Getting Aligned on Non-orthogonalities for MWD

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Speaker Bio

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- 15+ years in varying facets of wellbore positioning product support, survey corrections, & error modeling, etc

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Background

Sensor alignment issues cause a lot of confusion:

- With Operators who want confidence in their well position
- With Tool Vendors who want to qualify their instruments
- With MWD companies who ask about why surveys weren’t corrected

This could easily be (and has often been)
a 2-hour long conversation

Root Cause of Many Problems

Sensor alignment errors are intentionally omitted from the error model…

> Andy Brooks has demonstrated that if a sensor is subject to a scale error and two orthogonal misalignments, all independent and of similar magnitude, the combination of the three error terms is equivalent to a single bias term. This term need not appear explicitly in the error model, but may be added to the existing bias term to create a "lumped" error. This eliminates the need for 20 extra weighting functions corresponding to sensor misalignments.

…but it kinda looks like they are still there…

30	XYM1	Misalignment: XY Misalignment 1
31	XYM2	Misalignment: XY Misalignment 2
32	XYM3E	Misalignment: XY Misalignment 3
33	XYM4E	Misalignment: XY Misalignment 4

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…Analysis that may have been lost to time…

…but it kinda looks like they are still there…

NOT MWD sensor errors!

30	XYM1	Mis[illegible]ment: X[illegible]isalignment 1
31	XYM2	Misalign[illegible] Misalignment 2
32	XYM3E	Misalign[illegible]t. [illegible]Misalignment 3
33	XYM4E	Misa[illegible]ment: XY M[illegible]lignment 4

Three Major Themes

- How non-orthogonalities impact survey station measurements
- How these impacts relate to the error model
- How survey correction practices can complicate this relationship

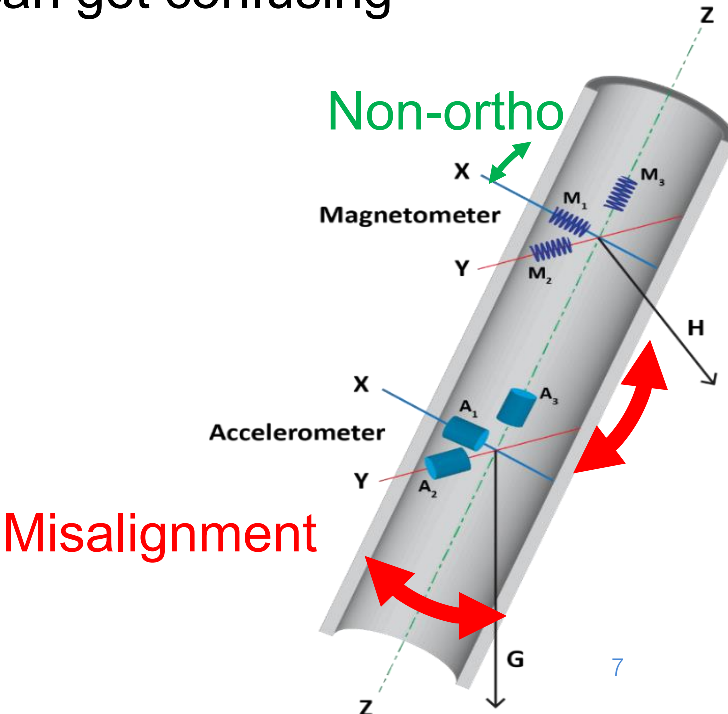
I have not seen Andy Brooks's analysis…but I agree with its conclusions
and enough people asked to have ISCWSA document something, so here we are

A Note on Nomenclature:

- With similar terminology these conversations can get confusing
    - I will try to stick to a particular convention

- **Non-orthogonality**:
    - Alignment error ***within a sensor triad***
    - Single sensor

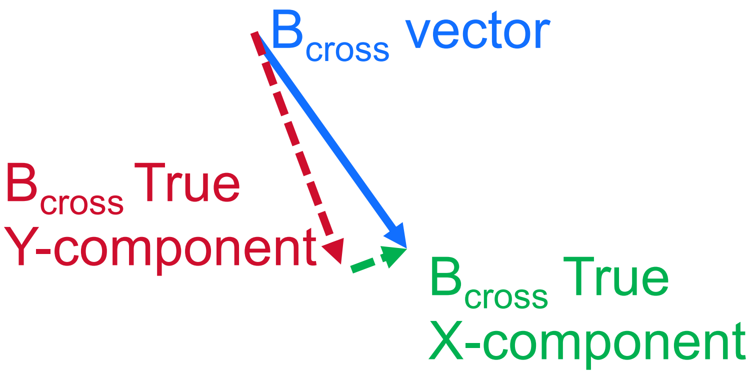
- **Misalignment:**
    - Alignment error ***between the sensor triads***
    - Bends, twists, etc – Multiple sensors

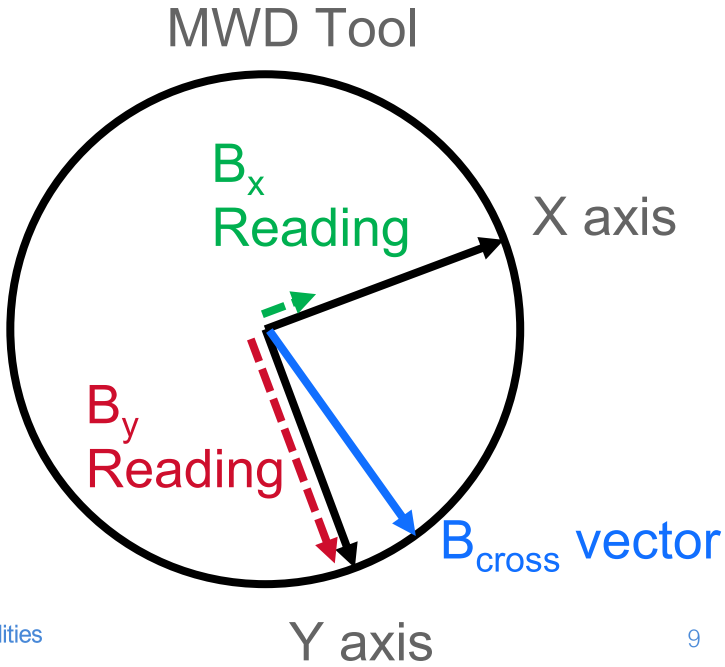


Impact of Alignment errors on Survey Stations

Two Axes of a Survey Station

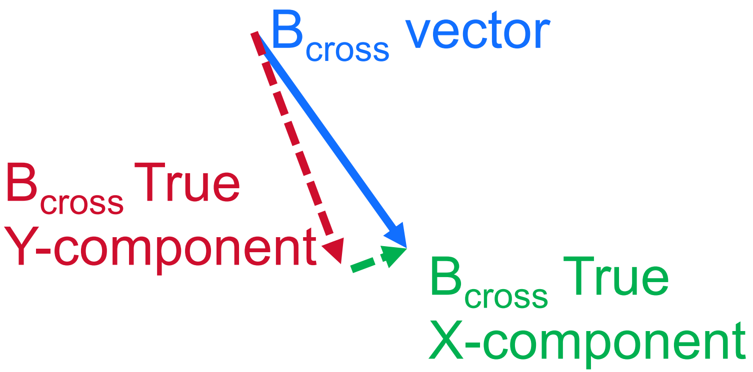
- Well aligned sensor in a magnetic field
  - B_x = “True” B_x ; B_y = “True” B_y

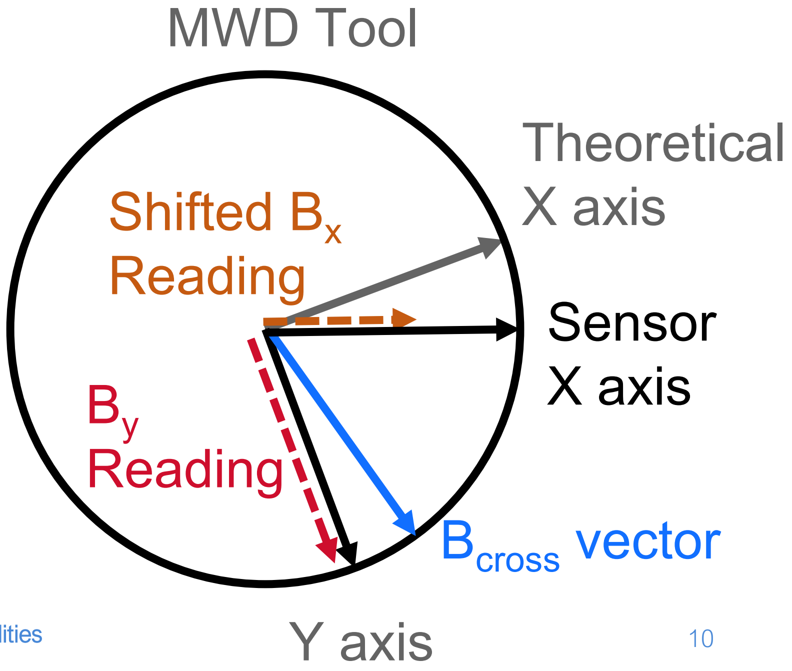


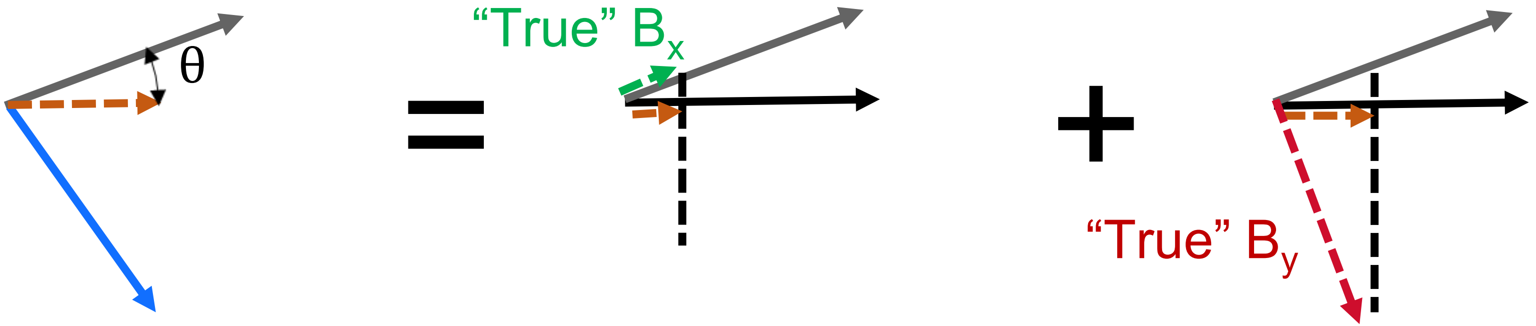


Non-Orthogonality on a Single Measurement

- Now shift one sensor (B_x)
  - B_y is still "True" B_y; B_x is off ☹







Shifted B_x Reading = Reduced amount of B_{cross} X-component + Some new amount of B_{cross} Y-component

$$B_{x,\ sensor} = B_{x,\ theoretical}\cos(\theta) + B_{y,\ theoretical}\sin(\theta)$$

Scale factor equivalent
(constant survey to survey)

bias equivalent
(varies survey to survey)

Quick note for completeness's sake:

- For small deviations, additional non-orthogonality terms can be added

$$B_{x,\ sensor} = B_{x,\ true} \cos(\theta_{xy})\cos(\theta_{xz}) + B_y \sin(\theta_{xy}) + B_z \sin(\theta_{xz})$$

- Misalignments can be considered a combination of non-orthogonalities
    - Hand-wavy way for me to say we don’t have time to talk about them in detail!

Impact of Alignment errors on Error Models

Error Terms / Weighting functions for Alignments

- For the single station, perfectly mapping non-orthogonality error is possible
  - Scale component is a mathematically identical error
  - Bias is also mathematically identical for *one survey*

$$B_{x,\ sensor} = B_{x,\ true} * Scale * \cos(\theta_{xy}) + Bias + B_y \sin(\theta_{xy})$$

Alignment errors have been lumped into existing terms with no loss of accuracy

Equivalent Scale Factor for Non-orthogonality

Scale Factor Error = cos(θ)

- Accel 1-σ scale factor: *0.0005*
  - cos(θ) = .9995; $\cos^{-1}(0.9995)$ ➔ **θ = ~1.8° or 31.4 milliRad**
- Mag 1-σ scale factor: *0.0016*
  - $\cos^{-1}(0.9984)$ ➔ **θ = ~3.2° or 56.6 milliRad**
- The scale factor errors are, in practice, of little consequence

Equivalent Bias for Non-orthogonality

Bias Error = sin(θ) * complementary-axis vector

"Worst Case" would be sensor perpendicular to G_t or B_t

- Accel 1-σ bias: *0.004m/s²*
  - $\sin(\theta)*9.81 m/s^2 \approx \theta*9.81 m/s^2 = 0.004 m/s^2$ ➔ **θ = ~0.02° or 0.4 milliRad**

- Mag 1-σ bias: *70nT*
  - $\sin(\theta)*50{,}000 nT \approx \theta*50{,}000 nT = 70 nT$ ➔ **θ = ~0.08° or 1.4 milliRad**

May consume a meaningful fraction of your error budget!

Propagation modes

- For the survey leg, it's a little trickier, but still ok
  - The errors will not propagate identically to an equivalent bias…
  - …but they will still be bounded by the cone of a "worst case" bias

$$|Bias + B_y \sin(\theta_{xy})| \leq |Bias \pm B_t \sin(\theta_{xy})|$$

For *ellipse of uncertainty* generation this has been good enough!

Practical Implications

- Instrument error budget should account for residual bias AND non-ortho
  - Pre-run roll check QC and downhole FAC should consider both!

- Could require geometry and geography considerations to validate sensors
  - A sensor that is adequate at vertical may fail at horizontal and vice versa
  - Estimating the alignment error magnitude not enough context to know the full impact

There's also the whole matter of survey corrections…

How Survey Corrections Complicate All of This

Standard vs. Multi-station Error Models

"Standard" MWD Magnetometer Biases

11	MBXY-TI1S	MWD TF Ind: X and Y Magnetometer Bias	MBXY-TI1	SPE 63275 + Andy Brooks	Sensor	70	nT
12	MBXY-TI2S	MWD TF Ind: X and Y Magnetometer Bias	MBXY-TI2	SPE 63275 + Andy Brooks	Sensor	70	nT

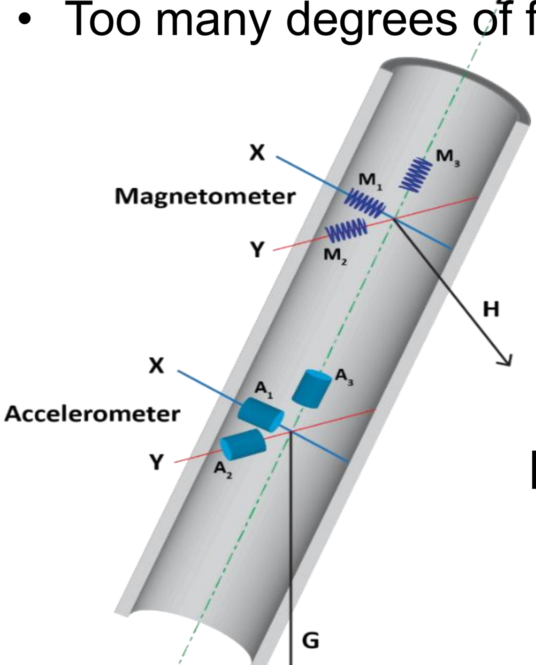
Multi-station MWD Magnetometer biases

11	MBXY-TI1S	MWD TF Ind: X and Y Magnetometer Bias	MBXY-TI1	SPE 63275 + Andy Brooks	Sensor	35	nT
12	MBXY-TI2S	MWD TF Ind: X and Y Magnetometer Bias	MBXY-TI2	SPE 63275 + Andy Brooks	Sensor	35	nT

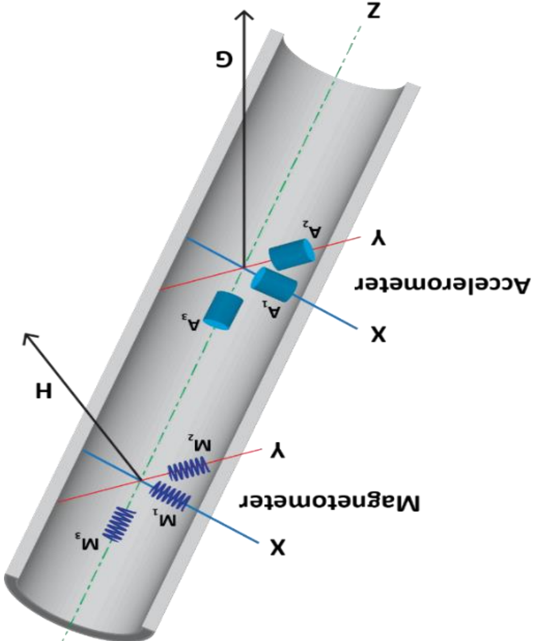
Corrections reduce the bias, but that also implies reduced alignment errors!

Possible issue with alignment corrections

- Downhole alignment adjustments can allow for arbitrary survey corrections
  - Too many degrees of freedom



Let’s rotate everything!



One Approach to 3rd Party Alignment Corrections

- Assume Z-accelerometer defines the instrument chasis
  - Avoids arbitrary orientation corrections
  - If incorrect, then solutions will create an *offset center*

- Assume Y-accelerometer defines the tool face
  - Ensures unique solutions for B-G misalignment
  - If incorrect, solutions will create a *toolface offset*

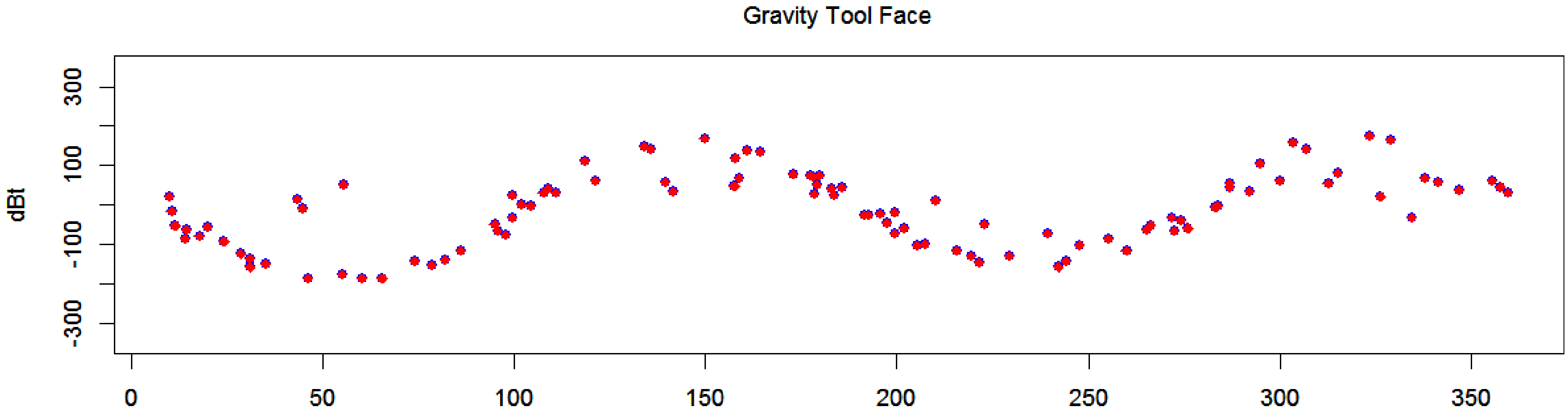
- Combined we reduce potential solution space with minimal risk to position

Alignment Corrections in Practice

- Vast Majority of Alignment Corrections are a non-issue
- X-to-Z and Y-to-Z non-orthogonalities are low impact by nature
- Tool “bends” are often straightforward to identify and correct

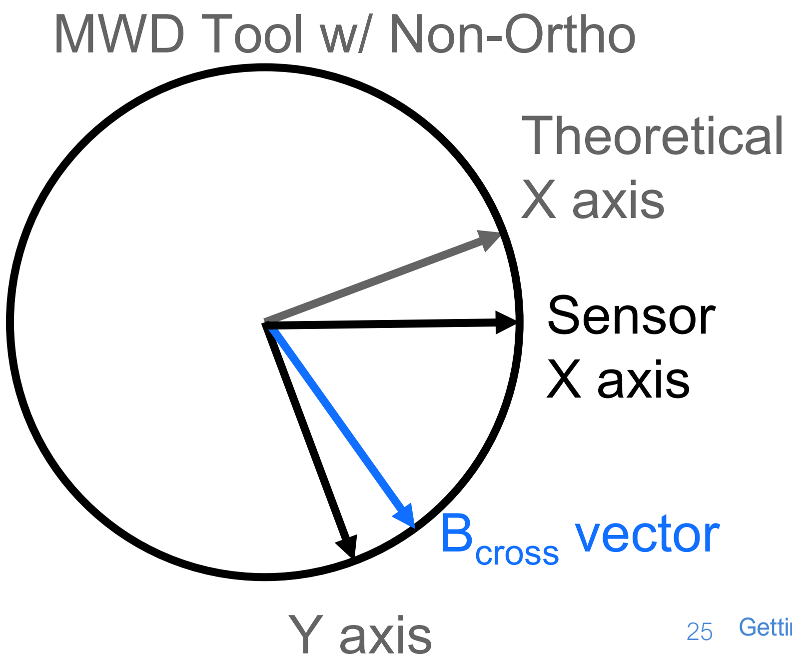
X-Y Non-Orthogonality: The Elephant in the Room

- Identifying the X-Y orthogonality is still easy…correction is often hard



QC is double-signed double sine-wave with tool face orientation

Back to our original example –



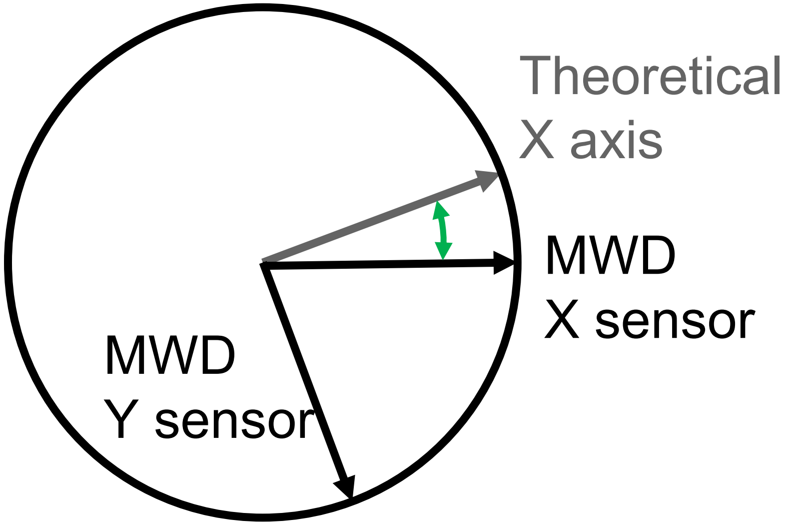
Assume you have an MWD instrument where it's known the cross-axis sensors are not orthogonal:

Two solutions exist that will restore orthogonality to the sensor triad

2 Solutions – Both Restore Orthogonality

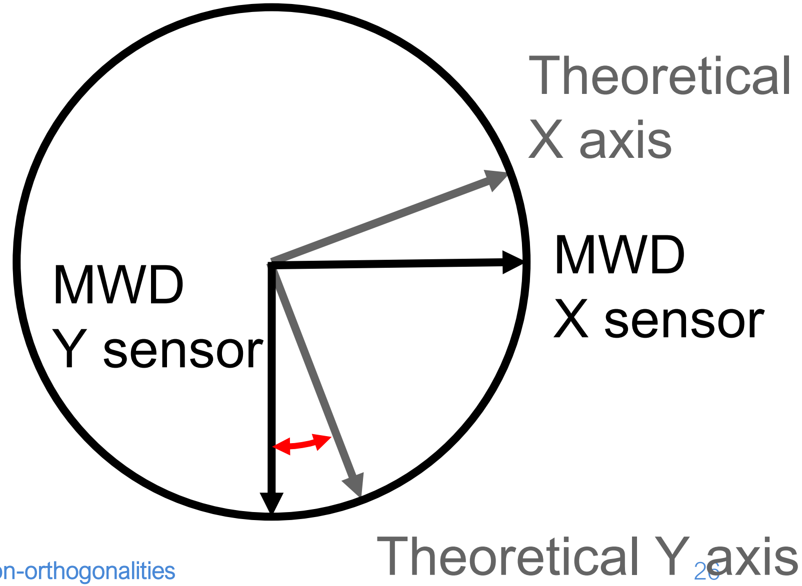
Assume X sensor is off

Good Solution



Assume Y sensor is off

Introduce a B-G Twist



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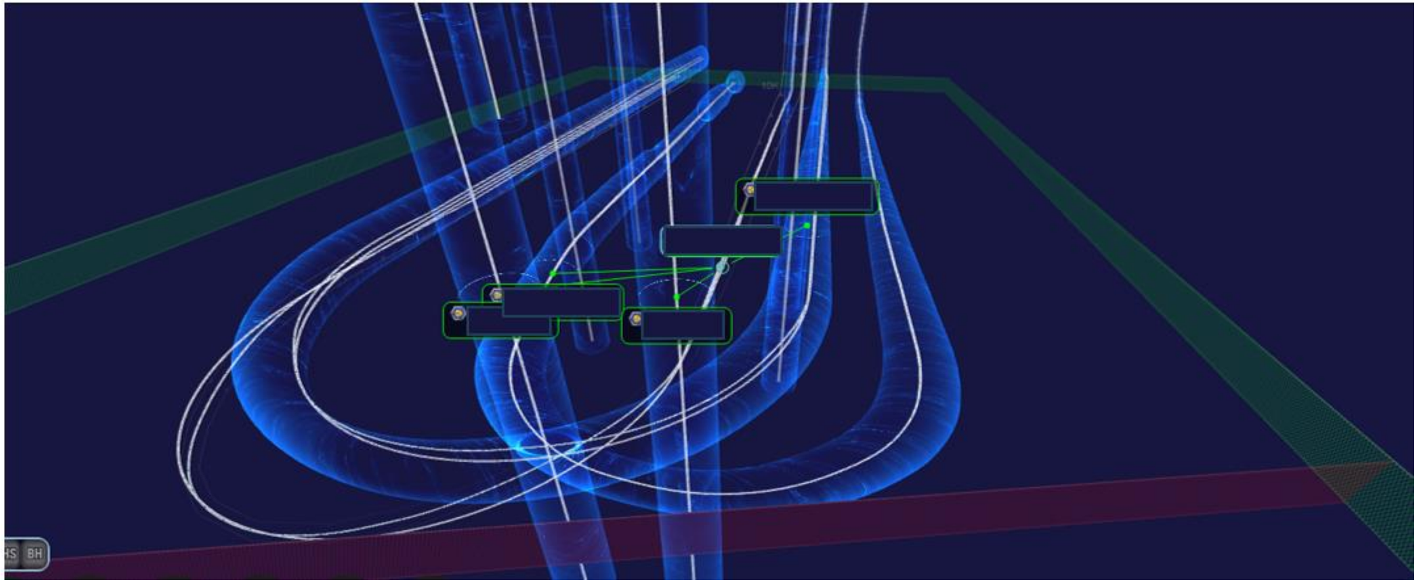
Sometimes you can solve for twists…

- Less common than your corrections provider would like though…



Twists are Problematic for Corrections in Practice

- Can create simple angle offsets in straight sections of wellbores
    - Angle Offsets = Dip or in Azimuth depending on tool orientation

- Highly co-linear with Drill String Interference and Magnetic Reference Error
    - Correction uncertainty can cause more issues than just the alignment problem

- Additional Surface testing often required to raise correction confidence
    - Ideally an East-West roll test to break colinearities

Bringing it All Together

- Non-orthogonalities and misalignments are adequately “error modelled”…
  - ..for the purposes of estimating positional uncertainty
  - They are lumped in with the sensor bias terms

- Lack of explicit definitions creates ambiguity concerns for providers
  - But also gives them flexibility in operational processes
  - Combination of orthogonality + bias more important than individual terms

- Those trade offs can add 2nd order complications to survey corrections
  - Processes that were historically fine, may fail once you start corrections
  - Merits a conversation between MWD provider and corrections provider

Thank you!
Questions / Comments?