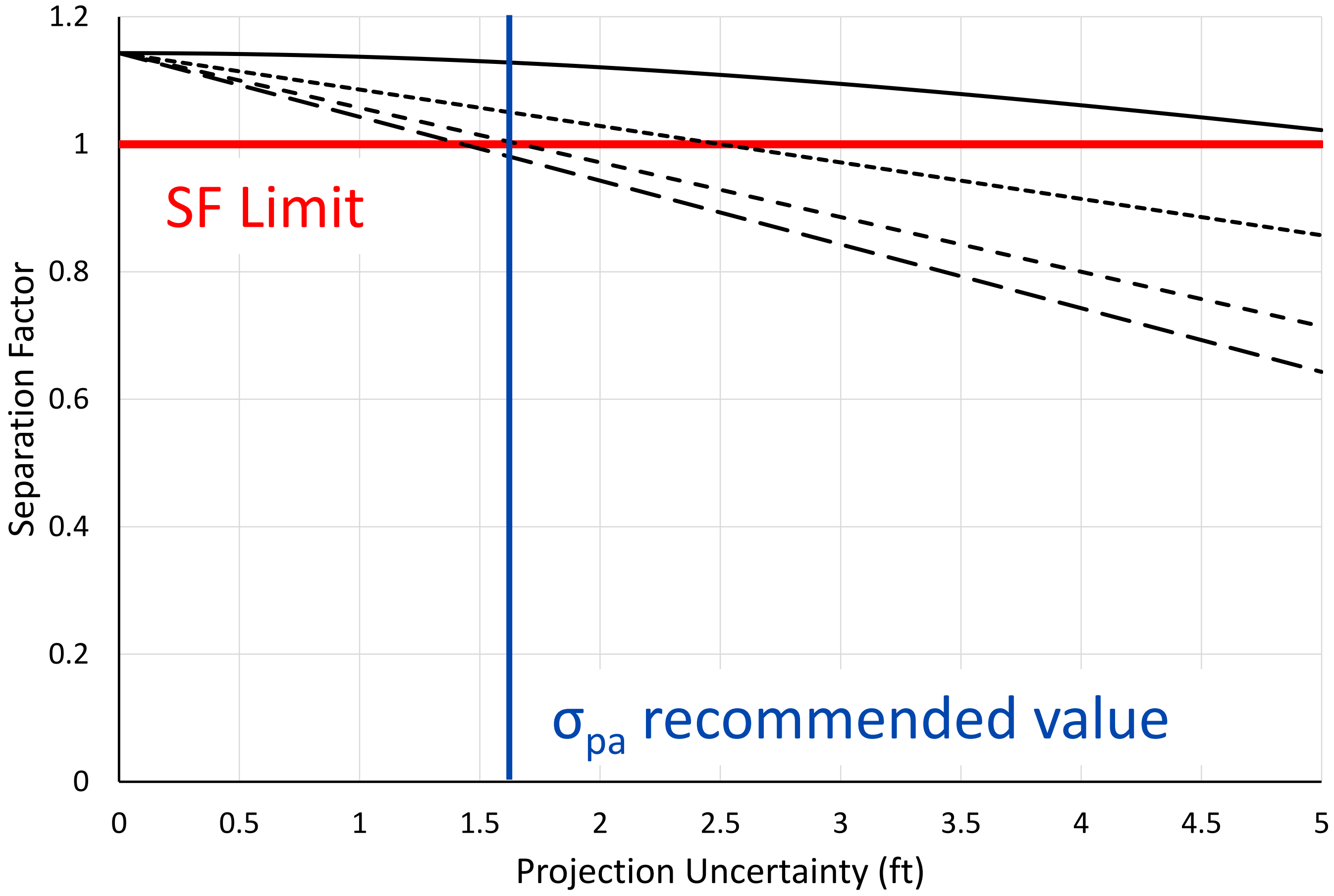
Drilling error is absorbed into Center-to-Center distance

$$SF = \frac{\boxed{D - R_r - R_o - S_m}}{k\sqrt{\sigma_s^2 + \boxed{\sigma_{pa}^2}}}$$

Projection Uncertainty becomes 0

Impact of Increasing Projection Uncertainty on the Separation Factor

40ft assumed separation, 10ft survey uncertainty, $k = 3.5$



$3.5\sigma_{pa}$ added to uncertainty (SF in planning)

$2\sigma_{pa}$
$3\sigma_{pa}$
$3.5\sigma_{pa}$
Subtracted from separation distance (SF after the survey)

Increasing Projection Uncertainty:

Small impact during planning

Large impact once you drill off plan

New Practical Tool for a Drilling Engineer

Ratio between σ_{pa} and allowable deviation from plan!

$$\frac{ADP}{\sigma_{pa}}$$

Estimates likelihood of successfully drilling a well section

- Still requires a traditional CA scan to determine ADP, also requires a model of σ_{pa}
  - Recall, σ_{pa} is a function of course length, sensor offset, uncertainty in directional performance, etc

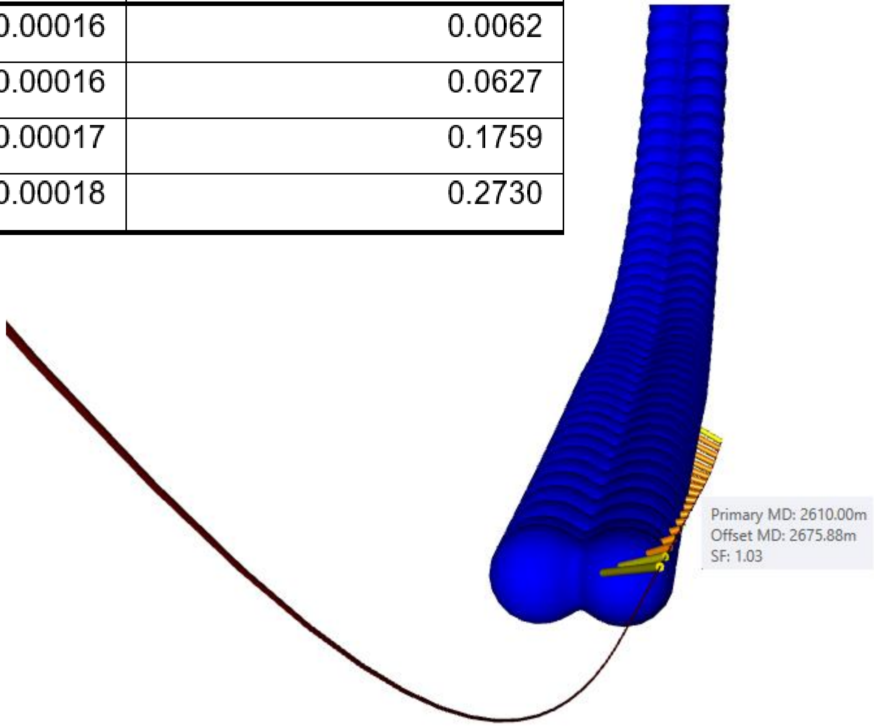
- Enables statistical tests on success likelihood that can be used for cost-benefit tradeoffs
  - E.g. single-tailed Z-test with $Z = \frac{ADP}{\sigma_{pa}}$ as a test statistic

Example of Risk Assessment Differences with Changing Uncertainty

ISCWSA Collision Avoidance Test Well Offset #6

Table 8—Comparison of modified Separation Factor vs. Relative ADP analysis for highest risk point on Offset Well 6

		Offset Well 6 – Point of Highest Risk				
		Minimum SF	ADP (m)	$\frac{ADP}{\sigma_{pa}}$	Probability of Crossing (from SF)	Probability of Stop Drilling (from $\frac{ADP}{\sigma_{pa}}$)
σ_{pa}	0.5m (1.6ft)	1.03	1.61	3.23	0.00016	0.0062
	1m (3.3ft)	1.03	1.53	1.53	0.00016	0.0627
	1.5m (4.9ft)	1.02	1.40	0.93	0.00017	0.1759
	2m (6.6ft)	1.02	1.21	0.60	0.00018	0.2730



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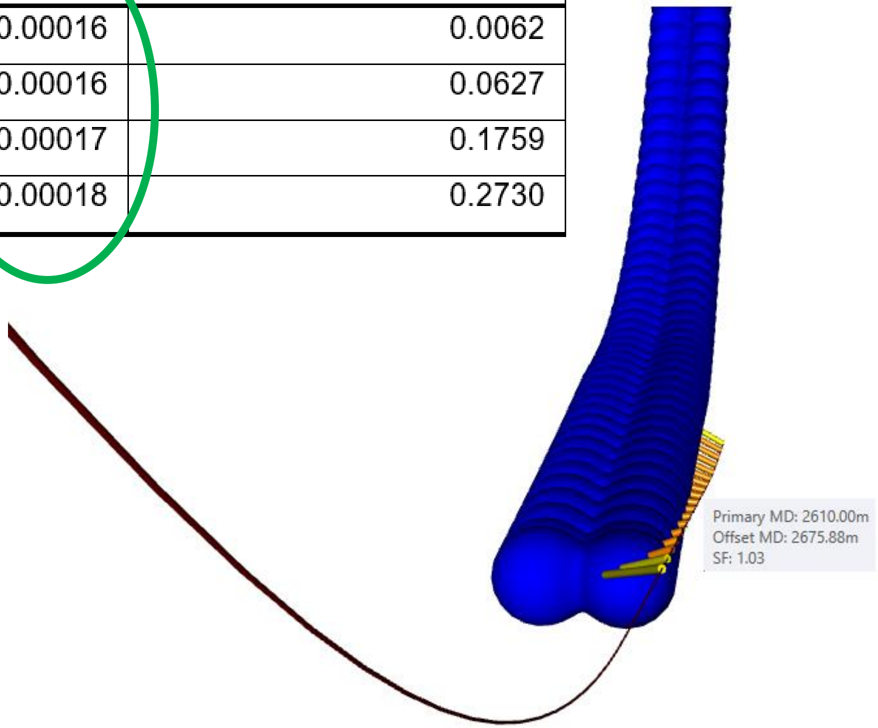
Minimum SF is robust against σ_{pa} changes



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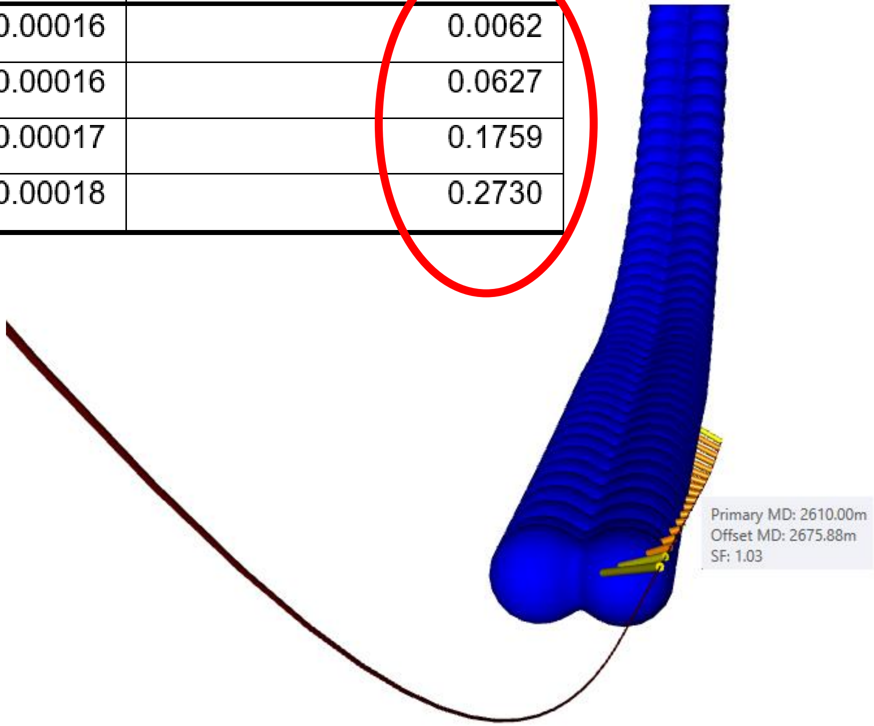
	1.5m (4.9ft)	1.02	1.40	0.93	0.00017	0.1759
	2m (6.6ft)	1.02	1.21	0.60	0.00018	0.2730

Probability of stop drilling is a different story

Goes from rare (<1 in 160) to common (>1 in 4)



Takeaways

Projection uncertainty can impact collision avoidance in many ways

- Inclusion in Separation Rule is a first step, but additional guidance is needed
  - Implied guidance from API RP 78 and Separation Rule appear to be optimistic or incongruent
- Changing the generic value would have little practical effect except for shallow kick-offs

Work presents a generalized model of projection uncertainty

- Estimates maximum deviation after recovery based on drilling design parameters
- Assesses the future drilling path rather than just uncertainty at survey point
- Provides additional parameter ($\frac{ADP}{\sigma_{pa}}$) for analyzing drilling risk in a practical fashion

Thank You!

SPE Wellbore Positioning Technical Section & Subcommittees (ISCWSA)
Operator's / Operational Wellbore Survey Group (OWSG)
Our Section Chairs

Questions / Comments?