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The Industry Steering Committee on
Wellbore Survey Accuracy (ISCWSA)

Practical Implementation of Combining Wellbore Survey Tools for Optimized Wellbore Position Accuracy

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Outline

- Introduction
- Motivation
- Methodology
- Case Studies
- Practical Considerations
- Summary

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Practical Implementation of Combining Wellbore Survey Tools for Optimized Wellbore Position Accuracy

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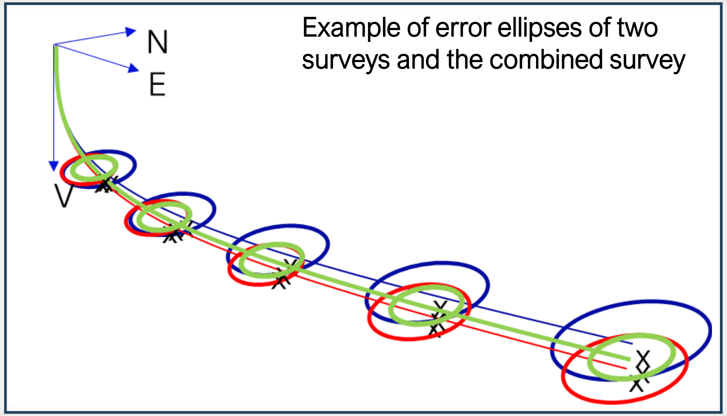
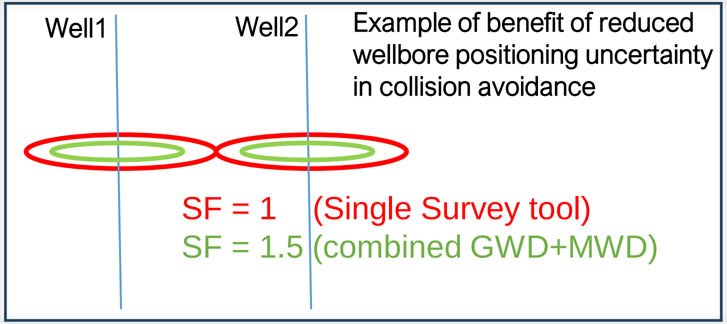
Introduction

- Wellbore position can be computed by surveying the wellbore using Measurement-While-Drilling (MWD) survey or gyroscopic surveys
- Methods exist to combine overlapping surveys to achieve an improvement in wellbore positioning accuracy (e.g., Chia et al (2003), Ledroz et al (2016), Bang et al (2019), ElGizawy et al (2023))
- Implementation of these methods on a practical level is not well understood
- The IPTC2024 paper outlines the practical implementation of combining MWD and gyro surveys to take advantage of the improved wellbore positioning accuracy

Motivation

- Gross error detection with independent overlapping surveys
  - Field Acceptance Criteria (FAC) of individual survey tool unable to detect to all errors
  - Example: Error in magnetic declination
- Take advantage of both surveys by creating a combined survey with uncertainty smaller than the most accurate of the two surveys
- Have a small wellbore positioning uncertainty
  - Maximize production by precisely placing the well within the reservoir
  - Safe drilling and collision avoidance in congested field
  - Enable the geoscientist to validate or update the reservoir model
  - Critical when a relief well must be drilled and for plug-and-abandonment purposes





Methodology – Individual and Mutual Survey QC

Individual QC: The two surveys must pass appropriate QC tests and procedures relevant for each survey tool

- Magnetic field strength and dip tests for magnetic tool
- Earth rate for gyroscopic tools
- Gravity strength test for both tool types
- Other QC, e.g., rotational shot, MSA/MSC

Mutual QC: The two surveys must pass mutual QC tests to verify that they are in agreement with each other (e.g. Ekseth et al (2007), Naschenveng et al (2023))

- Relative Instrument Performance (RIP) test
- Chi-Square test
- EOU overlap test (qualitative)
- If applicable, company-specific tolerance levels e.g., on inclination and azimuth differences

Methodology – Combining Surveys

- After all relevant QC tests have been successfully passed, the overlapping survey data are combined
  - Interpolated to common measured depth points
  - Weighted average using weights derived from the uncertainties of both data sets
  - The new (combined) survey has a listing of MD, inclination, and azimuth values as any other survey
- Error model for the combination of tools
  - Independent of the actual survey data
  - Weak geographic location dependency
  - Realized as a standard format Instrument Performance Model (IPM) text file that can be utilized by common error analysis software

Example of azimuth weights as function of inclination and azimuth used for survey averaging

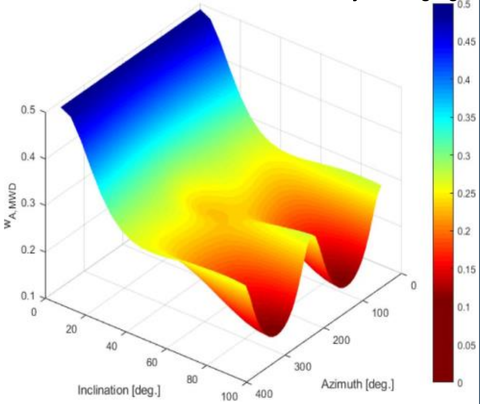


Figure from Bang et al. SPE-195621-MS (2019)

```
# Averaged IPM
# Averaged IPM created for location:     NorthSea
# Original tool model 1:                 MWDtool
# Original tool model 2:                 GWDtool

#Name    Vector  Tie-On  Unit    Value   Formula
Weights  n       n       -       0       0
wI1      n       n       -       1       function1(inc)
wI2      n       n       -       1       1-wI1
wA1      n       n       -       1       function2(inc,azi)
wA2      n       n       -       1       1-wA1
Common   n       n       -       0       0
drfr     e       r       m       0.35    1
drfr     s       r       m       2.2     1
drfs     s       s       m       1       1
dsfs     e       s       -       0.00056 tmd
dstg     e       g       im      2.50E-07        tmd*tvd
w_12     n       n       -       1       sin(inc)
w_34     n       n       -       1       sqrt(1-(w_12)^2)
MWDtool  n       n       -       0       0
xym1     i       s       d       0.1     wI1*w_12
xym2     l       s       d       0.1     wA1*w_12
xym3     i       s       d       0.1     wI1*cos(azi)*w_34
xym3     l       s       d       0.1      -wA1*SIN(azi)*w_34
xym4     i       s       d       0.1     wI1*sin(azi)*w_34
xym4     l       s       d       0.1     wA1*cos(azi)*w_34
sag      i       s       d       0.08    wI1*(sin(inc))
decg     a       g       d       0.15    wA1*1.0
...
GYROtool         n       n       -       0       0
mxy1     i       s       d       0.1     wI2*w_12
mxy2     l       s       d       0.1     wA2*w_12
mxy3     i       s       d       0.1     wI2*cos(azi)*w_34
mxy3     l       s       d       0.1      -wA2*SIN(azi)*w_34
mxy4     i       s       d       0.1     wI2*sin(azi)*w_34
mxy4     l       s       d       0.1     wA2*cos(azi)*w_34
sag      i       s       d       0.08    wI2*sin(inc)
axyz_mis         i       s       d       0.0154  wI2*1
...
```

Example combined IPM file

Methodology – Further Generalization

- The combined IPM is designed for the ideal case where both surveys are present in an entire section
- Frequently occurring complications
    - Gaps in surveys
    - Overlapping gyro survey covering multiple MWD sections
- The averaging procedure should ideally take this into account to avoid too optimistic or too pessimistic uncertainties
    - Correct weighting of error terms depending on which tools contribute to the average at a given MD
    - Correct treatment of systematic errors
    - Include survey indicator s_k and adjusted weights

MD	INCL	AZIM	S1	S2
520.5	10.12	92.43	0	1
531.8	11.07	92.73	0	1
549.4	12.14	91.21	0	1
560.5	12.69	90.39	0	1
578.3	13.33	91.12	0	1
598.8	14.03	90.36	0	1
607.0	14.48	89.53	0	1
635.9	16.48	86.75	0	1
664.8	19.02	84.34	0	1
693.6	20.91	84.10	0	1
713.9	22.43	84.25	0	1
722.1	23.13	84.23	0	1
751.1	25.46	84.53	0	1
757.5	26.01	84.46	1	1
779.8	28.01	85.85	1	1
786.2	28.52	86.24	1	1
808.7	29.95	87.56	1	1
815.1	30.34	87.91	1	1
837.5	31.78	88.45	1	1
…	…	…	…	…

Example combined survey listing with survey indicator for MWD (S1) and GWD (S2)

```
# Averaged IPM ADJUSTED
# Averaged IPM created for location:     NorthSea
# Original tool model 1:                 MWDtool
# Original tool model 2:                 GWDtool

#Name    Vector Tie-On Unit   Value   Formula
Weights n      n      -      0       0
wI1     n      n      -      1       function1(inc)
wI2     n      n      -      1       1-s1*wI1
wA1     n      n      -      1       function2(inc,azi)
wA2     n      n      -      1       1-s1*wA1
wI1_adj n      n      -      1       s1*wI1/(s1*wI1+s2*wI2)
wI2_adj n      n      -      1       s2*wI2/(s1*wI1+s2*wI2)
wA1_adj n      n      -      1       s1*wA1/(s1*wA1+s2*wA2)
wA2_adj n      n      -      1       s2*wA2/(s1*wA1+s2*wA2)
Common  n      n      -      0       0
drfr    e      r      m      0.35    1
drfr    s      r      m      2.2     1
drfs    s      s      m      1       1
dsfs    e      s      -      0.00056 tmd
dstg    e      g      im     2.50E-07      tmd*tvd
w_12    n      n      -      1       sin(inc)
w_34    n      n      -      1       sqrt(1-(w_12)^2)
MWDtool n      n      -      0       0
xym1    i      s      d      0.1     wI1_adj*w_12
xym2    l      s      d      0.1     wA1_adj*w_12
xym3    i      s      d      0.1     wI1_adj*cos(azi)*w_34
xym3    l      s      d      0.1      -wA1_adj*SIN(azi)*w_34
xym4    i      s      d      0.1     wI1_adj*sin(azi)*w_34
xym4    l      s      d      0.1     wA1_adj*cos(azi)*w_34
sag     i      s      d      0.08    wI1_adj*(sin(inc))
decg    a      g      d      0.15    wA1_adj*1.0
...
GYROtool       n      n      -       0       0
mxy1    i      s      d      0.1     wI2_adj*w_12
mxy2    l      s      d      0.1     wA2_adj*w_12
mxy3    i      s      d      0.1     wI2_adj*cos(azi)*w_34
mxy3    l      s      d      0.1      -wA2_adj*SIN(azi)*w_34
mxy4    i      s      d      0.1     wI2_adj*sin(azi)*w_34
mxy4    l      s      d      0.1     wA2_adj*cos(azi)*w_34
sag     i      s      d      0.08    wI2_adj*sin(inc)
axyz_mis       i      s      d       0.0154  wI2_adj*1
...
```

Example of generalized IPM (not handled in current software)

Case Studies

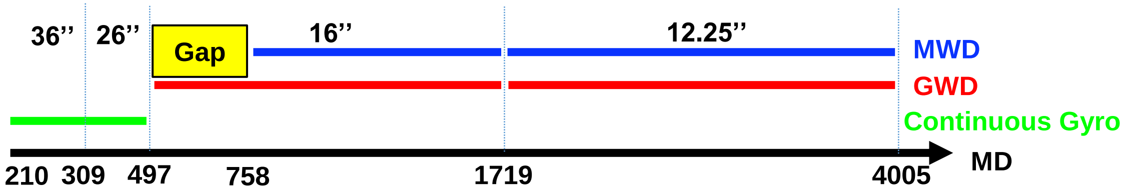
- Two case studies to illustrate survey averaging and practical complications
  - Case Study 1: Gap in MWD survey at KO interval due to magnetic interference from casing parent well
  - Case Study 2: Drop gyro survey covering three sections with independent MWD surveys
- The averaging procedure should ideally take these complications into account
- Currently this is not possible in existing software
- Generalized method was implemented by Monte Carlo simulation

Case Study 1 – Available Data

- Sidetrack with KO at 497m MD
- The objective is to combine MWD and GWD surveys in 16” and 12.25” sections
- Practical complication: No MWD between KO at 497 m and 758 m MD in 16” section due to magnetic interference from parent well
- Two approaches:
    1. Ignore gap in MWD
    2. Take gap into account (“adjusted approach”)

Directional surveys acquired in this well

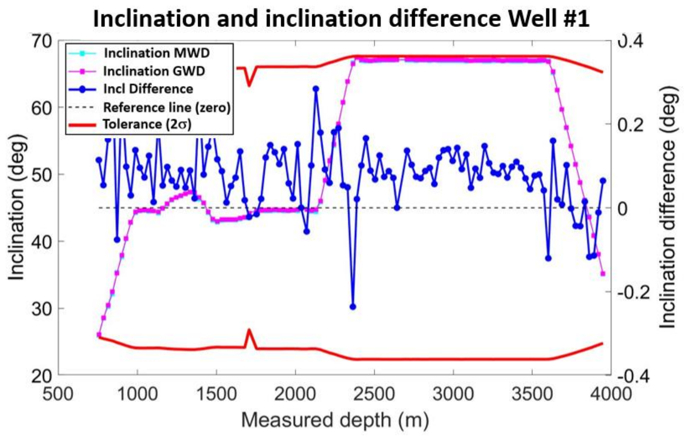
Survey name	Start MD (m)	End MD (m)	Relevant IPM	Remarks
Continuous gyro	210	497	Continuous Gyro	Parent well
MWD in 16”	758	1708	MWD+IFR1+SAG+MS	Gap between KO and 757 m MD
MWD in 12.25”	1755	3989	MWD+IFR1+SAG+MS	
MWD in 8.5”	4015	4145	MWD+IFR1+SAG+MS	Not used in this study
MWD in 6”	4149	4244	MWD+IFR1+SAG+MS	Not used in this study
Solid state GWD in 16”	520	1701	GWD	
Solid state GWD in 12.25”	1720	3960	GWD	

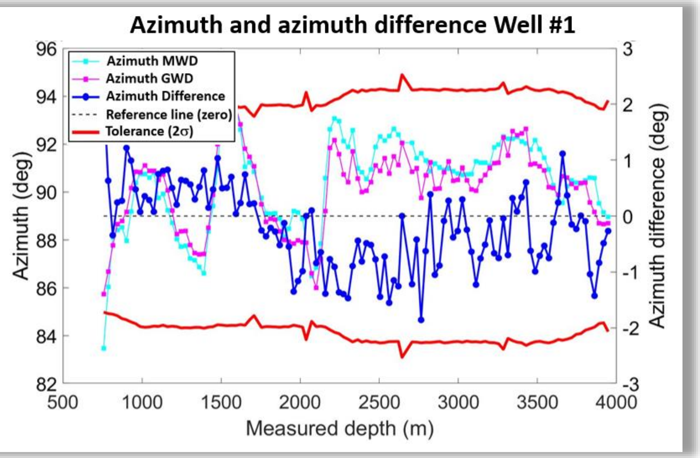


Schematic overview of available surveys in Case Study 1

Case Study 1 – Individual and Mutual QC Test Results

- <u>Individual QC:</u> Inclination and azimuth differences
- <u>Mutual QC:</u> RIP and Chi-square test results
- QC tests passed

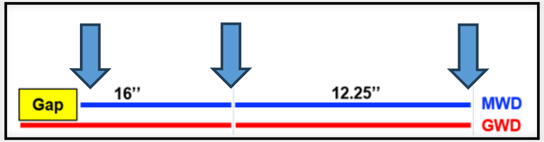


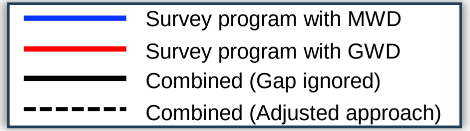


RIP test	Mean Results		STD Results	
Inclination 16''	0.58	Average agreement	0.52	Good agreement
Azimuth 16''	0.55	Average agreement	0.50	Good agreement
Inclination 12.25''	0.40	Good agreement	0.44	Good agreement
Azimtuh 12.25''	-0.51	Average agreement	0.54	Good agreement

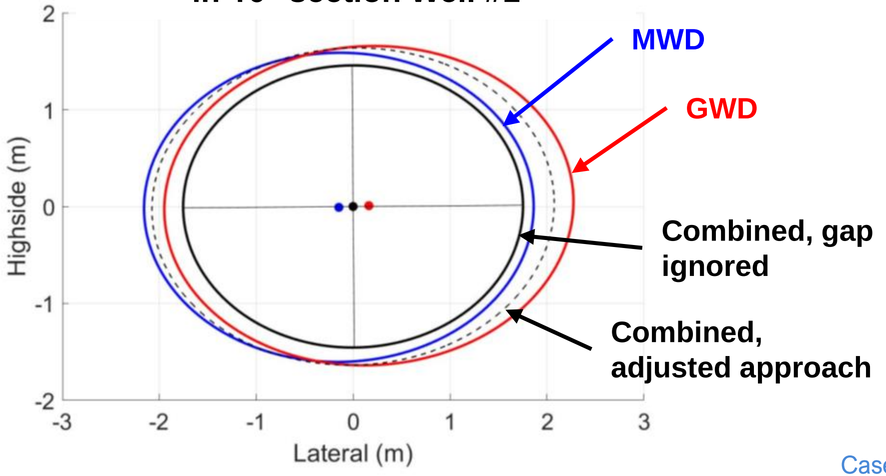
Co-ordinate Difference Test	Northing	Easting	TVD
Chi-square test value 16'' section:	10.03	7.29	4.50
Chi-square test value 12.25'' section:	9.83	3.38	3.15
Tolerance:	34.4	34.4	34.4
No. Overlapping survey stations used:	15	15	15
Pass/Fail	Pass	Pass	Pass

Case Study 1 – EOU Comparison

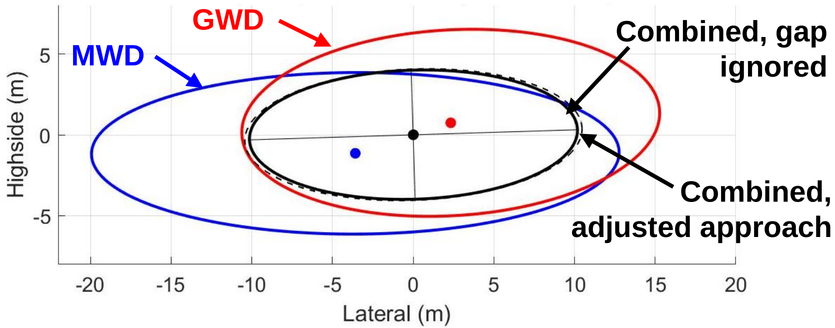




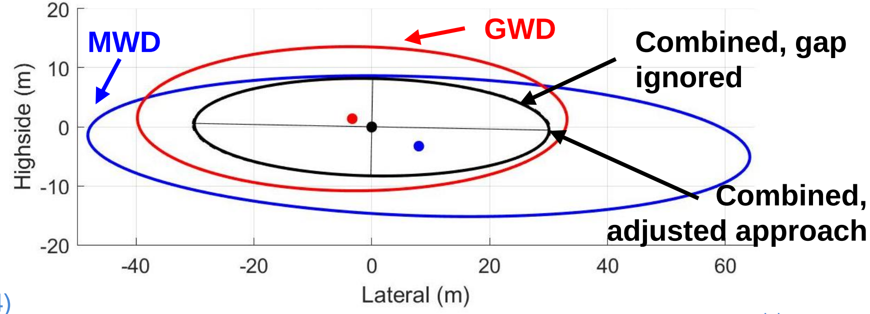
EOU (2.45σ) at first MWD station in 16'' section Well #1



EOU (2.45σ) at TD of 16'' section Well #1

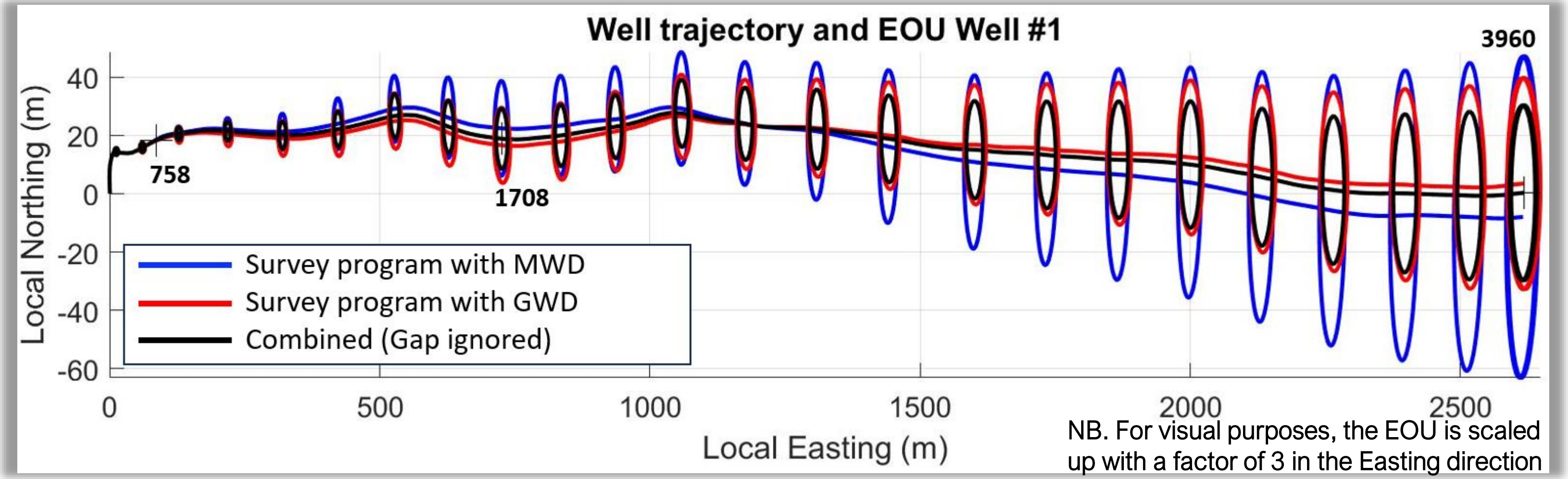


EOU (2.45σ) at TD of 12.25'' section Well #1



Case Study 1 – Summary

- EOU comparison shows gain in position accuracy of combined wellbore
- Ignoring gap in MWD survey results in too optimistic EOU in gap; effect disappears at larger MD



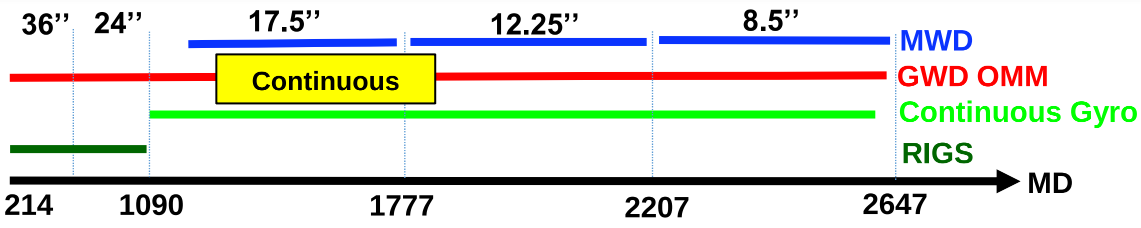
NB. For visual purposes, the EOU is scaled up with a factor of 3 in the Easting direction

Case Study 2 – Available Data

- Sidetrack with KO at 1150m MD
- The objective is to combine MWD surveys in the 17.5", 12.25" and 8.5" sections with the solid-state GWD Outrun Memory Mode (OMM) survey
- Practical complication: Continuity of systematic errors GWD OMM survey over three independent MWD surveys
- Two approaches:
    1. Concatenate MWD surveys
    2. Take systematic errors correctly into account ("adjusted approach")

Directional surveys acquired in this well

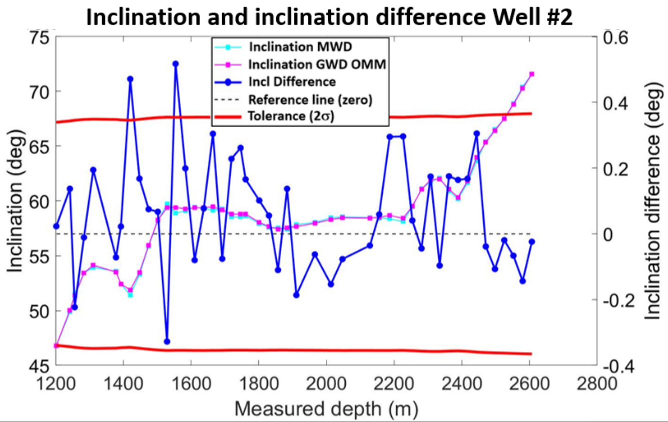
Survey name	Start MD (m)	End MD (m)	Relevant IPM	Remarks
RIGS continuous gyro	214	1090	RIGS	Parent well
Continuous gyro	1100	2590	Continuous Gyro	Parent well until 1150 m MD
MWD in 17.5"	1202	1761	MWD+IFR1+SAG+MS	
MWD in 12.25"	1801	2187	MWD+IFR1+SAG+MS	
MWD in 8.5"	2226	2632	MWD+IFR1+SAG+MS	
MWD in 6"	2670	3564	MWD+IFR1+SAG+MS	Not used in this study
Solid state GWD in 8.5"	2139	2600	GWD	Not used in this study
Solid state GWD OMM	214	2625	GWD	Outrun Memory Mode (OMM)

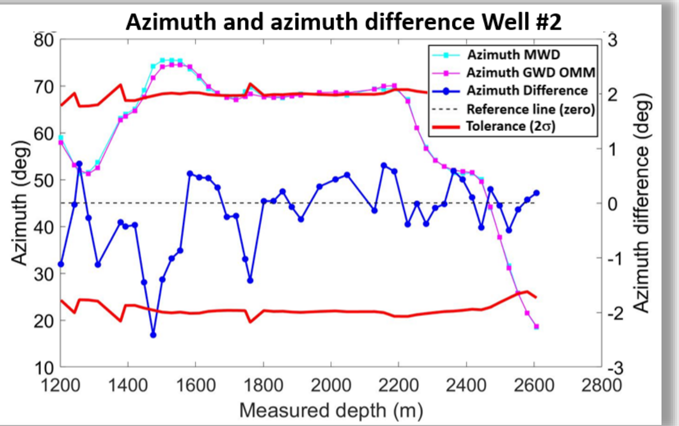


Schematic overview of available surveys in Case Study 2

Case Study 2 – Individual and Mutual QC Test Results

- Individual QC: Inclination and azimuth differences
- Mutual QC: RIP and Chi-square test results
- QC tests passed

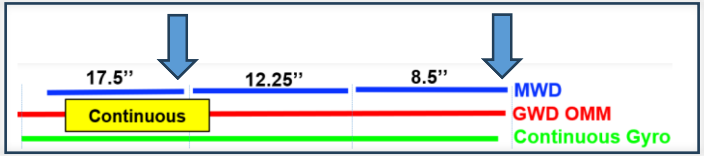


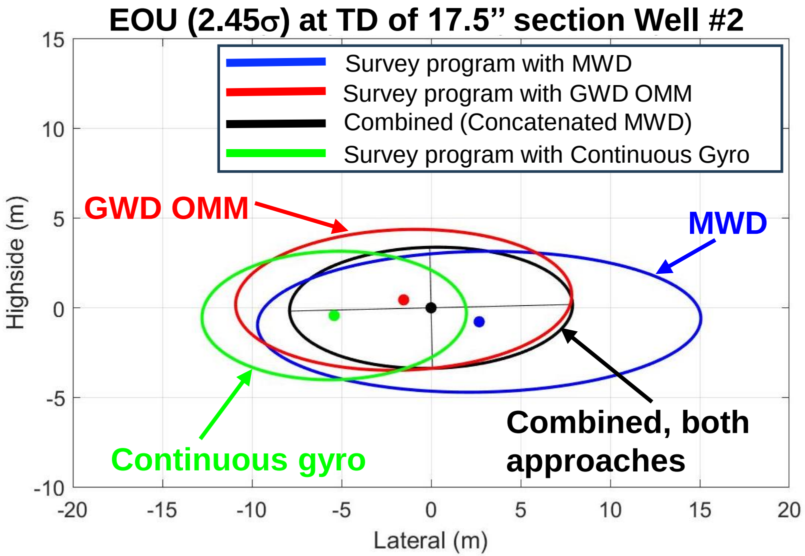


RIP test	Mean Results		STD Results	
Inclination 17.5"	0.57	Average agreement	1.16	Average agreement
Azimuth 17.5"	-0.55	Average agreement	0.83	Good agreement
Inclination 12.25"	0.01	Good agreement	0.81	Good agreement
Azimuth 12.25"	0.20	Good agreement	0.31	Good agreement
Inclination 8.5"	0.29	Good agreement	0.83	Good agreement
Azimuth 8.5"	-0.03	Good agreement	0.33	Good agreement

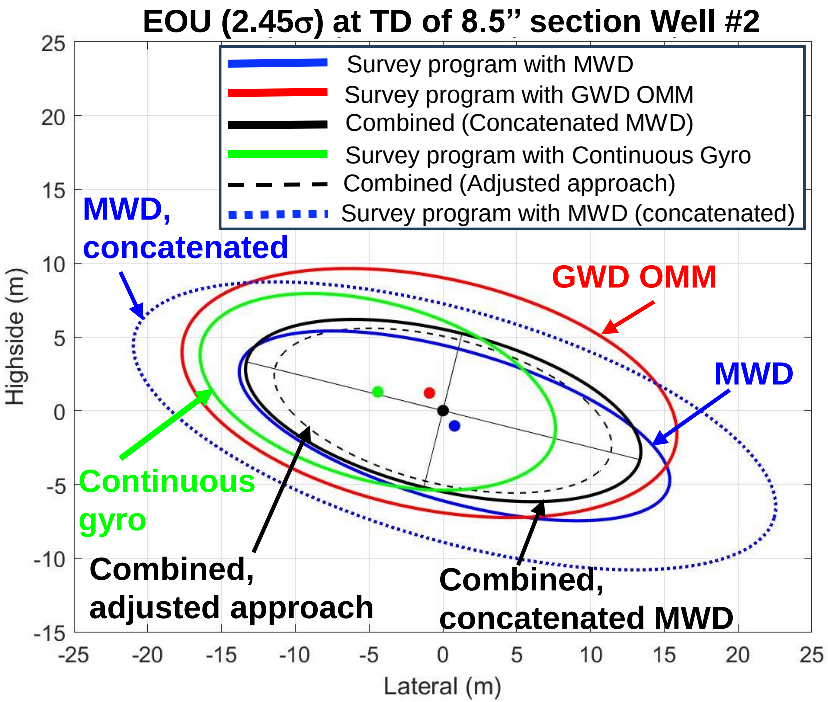
Co-ordinate Difference Test	Northing	Easting	TVD
Chi-square test value 17.5" section:	8.76	2.51	6.06
Tolerance:	34.4	34.4	34.4
No. Overlapping survey stations used:	15	15	15
Pass/Fail	Pass	Pass	Pass
Chi-square test value 12.25" section:	0.08	0.04	0.10
Chi-square test value 8.5" section:	0.22	0.09	1.32
Tolerance:	18.8	18.8	18.8
No. Overlapping survey stations used:	5	5	5
Pass/Fail	Pass	Pass	Pass

Case Study 2 – EOU Comparison





Case Study 2 (



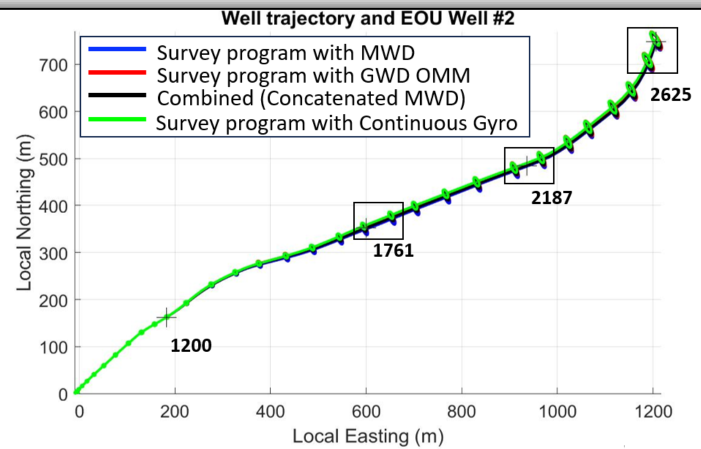
Case Study 2 – Summary

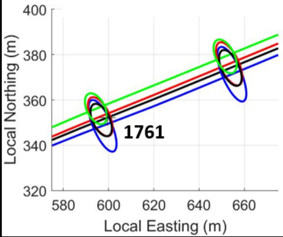
- EOU comparison shows improved accuracy combined surveys
- Full benefit of survey averaging only achieved with adjusted method
- RIP and Chi-Square tests Combined (MWD+OMM) vs Continuous Gyro show good agreement

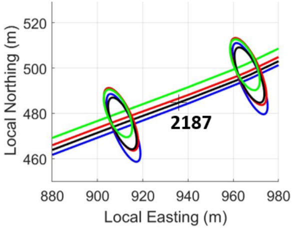
RIP and Chi-square test results Combined vs Cont Gyro

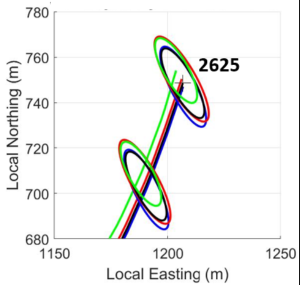
RIP test	Mean Results		STD Results	
Inclination	-0.04	Good agreement	0.81	Good agreement
Azimuth	-0.39	Good agreement	0.79	Good agreement

Co-ordinate Difference Test	Northing	Easting	TVD
Chi-square test value:	11.06	10.90	0.18
Tolerance:	34.4	34.4	34.4
No. Overlapping survey stations used:	15	15	15
Pass/Fail	Pass	Pass	Pass









Practical Considerations

Gaps in survey data and statistical outliers	• Acceptable size of gap • Correct computation of combined survey and treatment of systematic errors
Real-time data workflow	• Applicable for BHA with MWD and GWD • Requires sufficient survey stations for mutual QC
Survey data management	• Relation between combined survey and source data
Error model data management and dealing with error model revisions	• Many tool combinations • Geographic dependency of combined error model • Automatization of survey averaging process • Consistency between combined survey, its IPM, and the source survey data and their IPMs

Summary

- Discussed implementation of combining wellbore survey tools to achieve improved wellbore accuracy
- The process was illustrated with two field data examples
- Practical aspects must be handled appropriately when computing the average of overlapping surveys
- Benefit of combining surveys can be obtained with existing software, but to achieve the full benefit, some modifications are required
- Advantages with reducing the lateral and vertical uncertainty for mature and new developments can be significant

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THANK YOU

The views and opinions expressed in this presentation are those of the authors and are not necessarily shared by Equinor ASA