



Multi-station Analysis for Rotary Continuous Survey

Speaker:

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Authors:

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Baker Hughes The Baker Hughes logo, featuring the company name in a bold, black, sans-serif font followed by a stylized green symbol consisting of two interlocking, curved shapes.



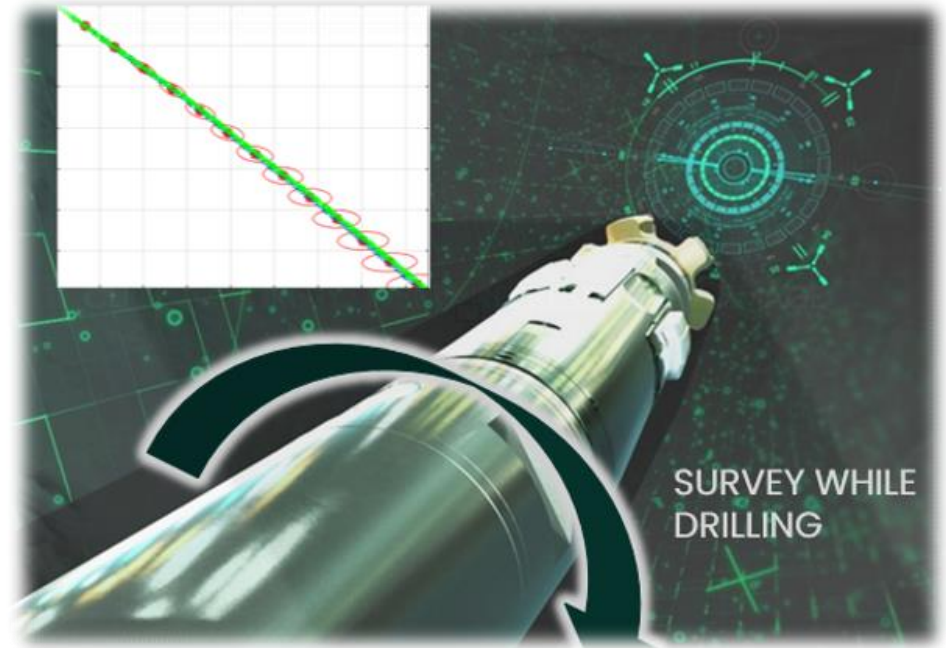
Speaker Bio

Dr.-Ing. Daniel E. Herrera Anda

- Lead R&D Engineer, Mathematics & Data Science, Product Design & Engineering, Baker Hughes
- PhD in Control Systems, National University of San Juan, Argentina (2017)
- Specialist in algorithmic modeling and simulation for drilling navigation systems
- Develops advanced technologies for:
 - Directional Estimation and Survey Quality Control (Steering-unit and Directional tools)
 - Advanced QC and corrections for directional surveys (Multi-station Analysis)
 - Advanced Reservoir Navigation Systems (Extra-deep azimuthal resistivity measurements)

Agenda

- Surveying in Directional Drilling
- Principle of Rotary Continuous Surveying (RCS)
- Sensor-Error Model and Error Sources
- The Proposed Method: cMSA
- Case Studies
- Conclusions



- ✓ Precise well placement
- ✓ Collision avoidance
- ✓ Optimal reservoir exposure
- ✓ Reduced operational risk & cost

Surveying in Directional Drilling

Accurate knowledge of wellbore trajectory is crucial for several **technical**, **operational**, and **economic** reasons

MWD Magnetic Surveying

Static Surveys

Rotary Continuous Surveys (RCS)

- ✓ No survey-stop requirements
- ✓ Reduced NPT
- ✓ Reduced stuck-pipe exposure
- ✓ No batteries (flow-on survey)
- ✓ Increased survey interval

Directional Sensor Measurements

3-axis Accelerometer G_x, G_y, G_z

- ✓ Inclination
- ✓ Azimuth

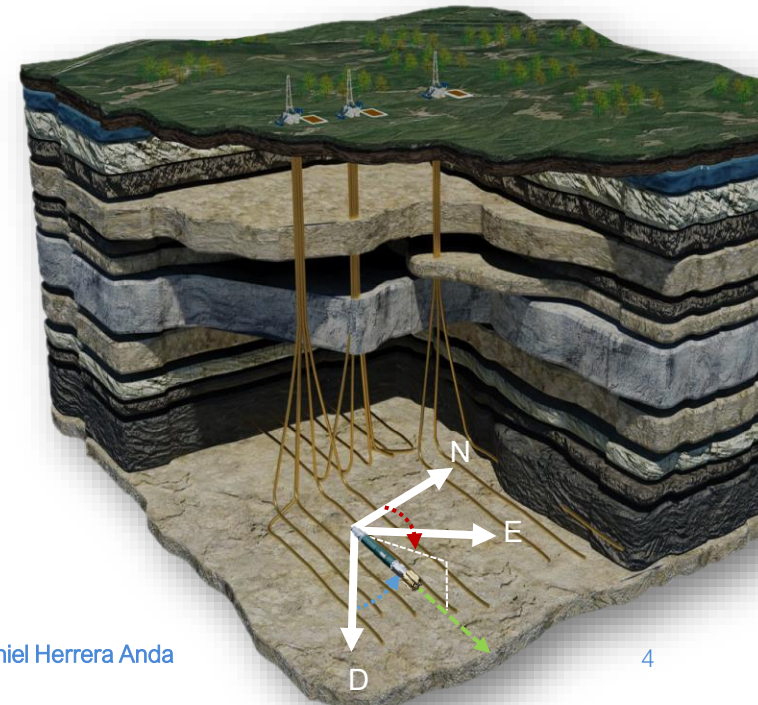
3-axis Magnetometer B_x, B_y, B_z

Problem statement

Static-Survey Multi-station Analysis (MSA) is not applicable to RCS.

Fundamental and new error sources impact RCS.

⇒ **Solution:** Extend MSA to RCS (cMSA/cMSC)



Static Surveying

Flow-off survey, no rotation

Noise filtering

Surface Survey QC (TMF, TGF, DIP)

$$I = \tan^{-1} \left(\frac{\sqrt{G_x^2 + G_y^2}}{G_z} \right),$$

$$A = \tan^{-1} \left(\frac{(G_x B_y - G_y B_x) \sqrt{G_x^2 + G_y^2 + G_z^2}}{B_z (G_x^2 + G_y^2) - G_z (G_x B_x + G_y B_y)} \right)$$

6-axis MWD sensor readings

Stand-still?

Yes

No

Rotary Continuous Surveying

Flow-on, on-bottom, with rotation

Transformation to rotary invariant sensor readings

Noise filtering

Eddy-Current Compensation & Downhole QC

Surface Survey QC (TMF, TGF, DIP)

$$(G_1, G_2, G_z, B_{xy}, B_z) \rightarrow (I, A, G_{tot}, B_{tot}, \Theta_{dip})$$

$$G_1 = (G_x B_x + G_y B_y) / B_{xy}, \quad G_2 = (G_x B_y - G_y B_x) / B_{xy}, \quad B_{xy} = \sqrt{B_x^2 + B_y^2}$$

equivalent

$$I = \tan^{-1} \left(\frac{\sqrt{G_1^2 + G_2^2}}{G_z} \right),$$

$$A = \tan^{-1} \left(\frac{G_2 B_{xy} \sqrt{G_1^2 + G_2^2 + G_z^2}}{B_z (G_1^2 + G_2^2) - G_z G_1 B_{xy}} \right)$$

Source: Tackmann G., Baker Hughes, US 12,565,832 B2

Sensor Error Model and Error Sources

Set of corrected survey values $\{G_{1,c}, G_{2,c}, G_{z,c}, B_{xy,c}, B_{z,c}\}$
is derived from the raw set of survey values
 $\{G_1, G_2, G_z, B_{xy}, B_z\}$

$$G_{1,c} = \frac{1}{1 + s_{G_{xy}}} (\cos(\phi_{\text{err}} + \chi) G_1 - \sin(\phi_{\text{err}} + \chi) G_2) + \varepsilon_{G_1}$$

$$G_{2,c} = \frac{1}{1 + s_{G_{xy}}} (\cos(\phi_{\text{err}} + \chi) G_2 + \sin(\phi_{\text{err}} + \chi) G_1) + \varepsilon_{G_2}$$

$$G_{z,c} = \frac{1}{1 + s_{G_z}} (G_z - b_{G_z}) + \varepsilon_{G_z}$$

$$B_{xy,c} = \frac{1}{1 + s_{B_{xy}}} B_{xy} + \varepsilon_{B_{xy}}$$

$$B_{z,c} = \frac{1}{1 + s_{B_z}} (B_z - b_z) + \varepsilon_{B_z}$$

$$\phi_{\text{err}} = \rho_{\text{EDDY,PSD}} \cdot f_{\text{rot}}$$

Source: SPE-230702-MS

Table —Mapping of sensor and reference error sources to ISCWSA Terms

	Error Description	State	Units	ISCWSA Terms
Sensor Errors	Cross-Axial Accelerometer Scale Factor/ Attenuation Error	$s_{G_{xy}}$	-	ASXY, AAXY
	Axial Accelerometer Scale Factor Error	s_{G_z}	-	ASZ
	Axial Accelerometer Bias	b_{G_z}	m/s ²	ABZ
	Cross-Axial Magnetometer Scale Factor/ Attenuation Error	$s_{B_{xy}}$	-	MSXY, AMXY
	Axial Magnetometers Scale Factor Error	s_{B_z}	-	MSZ
	Axial Magnetometers Bias and Axial Interference	b_{B_z}	nT	MBZ, AMIL
	Toolface frequency-dependent error	$\rho_{\text{EDDY,PSD}}$	°/Hz	EDDY, PSD
	Twist (Toolface frequency-independent error)	χ	°	-
	Random bias due to drilling noise	$\varepsilon_{G_1}, \varepsilon_{G_2}, \varepsilon_{G_z}$	m/s ²	AN1, AN2, ANZ
	Random bias due to centripetal accelerations	$\varepsilon_{G_1}, \varepsilon_{G_2}$	m/s ²	CA1, CA2
Random magnetometer bias	$\varepsilon_{B_{xy}}, \varepsilon_{B_z}$	nT	-	
Ref. Errors	Total Gravity Field Reference Error	$G_{t,\text{ref}}$	m/s ²	-
	Total Magnetic Field Reference Error1	$B_{t,\text{ref}}$	nT	MF1G
	Dip Angle Reference Error1	D_{ref}	°	MF1DG
	Total Magnetic Field Reference Uncertainty	$\varepsilon_{\text{MFIR}}$	nT	MFIR
	Dip Magnetic Angle Reference Uncertainty	$\varepsilon_{\text{MFDR}}$	°	MFDR

Proposed Method: cMSA/cMSC

Step 1
Define measurement model

$$\mathbf{y} = \begin{pmatrix} G_{t,ref} - G_t \\ B_{t,ref} - B_t \\ D_{ref} - D \end{pmatrix}$$

$G_{t,ref}$ Total Gravity Field Reference
 $B_{t,ref}$ Total Magnetic Field Reference
 D_{ref} Dip Angle Reference

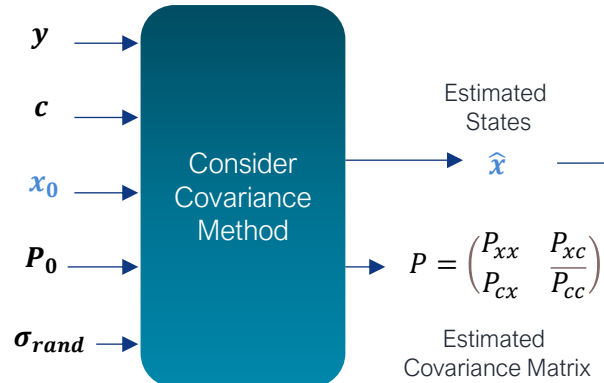
G_t Calculated Total Gravity Field
 B_t Calculated Total Magnetic Field
 D Calculated Dip Angle

Step 2
Split state vector

$$\mathbf{z} = \begin{pmatrix} S_{G_{xy}} \\ S_{G_z} \\ b_{G_z} \\ S_{B_{xy}} \\ S_{B_z} \\ b_{B_z} \\ \rho_{EDDY,PSD} \\ \chi \\ G_{t,ref} \\ B_{t,ref} \\ D_{ref} \end{pmatrix} = \begin{pmatrix} \mathbf{x} \\ \mathbf{c} \end{pmatrix}$$

Subset of to be estimated states
↓
Subset of to be considered states

Step 3
Apply Consider Covariance Method



\mathbf{x}_0 Initial state vector (a-priori information)
 \mathbf{P}_0 Initial Covariance Matrix (error model, geo-mag model)
 $\boldsymbol{\sigma}_{rand}$ Random noise vector (station-to-station)

Step 4
Correct survey log

$$(G_1, G_2, G_z, B_{xy}, B_z)$$



$$\begin{pmatrix} G_{1,c} \\ G_{2,c} \\ G_{z,c} \\ B_{xy,c} \\ B_{z,c} \end{pmatrix} \rightarrow \begin{pmatrix} I_c \\ A_c \end{pmatrix}$$

Sources: Baker Hughes, SPE-173098-MS, US10228987B2 (2013), SPE-230702-MS (2026)

Source: Baker Hughes, SPE-230702-MS (2026)

Case Study 1: “One tool, two deployments, zero excuses”

Middle East On-shore, 6-3/4" MWD with RCS in Shadow Mode; Second job used improved eddy-current parametrization

First deployment: Eddy-current compensation parametrization from laboratory experiments

cMSA results	$\rho_{\text{EDDY,PSD}}$ (°/RPM)	$s_{G_{xy}}$ (-)	b_{G_z} (m/s ²)	$s_{B_{xy}}$ (-)	b_{B_z} (nT)
Estimate	0.0015	-0.0012601	0.00023841	-0.0013654	25.611
Uncertainty (1 σ)	0.00253	0.00021801	0.0051275	0.0013228	57.409
Limit (3 σ)	0.6° (@Max.150RPM)	0.0015	0.012	0.003	910.07



Second deployment: Improved eddy-curr. compensation param. → better performance

cMSA results	$\rho_{\text{EDDY,PSD}}$ (°/RPM)	$s_{G_{xy}}$ (-)	b_{G_z} (m/s ²)	$s_{B_{xy}}$ (-)	b_{B_z} (nT)
Estimate	-0.0002	-0.0013468	0.0019779	-0.0012369	136.05
Uncertainty (1 σ)	0.0018391	0.00021129	0.0079793	0.0010557	55.746
Limit (3 σ)	0.6° (@Max.150RPM)	0.0015	0.012	0.003	910.07



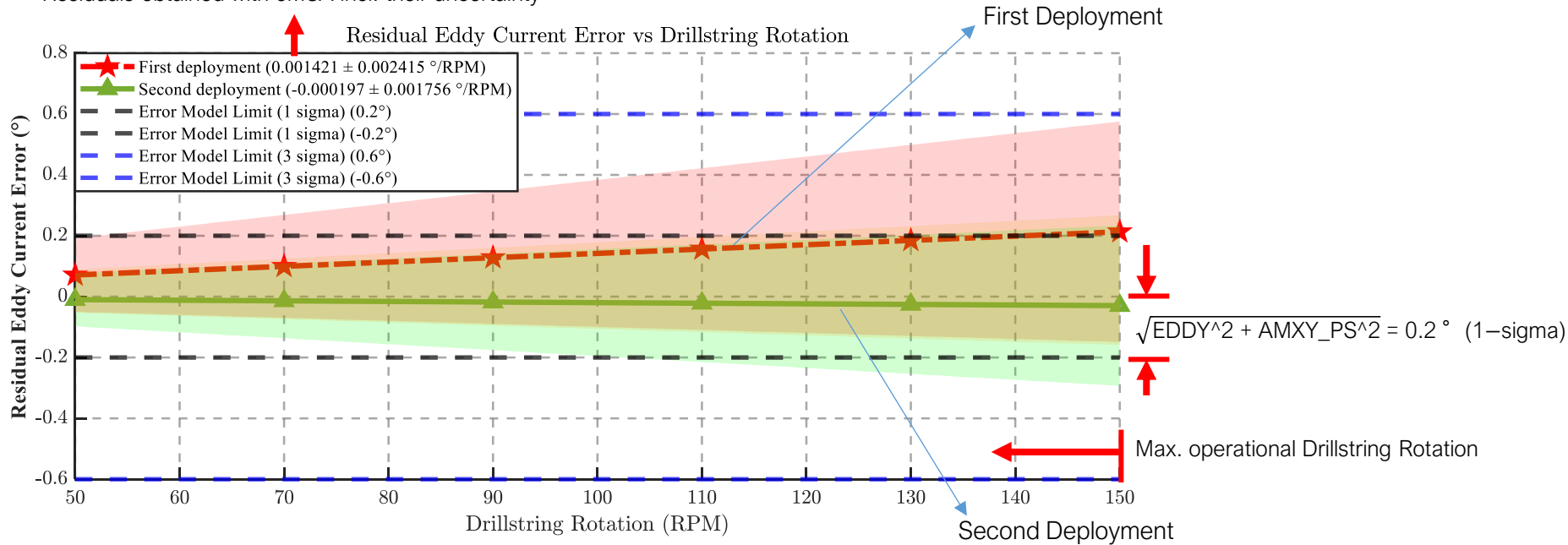
- ✓ Consistent parameters between two jobs
 - same tool (same material)
 - comparable operational conditions and BHA configuration

- ✓ Identified residual eddy-current led to improve performance in subsequent job
 - Both jobs are in-spec, but second one shows reduced residual eddy-current effects

Case Study 1: “One tool, two deployments, zero excuses”

Middle East On-shore, 6-3/4" MWD with RCS in Shadow Mode; Second job with improved eddy-current parametrization

Residuals obtained with cMSA incl. their uncertainty



Case Study 1: “One tool, two deployments, zero excuses”

Middle East On-shore, 6-3/4" MWD with RCS in Shadow Mode; Second job with improved eddy-current parametrization

✓ The goal of cMSA is achieved: Better matching to nominal field values.

First Deployment

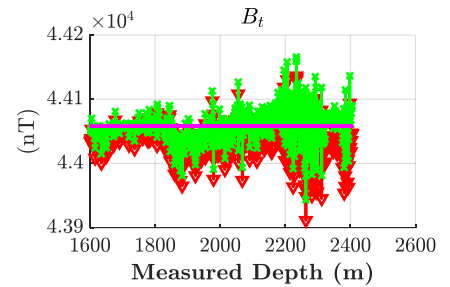
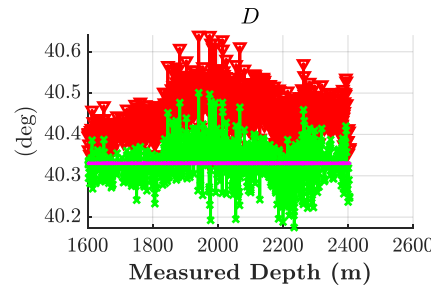
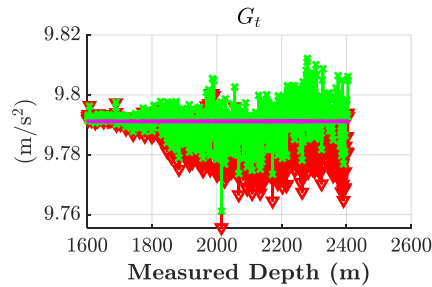
Inclination range: 2° – 80°

Azimuth range: 60 – 66°

DIP-angle: ~40.32°

800 m drilling:

- 1097 RCS
- 29 static surveys



Second Deployment

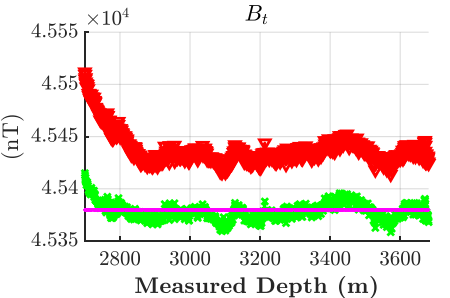
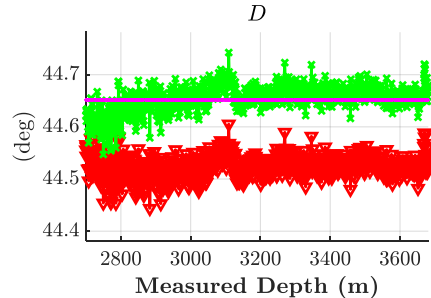
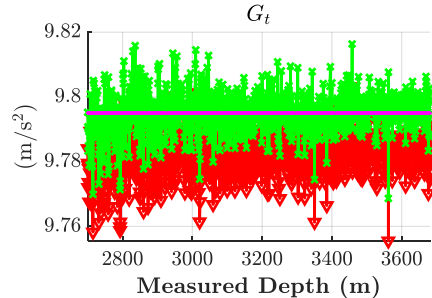
Inclination range: 20° – 90°

Azimuth range: 24.5°

DIP-angle: ~44.65°

1014 m drilling:

- 1010 RCS
- 36 static surveys



▼ Raw RCS
 ■ RCS cMSA
 - - - Nominal (RCS cMSA)

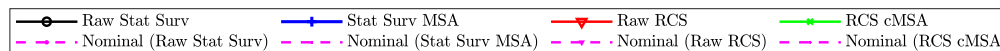
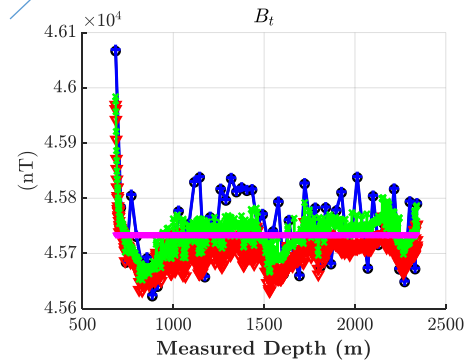
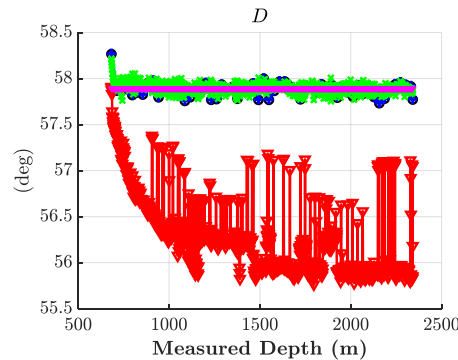
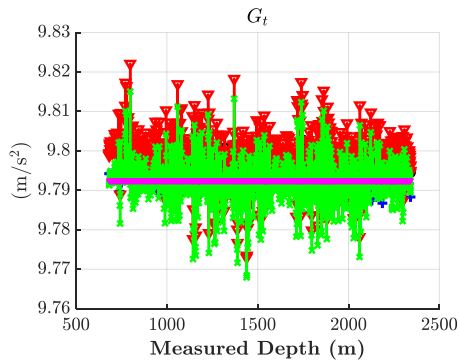
Case Study 2: Static Survey MSA vs RCS MSA

USA Offshore, 6 3/4" MWD tool; RCS in shadow mode; First-deployment with new tool material; Inclination range 22°–54°, azimuth 215°–260°

cMSA results	$\rho_{EDDY,PSD}$ (°/RPM)	$s_{G_{xy}}$ (-)	b_{G_z} (m/s ²)	b_{B_z} (nT)
Estimate	0.017	0.0006	0.0032	-57.67
Uncertainty (1 σ)	0.0019	0.0008	0.0084	129.06
Limit (3 σ)	0.6° (@Max.150RPM)	0.0015	0.012	910.0687

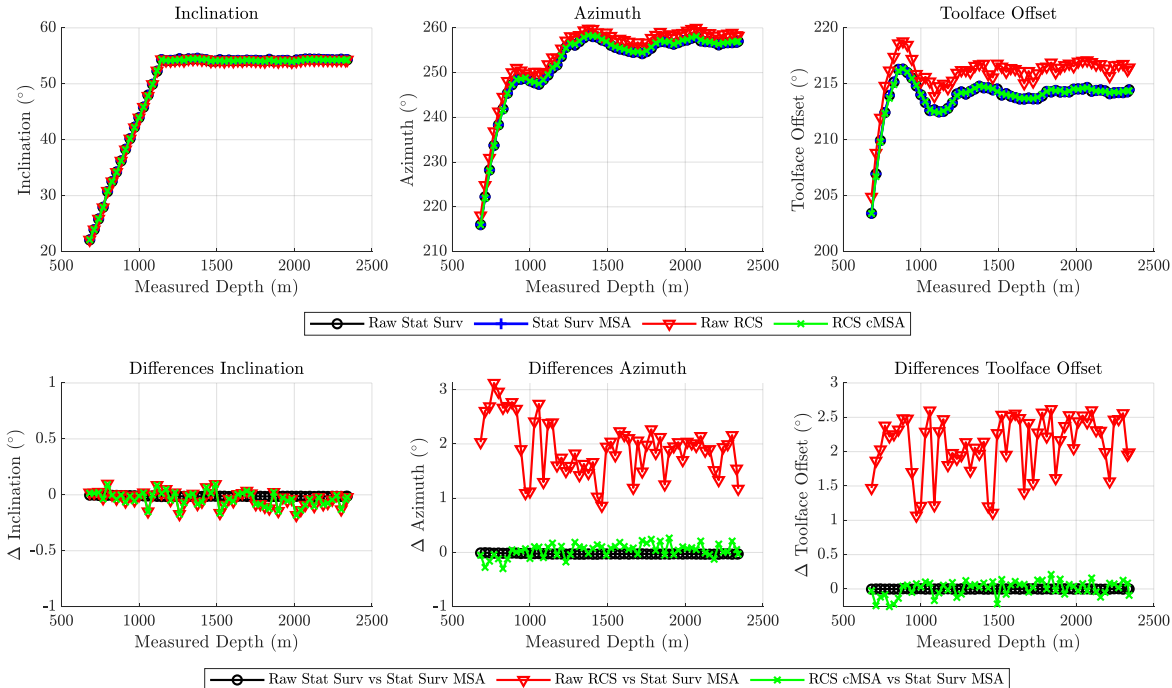
MSA results	s_{G_x} (-)	s_{G_y} (-)	b_{G_z} (m/s ²)	b_{B_z} (nT)
Estimate	0.0005	0.0004	0.0032	-4.4139
Uncertainty (1 σ)	0.0008	0.0007	0.0079	102.89

- Provides estimation for eddy-current compensation parameter
- Identified parameters are consistent between MSA/cMSA
- Better matching with nominal fields



Case Study 2: Static Survey MSA vs RCS MSA

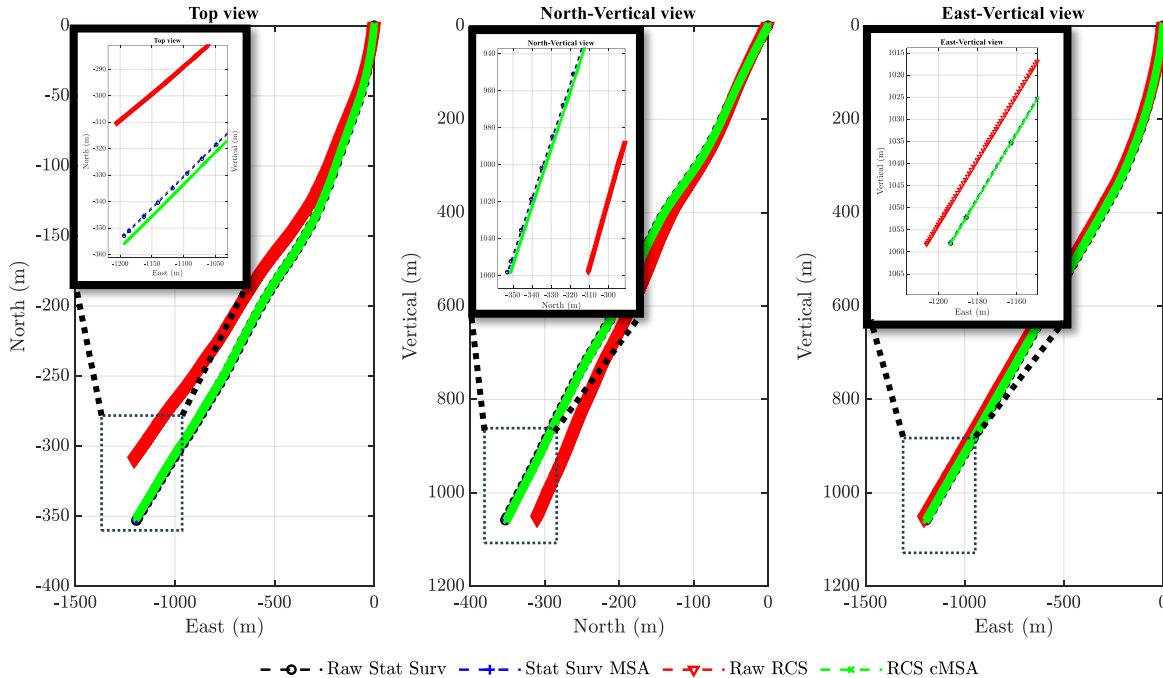
USA Offshore, 6 3/4" MWD tool, first-deployment with new tool material; RCS in shadow mode; Inclination range 22°–54°, azimuth 215°–260°



- ✓ Correction of systematic errors through cMSA/MSA
- ✓ Better matching with static survey azimuth

Case Study 2: Static Survey MSA vs RCS MSA

USA Offshore, 6 3/4" MWD tool, first-deployment with new tool material; RCS in shadow mode; Inclination range 22°–54°, azimuth 215°–260°



2159 m drilling:

- 1153 RCS (~one each 2 m)
- 51 static surveys (~one each 40 m)

Static vs High-dens. RCS	ΔN	ΔE	ΔV	C-C
Before cMSA	41.93	-12	0.40	43.61
After cMSA	1.23	0.002	0.44	1.30

- ✓ Pos. difference between static survey (MSA corrected) and RCS reduced from **43.61 m** to **1.30 m** at TD after applying cMSA

Remark:

High-density RCS survey log also reduces error caused by minimum curvature assumption (tighter course length)

→ for this case: $\Delta V \sim 0.4$ m



Conclusions

cMSA/cMSC for RCS:

- Extends MSA to RCS while remaining compatible with traditional static survey workflows.
- Improves wellbore positioning by correcting systematic errors in RCS datasets.
- Provides robust estimation of RCS systematic errors consistent with ISCWSA standard error model.
- Verifies tool calibration, and applies corrections if necessary
- Monitors survey quality
- Identifies out of spec conditions missed by the standard single-station survey QC

Acknowledgements

The authors would like to thank Baker Hughes for the support of this research and the approval to publish this work.



Thank you

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