SIMULATION OF TRI-AXIAL INDUCTION MEASUREMENTS IN THE PRESENCE OF TOOL ECCENTRICITY USING A FOURIER SERIES EXPANSION IN A NEW SYSTEM OF COORDINATES AND A SELF-ADAPTIVE *HP*-FINITE ELEMENT METHOD

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Outline

- Type of Problems Our Technology Can Solve.
- Methodology (Main Features of Our Technology).
- Introduction to Tri-Axial Induction.
- Previous Numerical Results:
  - Measurements in Deviated Wells.
- New Numerical Results for Borehole Eccentered Tools:
  - Verification of the 3D Method.
  - Measurements for Different Resistivity Tools.
- Conclusions.

Type of Problems Our Technology Can Solve

Main Application	Borehole Measurements		
Spatial Dimensions	2D	3D	
Well Type	Vertical Well	Deviated Well	Eccentered Tool
Logging Instruments	LWD/MWD	Normal/Laterolog	Dual-Laterolog
	Induction	Dielectric Instruments	Cross-Well
Frequency	0 ~ 10 GHz		
Materials	Isotropic	Anisotropic	
Physical Devices	Magnetic Buffers	Insulators	Casing
	Casing Imperfections	Displacement Currents	Combination of All
Sources	Finite Size Antennas	Dipoles in Any Direction	Solenoidal Antennas
	Toroidal Antennas	Electrodes	Combination of All
Invasion	Water	Oil	etc.
Other Applications	Marine Controlled Source EM and etc.		

MOST (OIL-INDUSTRY) GEOPHYSICAL PROBLEMS

Methodology (Main Features of Our Technology)

Combination of:

1. A Self-Adaptive Goal-Oriented *hp*-FEM for AC problems.

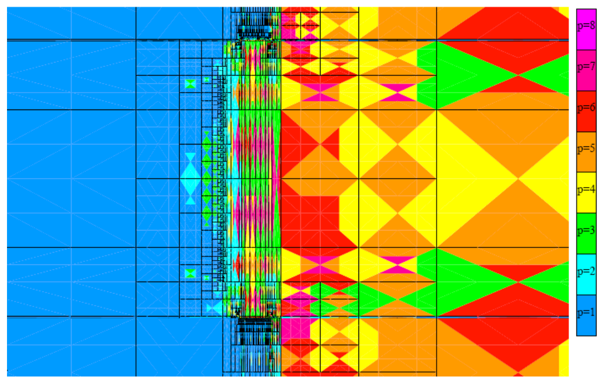
2. A Fourier Series Expansion in a New System of Coordinates.

3. Parallel Implementation.

Self-Adaptive Goal-Oriented *hp*-FEM

We vary locally the element size ***h*** and the polynomial order of approximation ***p*** throughout the grid.

Optimal grids are **automatically generated** by the *hp*-adaptive algorithm.

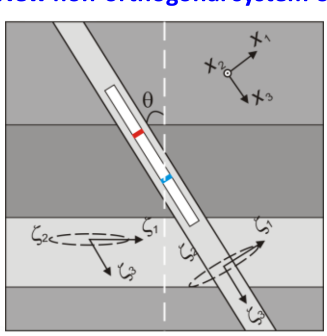


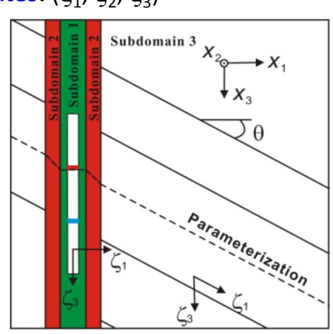
The self-adaptive goal-oriented *hp*-FEM provides **exponential convergence** rates in terms of the CPU time vs. the error in a user prescribed quantity of interest.

3D Deviated Well

Cartesian system of coordinates: (x_1, x_2, x_3)

New non-orthogonal system of coordinates: $(\zeta_1, \zeta_2, \zeta_3)$





Subdomain 1

$$\begin{cases} x_1 = \zeta_1 \cos\zeta_2 \\ x_2 = \zeta_1 \sin\zeta_2 \\ x_3 = \zeta_3 \end{cases}$$

Subdomain 2

$$\begin{cases} x_1 = \zeta_1 \cos\zeta_2 \\ x_2 = \zeta_1 \sin\zeta_2 \\ x_3 = \zeta_3 + \tan\theta \dfrac{\zeta_1 - \rho_1}{\rho_2 - \rho_1} \rho_2 \cos\zeta_2 \end{cases}$$

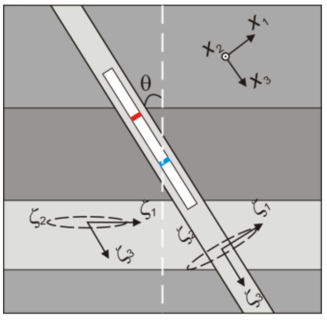
Subdomain 3

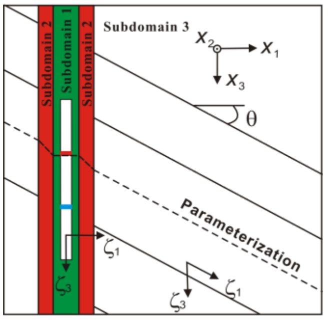
$$\begin{cases} x_1 = \zeta_1 \cos\zeta_2 \\ x_2 = \zeta_1 \sin\zeta_2 \\ x_3 = \zeta_3 + \zeta_1 \tan\theta \cos\zeta_2 \end{cases}$$

3D Deviated Well

Cartesian system of coordinates: (x_1, x_2, x_3)

New non-orthogonal system of coordinates: (ζ_1, ζ_2, ζ_3)



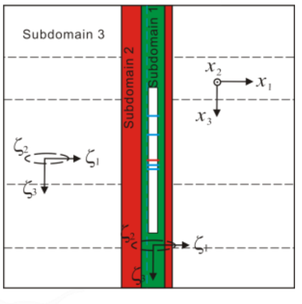


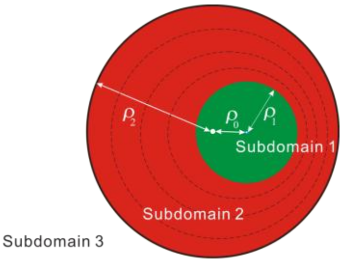
Constant material coefficients in the quasi-azimuthal direction ζ_2 in the new non-orthogonal system of coordinates!!!!

3D Problem of Tool Eccentricity

Cartesian system of coordinates: (x_1, x_2, x_3)

New system of coordinates: (ζ_1, ζ_2, ζ_3)





Subdomain 1

$$\begin{cases} x_1 = \rho_0 + \zeta_1 \cos\zeta_2 \\ x_2 = \zeta_1 \sin\zeta_2 \\ x_3 = \zeta_3 \end{cases}$$

Subdomain 2

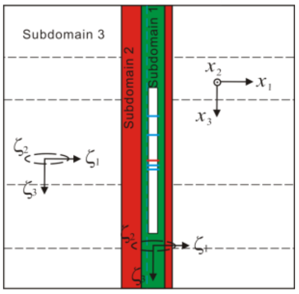
$$\begin{cases} x_1 = \dfrac{\zeta_1 - \rho_2}{\rho_1 - \rho_2}\rho_0 + \zeta_1 \cos\zeta_2 \\ x_2 = \zeta_1 \sin\zeta_2 \\ x_3 = \zeta_3 \end{cases}$$

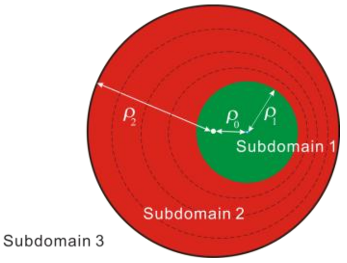
Subdomain 3

$$\begin{cases} x_1 = \zeta_1 \cos\zeta_2 \\ x_2 = \zeta_1 \sin\zeta_2 \\ x_3 = \zeta_3 \end{cases}$$

3D Problem of Tool Eccentricity

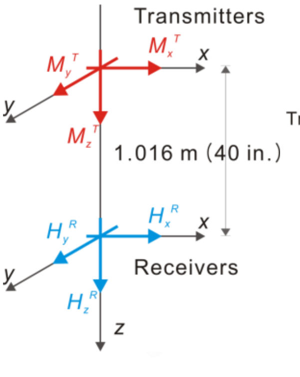
Cartesian system of coordinates: (x_1, x_2, x_3)
New system of coordinates: (ζ_1, ζ_2, ζ_3)

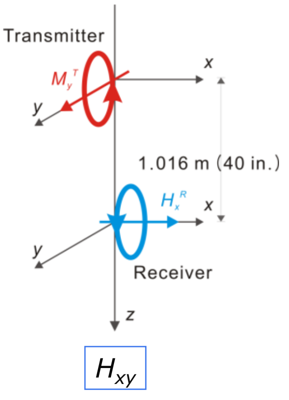


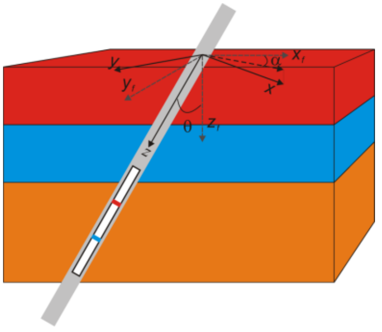


Constant material coefficients in the quasi-azimuthal direction ζ_2 in the new system of coordinates!!!!

Tri-Axial Induction Tool





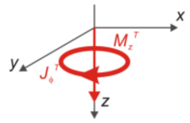


θ: dip angle

α: tool orientation angle

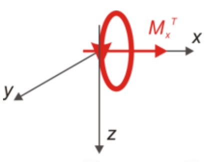
3D Sources and Receivers

1. *Solenoidal Coil (J_ϕ) for M_z.*



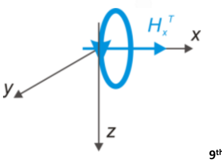
It becomes a 2D source in (ρ, ϕ, z)

2. *Properly Oriented Dipoles for 3D source M_x or M_y.*

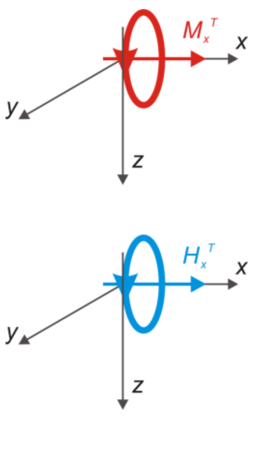


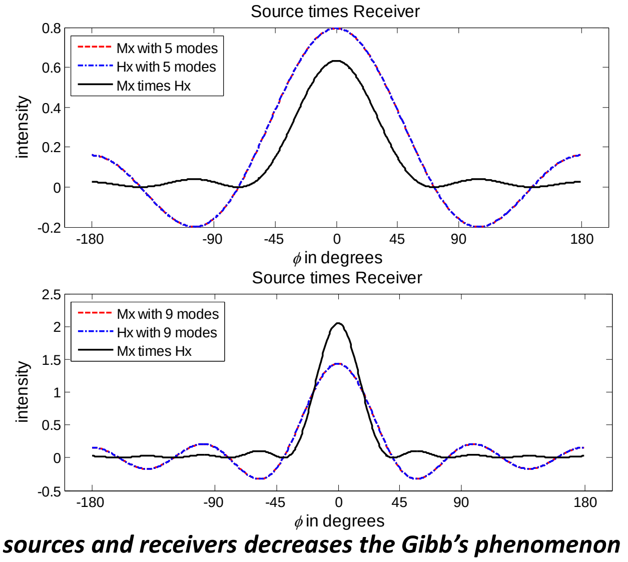
$M(\varphi)=\delta(\varphi-\varphi_0)\, H(\rho-\rho_0)\, H(z-z_0)$, where φ_0 is the azimuthal direction of the source (0° for M_x; 90° for M_y).

3. *Similar Implementation for Receivers H_x, H_y, and H_z.*



3D Sources and Receivers

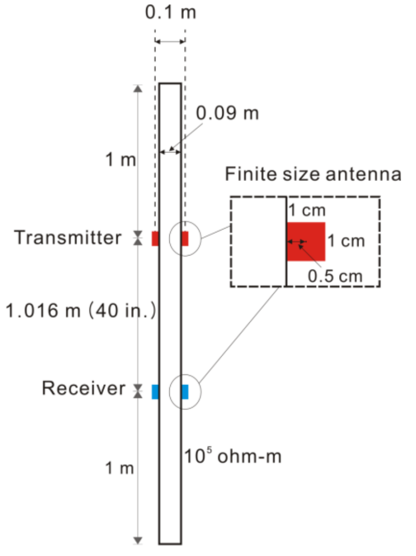


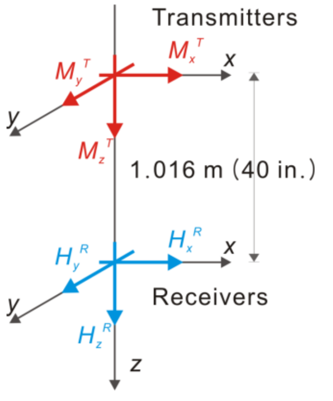


The coupling between sources and receivers decreases the Gibb's phenomenon

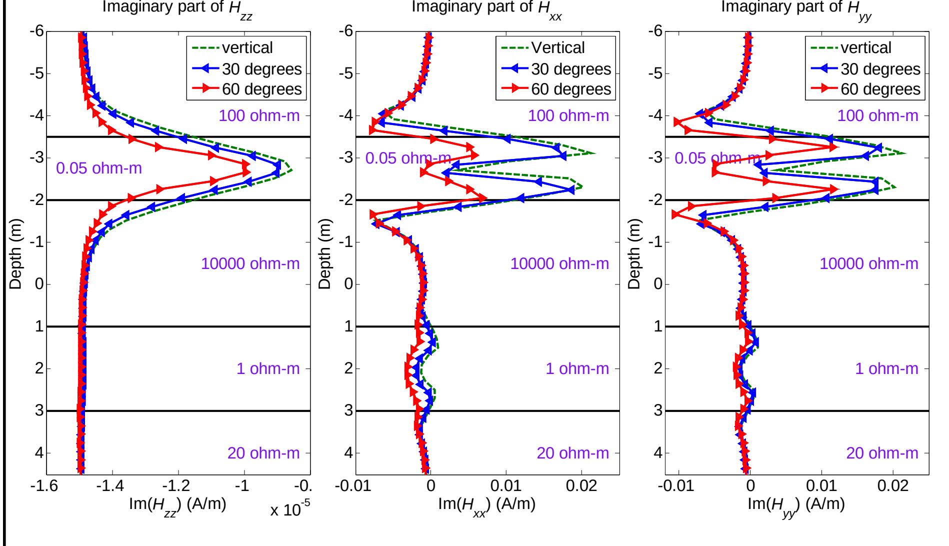
Previous Work: Description of Tool

Operating frequency: 20 kHz

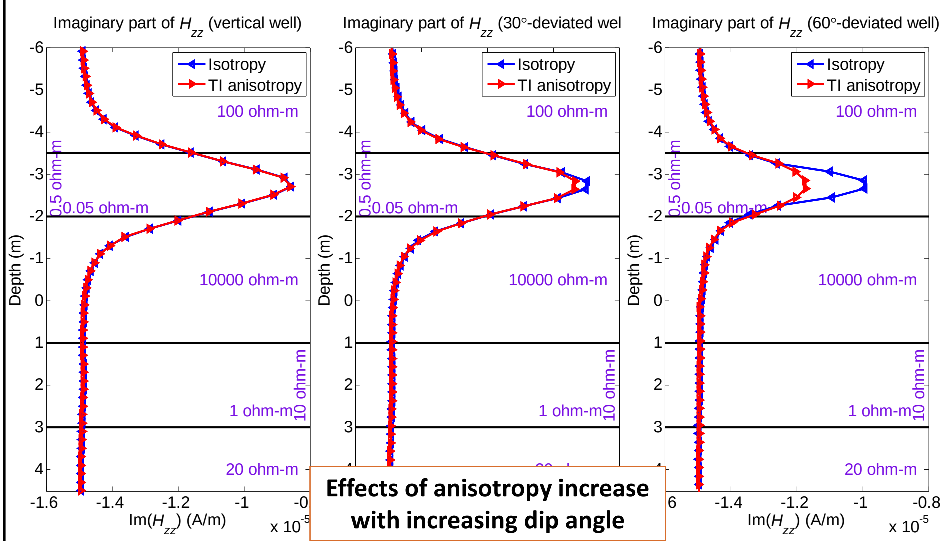




Previous Work: Deviated Wells (0, 30 & 60°)



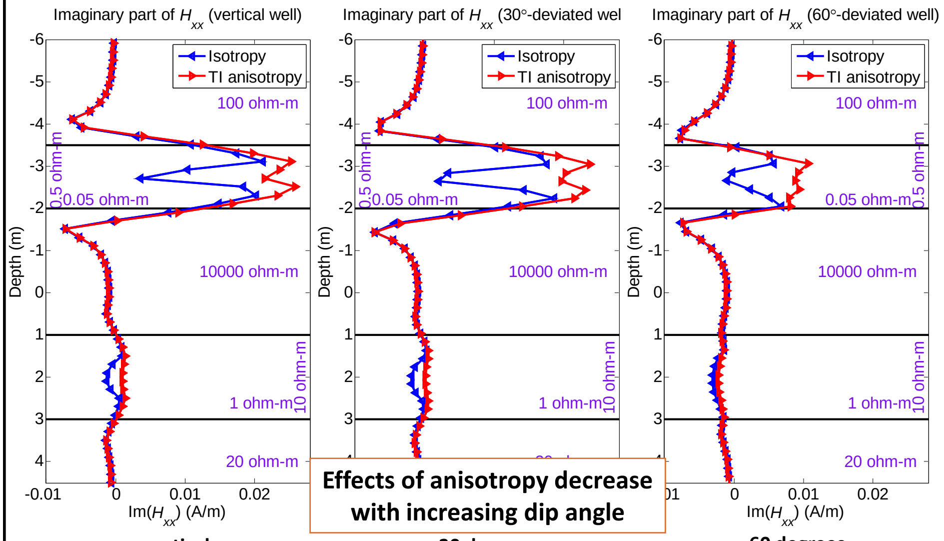
Previous Work: H_{zz} in Deviated Wells with Anisotropy



Effects of anisotropy increase with increasing dip angle

vertical **30 degrees** **60 degrees**

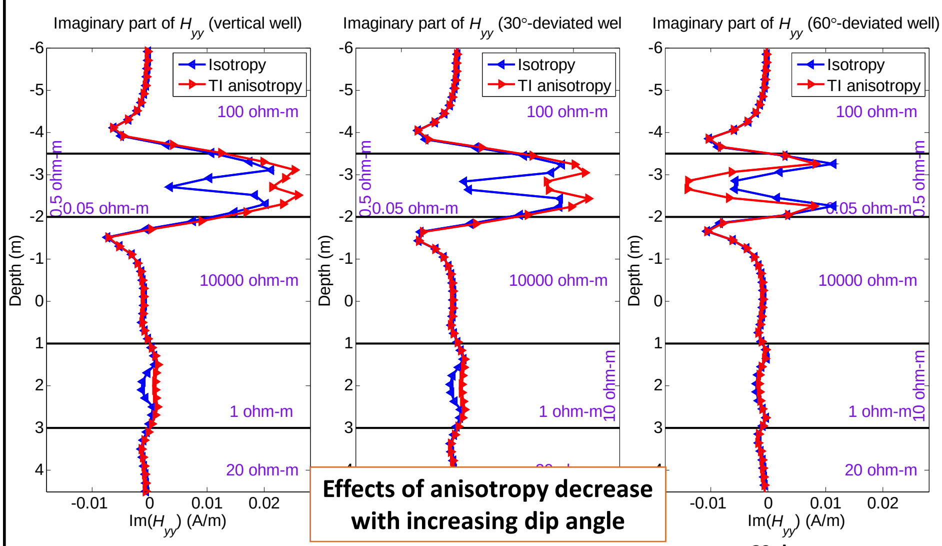
Previous Work: H_{xx} in Deviated Wells with Anisotropy



Effects of anisotropy decrease with increasing dip angle

vertical **30 degrees** **60 degrees**

Previous Work: H_{yy} in Deviated Wells with Anisotropy

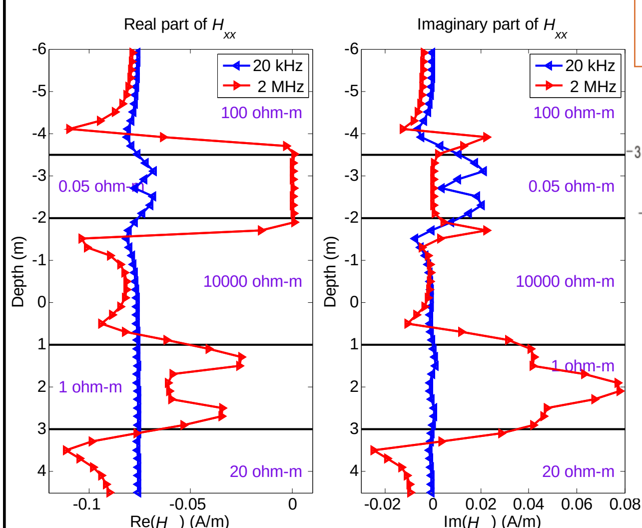


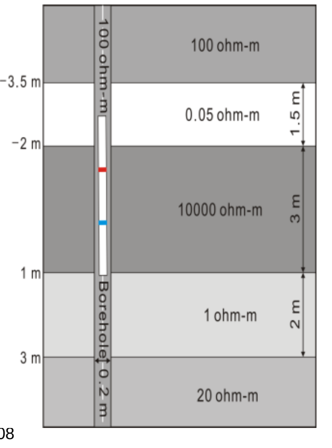
Effects of anisotropy decrease with increasing dip angle

vertical **30 degrees** **60 degrees**

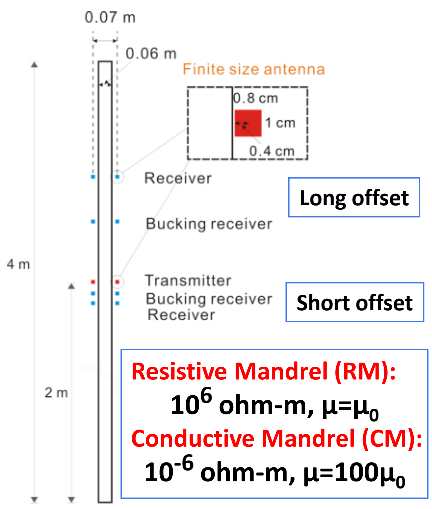
Previous Work: H_{xx} at 20 KHz and 2 MHz in Vertical Well

Larger variations at 2 MHz than at 20 kHz

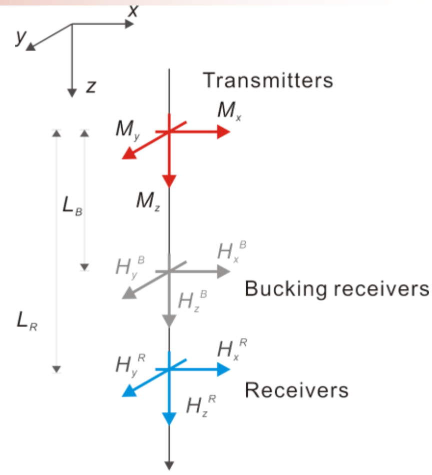




Description of the Tri-Axial Tool

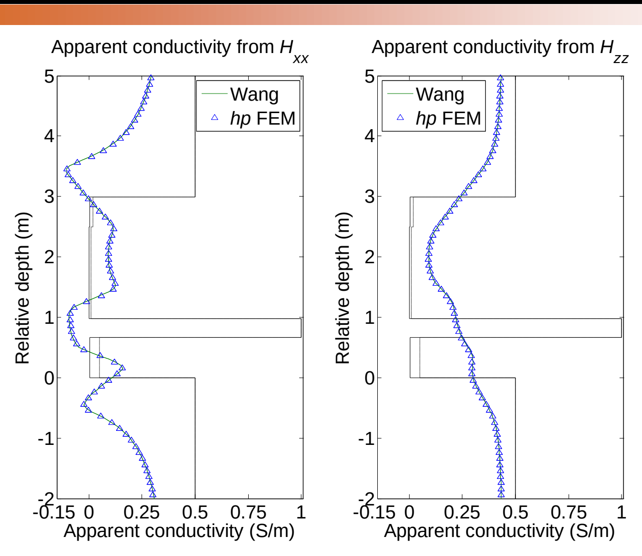


Resistive Mandrel (RM):
10^6 ohm-m, $\mu=\mu_0$
Conductive Mandrel (CM):
10^{-6} ohm-m, $\mu=100\mu_0$



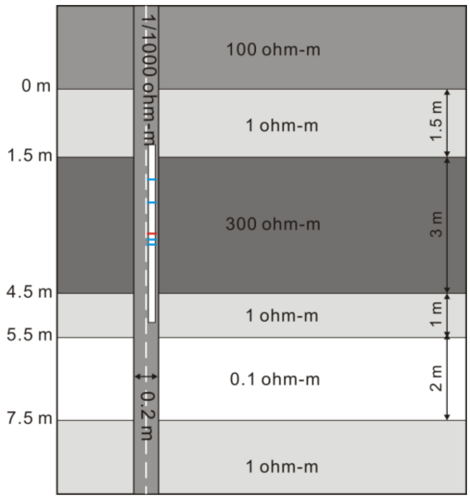
Vertical locations and operating frequencies followed those of a commercial tool

Verification of the 3D hp-FE Method



Good agreement between the two different numerical methods

Model for Numerical Experiments



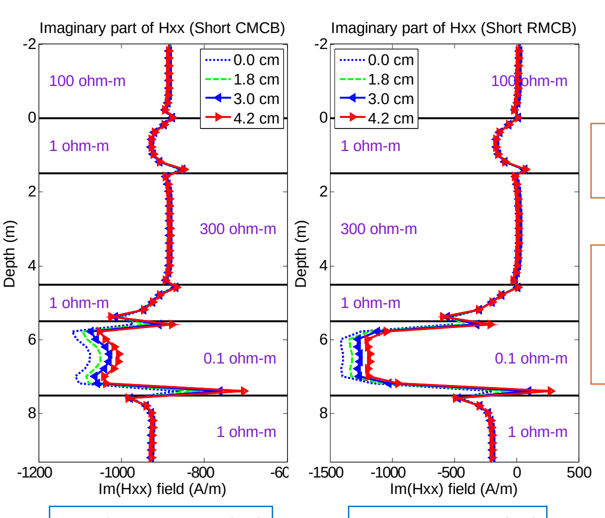
Deepwater Gulf of Mexico

Six layers:
100, 1, 300, 1, 0.1, and 1 ohm-m from top to bottom.

Borehole:
0.1 m in radius.
1/1000 ohm-m in resistivity (conductive/resistive BH).

Eccentered distances:
1.8, 3.0 and 4.2 cm.

Short Offset: Conductive Borehole (H_{xx})



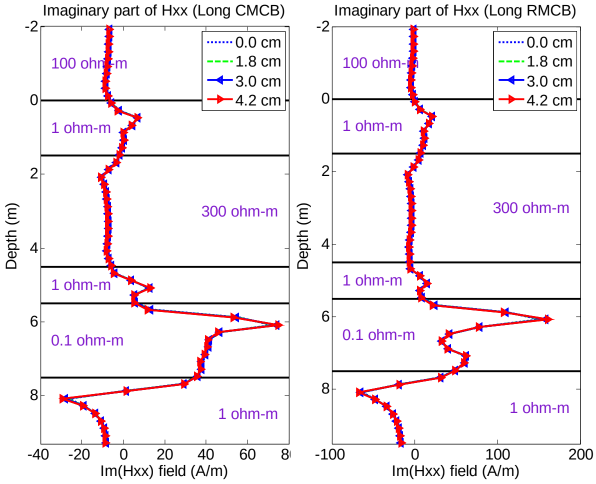
Conductive Mandrel **Resistive Mandrel**

Large effects of eccentricity in the most conductive layer

⇩

Maximum relative differences
Conductive mandrel: 6.5%
Resistive mandrel: 16.0%

Long Offset: Conductive Borehole (H_{xx})

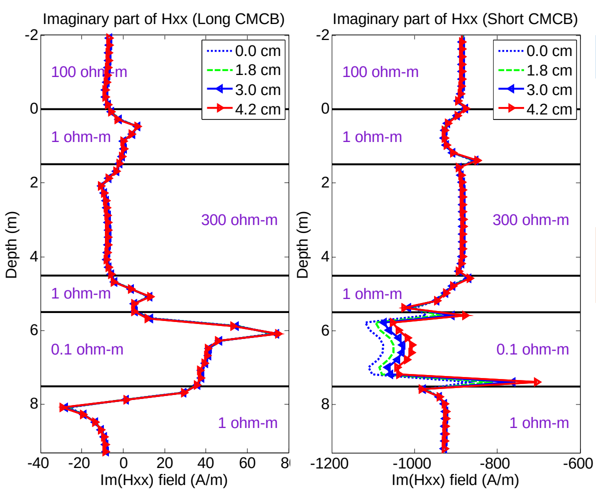


Conductive Mandrel

Resistive Mandrel

Eccentricity effects are negligible for both conductive and resistive mandrels

Long Offset vs. Short Offset (H_{xx})



Long Offset

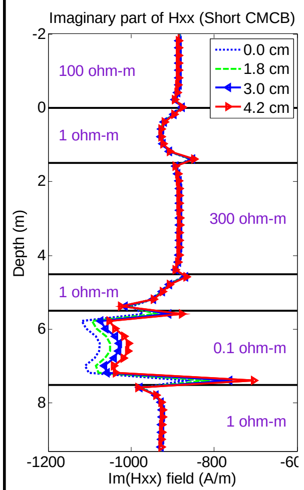
Short Offset

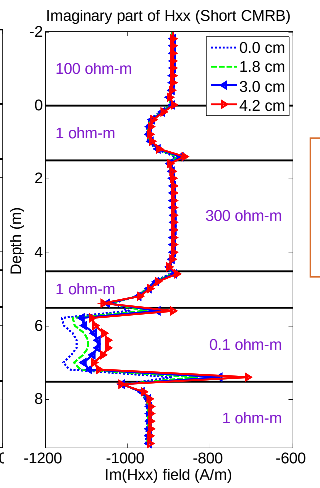
Conductive Borehole

Conductive Mandrel

Short offset: Larger effects of eccentricity

Short Offset: Conductive Mandrel (H_{xx})



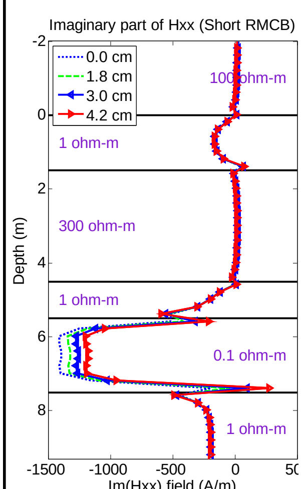


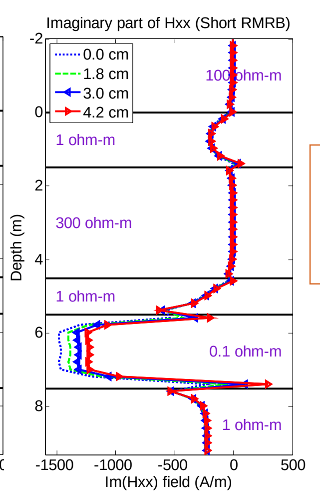
Conductive Borehole

Resistive Borehole

No notable difference between measurements in conductive and resistive boreholes

Short Offset: Resistive Mandrel (H_{xx})



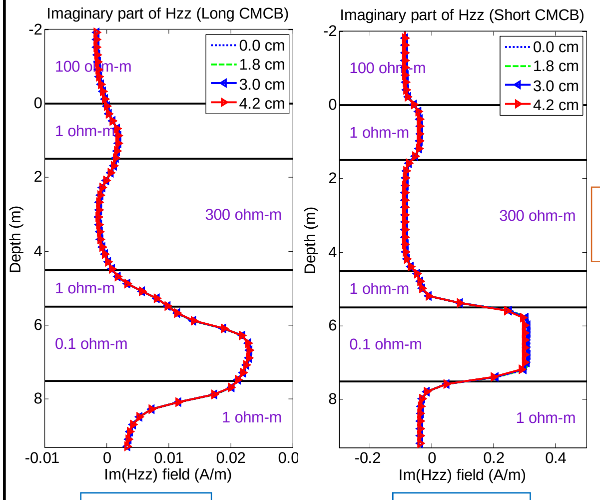


Conductive Borehole

Resistive Borehole

No notable difference between measurements in conductive and resistive boreholes

Long Offset vs. Short Offset (H_{zz})



Long offset

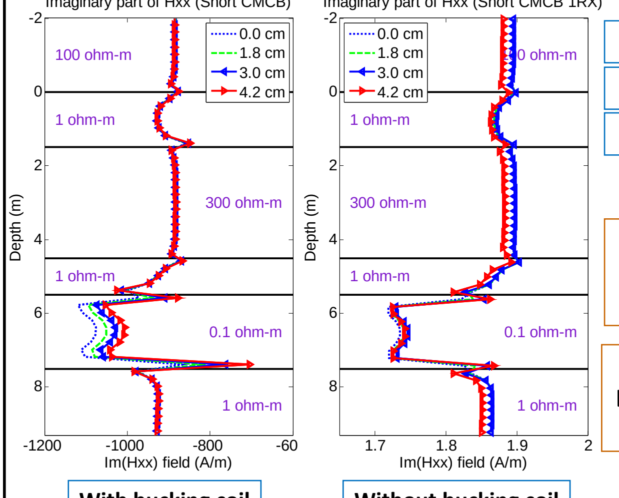
Short offset

Conductive Borehole

Conductive Mandrel

Short offset: Slight eccentricity effects on H_{zz}

With and Without Bucking Coil (H_{xx})



With bucking coil

Without bucking coil

Short Offset

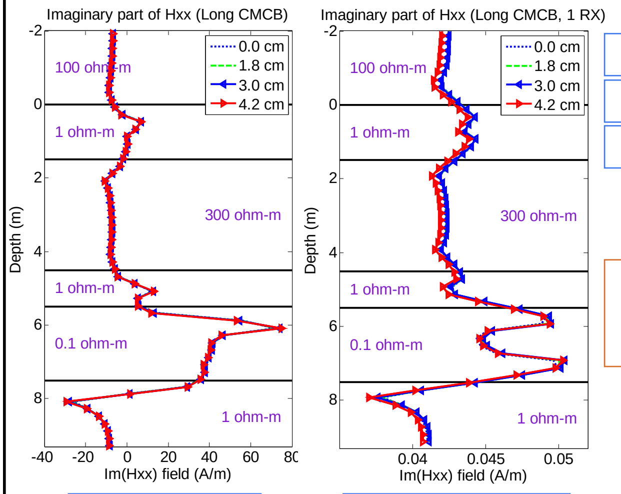
Conductive Borehole

Conductive Mandrel

Without bucking coil: Smaller eccentricity effects on conductive layers

With bucking coil: Larger eccentricity effects on conductive layers

With and Without Bucking Coil (H_{xx})



With bucking coil

Without bucking coil

Long Offset

Conductive Borehole

Conductive Mandrel

Less eccentricity effects when employing bucking coil

Conclusions

- We have successfully simulated tri-axial induction measurements (including the logging tool).
- Effects of borehole-eccentered tools on H_{xx} are:
  - Larger for a short offset than for a long offset.
  - Highly affected by the presence of a bucking coil.
  - Larger when using a conductive mandrel rather than a resistive mandrel.
- Effects of borehole-eccentered tools on H_{zz} are:
  - Observed in the presence of short transmitter-receiver offsets.

Acknowledgments

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ConocoPhillips
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HALLIBURTON
HESS
IMP Innovar AL SERVICIO DEL INSTITUTO MEXICANO DEL PETROLEO
MARATHON
nexen leading the way in global exploration
Schlumberger
StatoilHydro
BR PETROBRAS
RWE The energy to lead
TOTAL
Weatherford