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SPE International
Wellbore Positioning Technical Section

ISCWSA
The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA)

Downhole Automatic Calibration of Rotary Steerable System for Real-Time Precision Surveying

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Speaker BIO

- Makito Katayama
- Senior Physicist at SLB for 13 years
- Measurement physics & algorithm development for surveying tools
    - MWD, RSS & Gyroscopic tools

Motivation

Survey | Steering

MWD | Rotary Steerable System (RSS)

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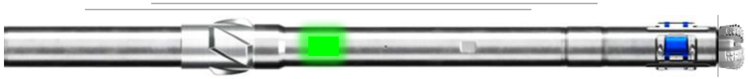
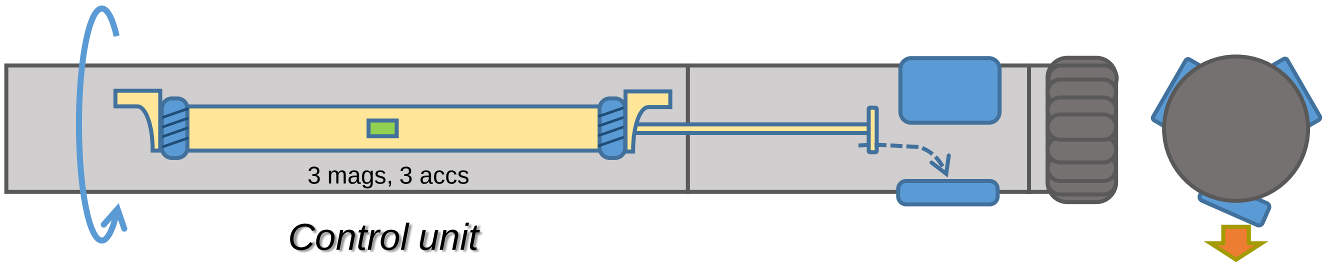


New RSS

✓ Offering MWD grade surveying closer to the bit!

Rotary Steerable System: PowerDrive



Challenges for surveying

1. Survey under dynamic condition (collar rotating) as no battery in the system
   1. Eddy current, Dynamic noise.. etc
2. Prone to severe magnetic interference (several mechanics/electronics has impact to mag)

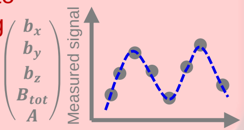
Positive features for surveying

1. Control unit rotates slow toward geostatic condition (relatively easy to suppress the vibration noise)

Modeling of Measurement Error and Compensation

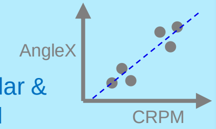
MSA for Bias offset estimation

Simplified MSA run in downhole to estimate mag interferences



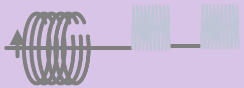
Eddy current compensation

Eddy current coefficient is estimated by detecting collar & chassis RPM change and AngleX change



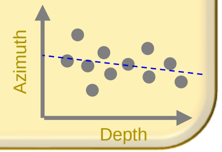
Actuator interference

Active filtering and bias compensation for actuator noise compensation



Suppressing randomness

Use Kalman filter to suppress randomness of the resultant azimuth



Four algorithms to run in downhole

Eddy current model | Mag Bias offset | Actuator noise | Random noise

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}_i = \begin{pmatrix} 1 & -\gamma_c\omega_c & 0 \\ \gamma_c\omega_c & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \widehat{B_x} \\ \widehat{B_y} \\ \widehat{B_z} \end{pmatrix} + \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} + s\begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} + \begin{pmatrix} \varepsilon_{B_x} \\ \varepsilon_{B_y} \\ \varepsilon_{B_z} \end{pmatrix}$$

γ_c : Eddy current coefficient
ω_c, : Collar Rotation speed
b_x, b_y, b_z: Bias offset of mags
s_x, s_y, s_z: Actuator noise amplitude
$\widehat{B_x}$, $\widehat{B_y}$, $\widehat{B_z}$: True magnetic field around BHA
B_x, B_y, B_z: Measured mag by sensor

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Bias Estimation

- Measurement Forward model

$$\boldsymbol{B}_i = \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}_i = \underbrace{BP(\gamma)\begin{pmatrix} \sin D \sin I \sin\phi - \cos D\,(\cos\phi \sin\psi + \cos\psi \cos I \sin\phi) \\ \cos D\,(\sin\psi \sin\phi - \cos\psi \cos I \cos\phi) + \cos\phi \sin D \sin I \\ \cos I \sin D + \cos\psi \cos D \sin I \end{pmatrix} + \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} + \begin{pmatrix} \varepsilon_{B_x} \\ \varepsilon_{B_y} \\ \varepsilon_{B_z} \end{pmatrix}}_{\boldsymbol{F}}$$

ψ: Azimuth
B: Total B
b: Bias
γ: Eddy current coef.
ω_c: Collar RPM
I: Inclination
D: Dip angle
ϕ: Roll angle
ε: Error component
$\boldsymbol{P}$: Eddy current model

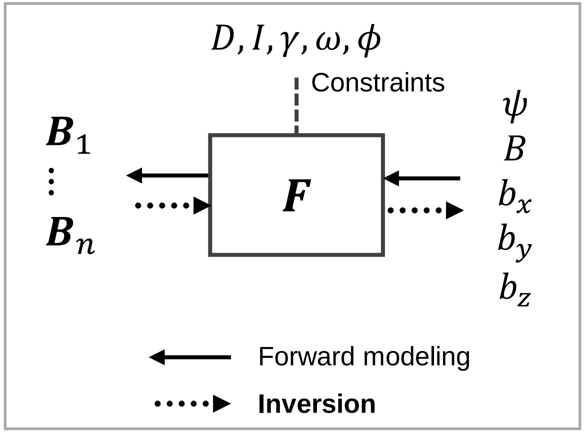
$$\begin{pmatrix} \boldsymbol{B}_1 \\ \vdots \\ \boldsymbol{B}_n \end{pmatrix} = \begin{pmatrix} \boldsymbol{F}_1 \\ \vdots \\ \boldsymbol{F}_n \end{pmatrix}_{\boldsymbol{x}} + \begin{pmatrix} \boldsymbol{w}_1 \\ \vdots \\ \boldsymbol{w}_n \end{pmatrix}$$

- Estimation of parameters

$$\boldsymbol{x} = (\psi\ B\ b_x\ b_y\ b_z)^T$$

- Sampling mag signals during rotation of controller unit

Toolface change over time



Optimization process

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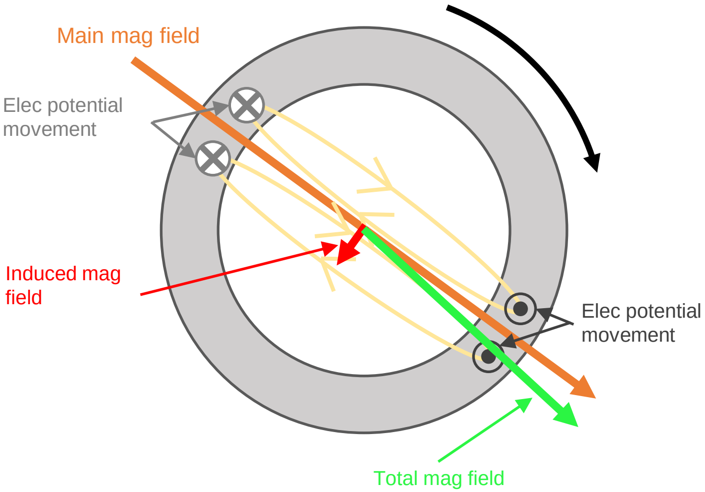
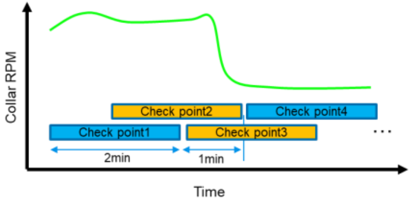
Eddy Current Effect Estimation

- Eddy current model
  - Orthogonal to main field
  - Magnitude is relative to collar RPM

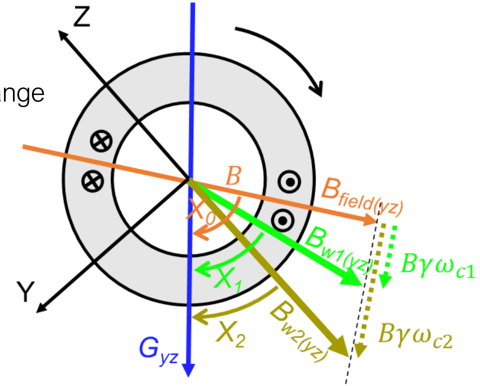


Eddy current phenomenon

- Angle X vs Collar RPM
  - Angle X changes as collar RPM to change
  - Detect change of collar RPM

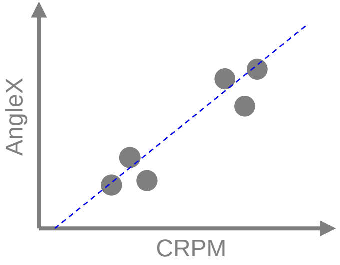


Check window



Angle X and eddy current impact

  - Least square to estimate γ



Angle X and CRPM relationship

Model

$$\begin{pmatrix} X_{\omega_{c1}} \\ \vdots \\ X_{\omega_{cn}} \end{pmatrix} = \boldsymbol{F} \begin{pmatrix} \gamma \\ X_0 \end{pmatrix} + \boldsymbol{w}$$

Inversion model

$$\begin{pmatrix} \gamma \\ X_0 \end{pmatrix} = (\boldsymbol{F}^T\boldsymbol{F})^{-1}\boldsymbol{F}^T \begin{pmatrix} X_{\omega_{c1}} \\ \vdots \\ X_{\omega_{cn}} \end{pmatrix} \qquad \boldsymbol{F} = \begin{pmatrix} \omega_{c1} & 1 \\ \vdots & \vdots \\ \omega_{cn} & 1 \end{pmatrix}$$

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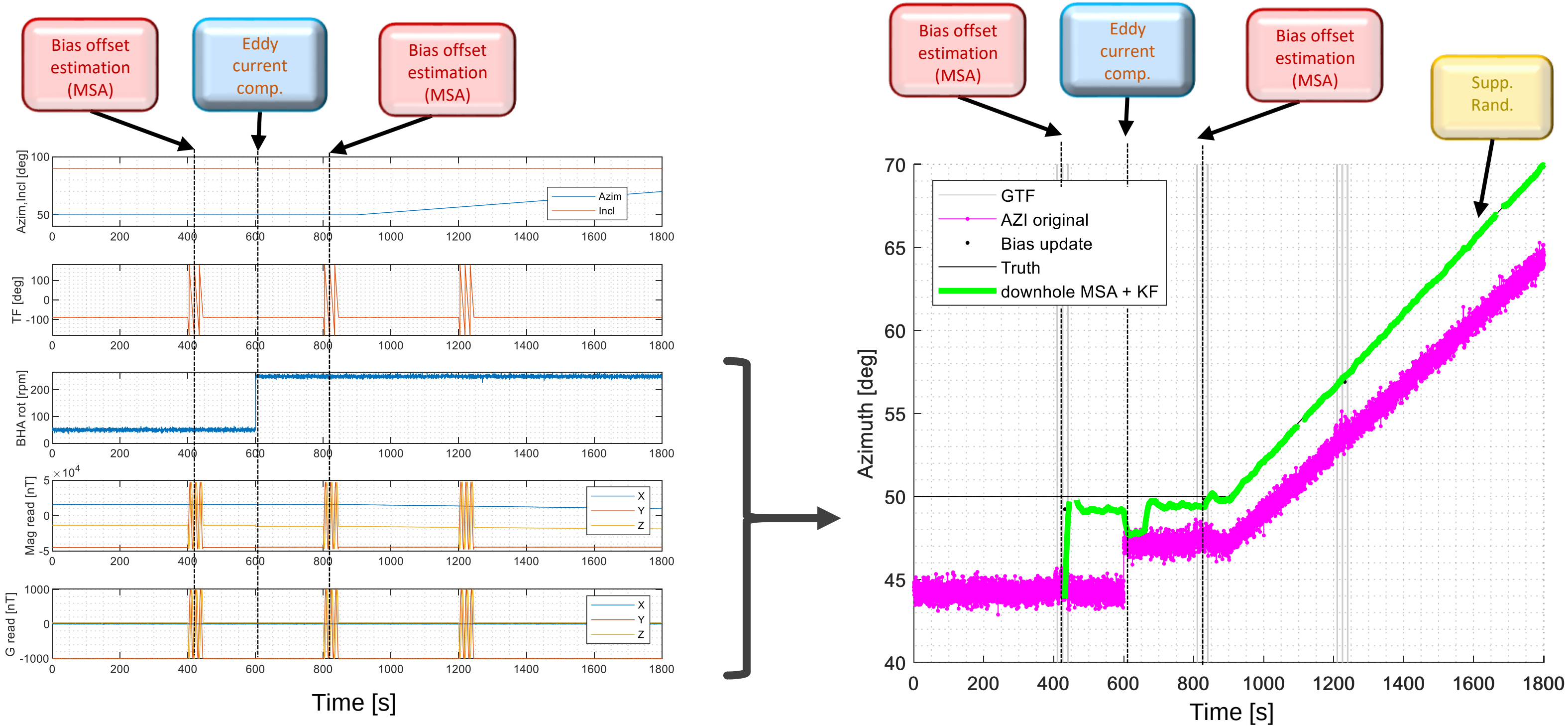
Simulation Result



Simulated Signals

Estimation Result

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Downhole Processing Field Test

- All processing done in RSS downhole, sending only compensated surveys (used for the statistics analysis)
- Various reference tools (Drop gyro, MWDs)
- Error model: MWD rev5

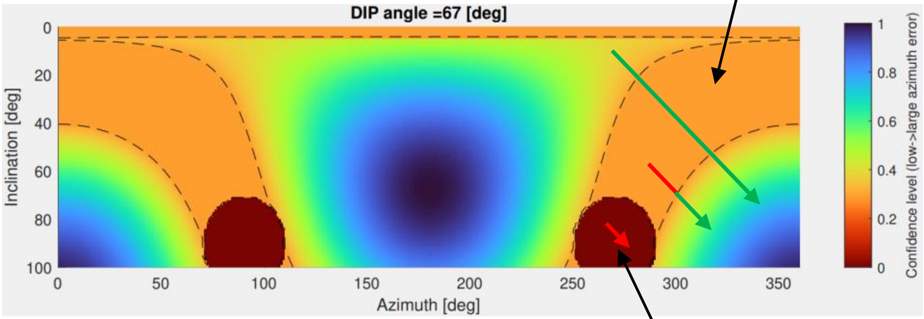
Run	Reference vs Comparison							Comp Type
	Chi-Square (Tor: 34.4)			RIP Test				
	N	E	TVD	Norm Incl Mean	Norm Incl STD	Norm Azi mean	Norm Azi STD	
#1								Gyro Omega (drop)
#2								Gyro Omega (drop)
#3								Gyro Omega (drop)
#4								DDS
#5								Gyro Omega (drop)
#6								MWD

abs(mean_diff) <= 0.50 : Good agreement	std_diff <= 1.00 : Good agreement
abs(mean_diff) <= 0.75 : Average agreement	std_diff <= 1.50 : Average agreement
abs(mean_diff) <= 1.25 : Poor agreement	std_diff <= 2.00 : Poor agreement
abs(mean_diff) > 1.25 : Disagreement	std_diff > 2.00 : Disagreement

Survey Limitations

Good survey quality
Poor survey quality

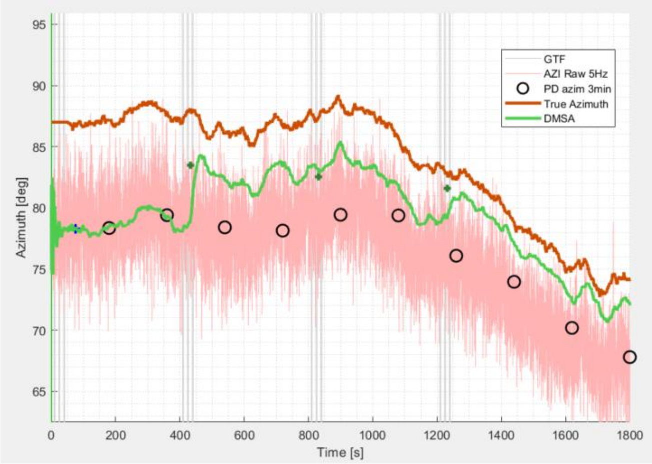
Bias update inaccurate



*Signal uncertainty & reference error is the key

Zone of exclusion

Bias & azimuth accuracy MAP



"Simulated" example at zone of exclusion when <u>forced</u> to update bias

Conclusion

- Rotary steerable system allows at bit definitive survey
- Bias correction, eddy current correction, actuator noise and random noise suppression are key algorithm components for the autonomous downhole calibration
- Algorithms were implemented to the PowerDrive downhole rotary steerable
- Surveying results from field test were compared with DropGyro or MWD tools, and passed RIP and χ^2 test for MWD rev5 error model
- Survey accuracy limitations were defined, and continue to be explored