FMI & UBI Image QC Report

Company: Santos Ltd
Well: Tanumbirini 1
Tool String: FMI-SSCAN-PEX-GR & UBI-PPC-GR
Logging Date: 1 & 2-Oct-2014
Logged Interval: 1474.5-3929m MD
Report Date: 29-Oct-2014
Processed by: Francis Kalukal, Senior Geologist, PetroTechnical Services, Schlumberger Australia Pty Ltd.
Data Quality - Inclinometry – Raw Data Summary & QC (FMI pass)

The General Purpose Inclinometry Tool uses single axis magnetometer (FX, FY, FZ) & accelerometer (AX, AY, AZ) measurements to compute the following:

- **Geomagnetic Components:** Magnetic Field Strength (FNOR), Magnetic Field Inclination (FINC) & Average Gravity (ANOR).
- **Hole Orientation:** Hole Deviation (DEVI), Hole Azimuth (HAZI).
- **Image Tool Orientation:** Pad 1 Azimuth in horizontal Plane (P1AZ), Relative Bearing (RB).

### Raw GPIT axis measurements
- Accelerometer measurements appear fine, although some irregularities on the vertical axis (AZ) due to irregular vertical movements of the tool. Some zones with larger spikes due to washout and sticking.
- Magnetometer measurements appear fine.

### Geomagnetic Components
- Computed Gravity readings are consistent throughout the interval (which is good).
- Inclination and Magnetic Field Strength also seem consistent.

### Hole Orientation
- Computed Hole Azimuth (HAZI) shows SW'ly direction mostly. Computed Hole Deviation (DEVI) shows near vertical hole (<3 deg).

### Image Tool Orientation
- Computed rotational position of tool (Pad 1 Azimuth) indicates tool rotated during logging, though not as frequently as UBI pass.
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**Raw GPIT axis measurements**
- Accelerometer measurements appear fine, although some irregularities on the vertical axis (AZ) due to irregular vertical movements of the tool. Some larger spikes in places due to stick-slip and washout.
- Magnetometer measurements appear fine.

**Geomagnetic Components**
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- Magnetic Field Strength also consistent.

**Hole Orientation**
- Computed Hole Azimuth (HAZI) shows SW’ly direction mostly. Computed Hole Deviation (DEVI) shows near vertical hole (<3 deg).

**Image Tool Orientation**
- Computed rotational position of tool (Pad 1 Azimuth) indicates tool rotated during logging, mostly below 2500m.
Data Quality - Inclinometry – QC test (FMI pass)

A basic QC test of the inclinometry data was used to determine if the borehole image is correctly oriented. This test computed the offsets needed to correct accelerometer & magnetometer variables & determined if correction was required.

QC Test workflow

1. The test firstly uses the BGS Global Magnetic Model (BGGM) to calculate theoretical magnetic field & gravity parameters.
2. Average RAW (“Before”) magnetic field & gravity values are calculated.
3. Average CORRECTED (“After”) magnetic field & gravity values are calculated using computed offsets.
4. Error % for average magnetic field & gravity values compared to theoretical values “Before” & “After” correction.
5. Difference between orientation curves calculated using original & corrected accelerometer & magnetometer values.

QC Test results

- Input Data:
  - Magnetic Declination: 4.19661
  - Magnetic Inclination: -45.4648
  - Magnetic Field: 0.48069
  - Gravity: 9.78444

- Data Average:
  - Acceleration: 9.78121, 9.78448
  - Magnetometer: 0.483953, 0.48412
  - Minv: -45.3402, -45.3877

- Errors (RMS %):
  - ANCR: 0.93277, 0.932466
  - FNOR: 0.562689, 0.56746
  - Sin(Minv): 0.682893, 0.663755

- Difference (RMS deg):
  - SDEV: 0.102497
  - HAZI: No relevant data - Deviation is < 5 deg
  - RB: No relevant data - Deviation is < 5 deg
  - PINO: 0.0334011

Senors and inclinometry channels are OK.

QC test results summary & conclusion:
- Inclinometry channels are OK. Offsets within tolerance.
- Borehole image will be correctly oriented.

QC Test plots

Crossplots of the X & Y axes of the magnetometer & accelerometer data are provided before and after correction.

The accelerometer X & Y axis crossplot displays cluster with spiral distribution. This is a result of the combined effect of small changes in hole deviation and minor horizontal movement of the tool whilst rotating. Insignificant difference between data before & after correction.

A circular distribution shown by the magnetometer X & Y axis cross plot indicating rotation of the tool during logging. No significant erratic values are visible. Data before & after correction match well.
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**QC Test results**

- **Input Data**
  - Magnetic Declination: 4.19691
  - Magnetic Inclination: -45.4646
  - Magnetic Field: 0.484489
  - Gravity: 9.78444

- **Data Average**:
  - Before:
    - Acceleration: 9.78504
    - Magnetometer: 0.484289
    - Mnc: -45.393
  - After:
    - Acceleration: 9.78445
    - Magnetometer: 0.484537
    - Mnc: -45.4283

- **Errors (RMS %)**:
  - ANOR: 0.066961
  - FNOR: 0.084676
  - Sin(Mnc): 0.110231

- **Difference (RMS deg)**:
  - SDEV: 0.0068611
  - HA2ZI: No relevant data - Deviation is < 5 deg
  - RB: No relevant data - Deviation is < 5 deg
  - PING: 0.028533

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**Quality Control Test Workflow**

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**Crossplots of the X & Y axes of the magnetometer & accelerometer data are provided before and after correction.**

- The accelerometer X & Y axis crossplot displays circular spiral distribution. This is a result of the combined effect of small changes in hole deviation and minor horizontal movement of the tool whilst rotating. Insignificant difference between data before & after correction.

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5. Difference between orientation curves calculated using original & corrected accelerometer & magnetometer values.

**QC Test results**

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Declination</td>
<td>4.1954</td>
<td></td>
</tr>
<tr>
<td>Magnetic Inclination</td>
<td>-45.4647</td>
<td></td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>0.48166</td>
<td></td>
</tr>
<tr>
<td>Gravity</td>
<td>9.78444</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Average</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>9.78553</td>
<td>9.78451</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>0.48312</td>
<td>0.484211</td>
</tr>
<tr>
<td>Minc</td>
<td>-45.5683</td>
<td>-45.4539</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Errors (RMS %)</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOR</td>
<td>0.0538184</td>
<td>0.053847</td>
</tr>
<tr>
<td>FNOR</td>
<td>0.221343</td>
<td>0.100776</td>
</tr>
<tr>
<td>Sin(Minc)</td>
<td>0.153973</td>
<td>0.0845579</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difference (RMS deg)</th>
<th>After/Before</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDEV</td>
<td>0.0107542</td>
</tr>
<tr>
<td>HAZI</td>
<td>No relevant data - Deviation is &lt; 5 deg</td>
</tr>
<tr>
<td>RB</td>
<td>No relevant data - Deviation is &lt; 5 deg</td>
</tr>
<tr>
<td>PINO</td>
<td>0.0311221</td>
</tr>
</tbody>
</table>

Sensors and inclinometry channels are OK.

**QC Test results summary & conclusion:**

- Inclinometry channels are OK. Offsets within tolerance.
- Borehole image will be correctly oriented.

**QC Test plots**

Crossplots of the X & Y axes of the magnetometer & accelerometer data are provided before and after correction.

A circular distribution shown by the magnetometer X & Y axis cross plot indicating rotation of the tool during logging. No significant erratic values are visible. Data before & after correction match well.

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QC Test results summary & conclusion:

- Inclinometry channels are OK. Offsets within tolerance.
- Borehole image will be correctly oriented.
- Casing effect has been removed from this cross-plot by truncating top depth >10m below casing.

Crossplots of the X & Y axes of the magnetometer & accelerometer data are provided before and after correction.

A circular distribution shown by the magnetometer X & Y axis cross plot indicating rotation of the tool during logging. No significant erratic values are visible. Data before & after correction match well.

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Sensors and inclinometry channels are OK.
FMI Image Quality – effect of hole conditions

Hole conditions

FMI calipers indicate borehole is in-gauge mostly in bottom half to overlized in top half.

As part of the image QC, the caliper data from the tool was compared to bitsize in order to determine washout and/or underage sections of the borehole.

The caliper plot to the left displays such information indicating the borehole to be mostly in-gauge in the lower half to mostly ovalized in the top half. The ovality of the hole is due mainly to borehole breakout which characterizes much of the top half of the logged section. This to some degree has affected the clarity and overall quality of the image log.
FMI Image Quality – effect of tool sticking

Tool sticking

Minor, erratic vertical movements of tool usually correctable by speed correction processing. Sticking occurs throughout, yet mostly correctable.

As part of the image QC, GPIT-based speed correction was performed using Techlog to detect & correct for sticking & irregular tool motion during logging which can cause squashing & stretching of the image. A plot is shown above of curves involved in the speed correction.

**Sticky Indicator**
- Where the accelerometer detects a sticking event beyond where it can reconstruct the data - speed correction will need to be applied to correct.

**Depth Shift**
- Indicates the GPIT speed correction DCS processing has applied to the FMI data.

**Tool Acceleration**
- A measure of how the tool is moving in both a positive and negative direction vertically in the borehole.
**Image quality issues – phase shift**

**Phase shift issues**

**Phase shift phenomenon**

The phase shift is the difference in phase between the injected EMEX current and the phase of button current (see Figure below). The phase shift origin is the natural factor due the conductivity of environment and skin effect.

![Phase shift phenomenon diagram](image)

**Conditions that cause the problem**

The phase shift problems turn up when the mud is very conductive for example due to high salinity of the mud (Rm < 0.2 ohm). High rugosity or washouts will increase the problem due to increasing of standoff between pad/flap and formation. When the mud resistivity is low and the standoff is large, the input amplifiers will face an input impedance which is lower than the one specified for the board. When this occurs, the amplifiers will introduce the phase shift to the input signal.

**Recommendation**

To improve the data quality of FMI image in such conditions the new generation of formation micro resistivity imaging tool (FMI-HD) is designed to solve this phase shift issue. It is highly recommended for such mud environments conditions.

*The phase-shift existed in this logged section was moderate in a few places but generally geological features were still exhibited with good interpretation quality possible.*
FMI Image quality issues – poor image quality due to borehole breakout

The FMI image shows clear evidence of borehole breakout, which exist mostly in the upper half of the logged interval. This is of course great, but breakouts can also degrade the images quality to an extent that other geological features like beddings may be difficult to trace. In this well, however, majority of sedimentary features remain reasonably clear.
FMI Image quality issues – poor image quality due to sticking

An example of section of the FMI log where sticking has been detected (yellow flags). The image appears blurred and stretched.
Image quality - FMI Image quality summary

Quality rating system used in this report

<table>
<thead>
<tr>
<th>Quality rating</th>
<th>Description of category</th>
<th>Example Criteria</th>
<th>Usability of image data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent A</td>
<td>No log quality defects identified.</td>
<td>Crisp, clear images with geological features easily identifiable. No significant blurring, stretching or temporary loss of image.</td>
<td>Data can be used with high degree of confidence.</td>
</tr>
<tr>
<td>Good B</td>
<td>Good quality data with only minor defects.</td>
<td>Some vertical or diagonal striations/grooves present caused during drilling/logging. Minor blurring of image (e.g., under-gauge hole, mudcake and high mud salinity; the high salinity affected the phase offset of the tool and the image shows some image degradation). Minor stick-slip effects.</td>
<td>Data can be used for reliable interpretation. Only minor defects present which may degrade image quality but which would not hinder analysis/interpretation.</td>
</tr>
<tr>
<td>Fair C</td>
<td>OK quality data with some significant defects</td>
<td>Mottled image due to extreme formation characteristics. Severe EMEX noise. Significant stretch/compression of image due to speed anomalies. Significant breakout/rugosity/washout. Mudcake effects. Partial failure of measurement systems (e.g., Caliper). Significant roller reamer effects (not correctable).</td>
<td>Data can be used for interpretation, yet ability to do so reduced to some degree by introduction of some uncertainty.</td>
</tr>
<tr>
<td>Poor D</td>
<td>Poor quality data with significant amount of severe defects</td>
<td>Total failure of vital measurement component (e.g., GPIT). Magnetic interference. Severe tool sticking.</td>
<td>Low confidence data not recommended for interpretation.</td>
</tr>
</tbody>
</table>

Rating of image data in this well, and general description

C-B

Fair to good data quality generally, the main effect on image quality being attributed to borehole breakout, sticking and minor phase shift. Geological features are still discernable over a significant portion of the logged interval and interpretation can be reliably performed.
1. Tool sticking

GPIT-based speed correction was performed using Techlog software to detect & correct for sticking & irregular tool motion during logging which can cause squashing & stretching of the image. A plot is shown below of curves involved in the speed correction.

"Depth_Shift" indicates the GPIT speed correction Techlog processing has applied to the UBI data. "Sticking_Indicator" flags sections of the image log in which sticking has been significant.

Frequent sticking. Some effects upon image quality correctable by image processing.

2. Hole conditions

A caliper plot & the radius image (below) indicate sections of washout/undergauge in the borehole.

The UBI has an average caliper (UCLI) which will correspond to colour changes seen on the static radius image. When UCLI is plotted with bitsize (BS), sections of the borehole in which UCLI > BS are considered to represent washout; whereas UCLI < BS are considered undergauge. RCMIN (min radius) & RCMX (max radius) indicate the variability (rugosity) of the borehole wall.

Highly rugose hole due to minor washout and/or borehole breakout—corresponds to dark parts of radius image.

3. Tool/Motor rotation

A plot of P1NO (Pad 1 North) (green) displays the azimuthal position of the tool relative to north with depth, thereby indicating tool rotation. RSAV shows the motor revolution speed of the UBI sub.

P1NO (green) refers to the azimuthal position of a marker on the UBI tool relative to north. By looking at this curve we can see the rotation of the tool with depth. The tolerance of the tool is one full rotation within 10m, with greater rotation causing negative effects upon image quality. Hole deviation (DEVI) can be used to understand changes in tool rotation as tools rotate less in deviated wells. Stoppages & erratic behavior of RSAV can cause image quality issues relating to sub rotation.

Constant tool rotation, yet within tolerance. RSAV mostly consistent. Minor effects on image quality.
There is a direct relationship between UBI image quality, mud properties and the operational parameters. As the tool relies on measuring the reflective energy of a returned sound wave that has been emitted through the mud column, a requirement for the UBI is a mud that is light enough for this sound wave to travel through. In fact, the true limitation is 12 db/cm/MHz, however the best way of measuring is through mud density. The following chart relates mud density to signal attenuation, limitations, as well as to the operational parameters, vertical resolution and logging speed of the tool. The higher the mud density the lower the resolution the image data. The upper limit of mud density in WBM is 1900 Kg/m³ / 15.9 lbs/galUS / 1.91 SG and the limit in OBM is 1400 Kg/m³ / 11.6 lbs/galUS / 1.39 SG.

Additionally, additives to the mud may change the attenuative nature of the emitted sound pulse while not affecting mud density a great deal. If the mud system is near the upper limit of mud density, it is wise to inquire with the mud company as to what additives added that would increase attenuative properties to the mud. This would not be recommended.

<table>
<thead>
<tr>
<th>Mud Type</th>
<th>Attenuation (dB/cm/MHz)</th>
<th>Mud Density</th>
<th>Firing Mode &amp; Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WBM</td>
<td>OBM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Black = Kg/m³</td>
<td>Blue = lbs/galUS / Red = Specific Gravity</td>
</tr>
<tr>
<td>New Weighted</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Bases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>Less than 3</td>
<td>Less than 125</td>
<td>Less than 1025</td>
</tr>
<tr>
<td>Weighted Mud</td>
<td></td>
<td>Less than 10</td>
<td>Less than 6.6</td>
</tr>
<tr>
<td>Type 2</td>
<td>3-6</td>
<td>1225–1450</td>
<td>1025–1150</td>
</tr>
<tr>
<td>Weighted Mud</td>
<td></td>
<td>10.1–12.1</td>
<td>8.6–9.6</td>
</tr>
<tr>
<td>Type 3</td>
<td>6-9</td>
<td>1450–1675</td>
<td>1150–1275</td>
</tr>
<tr>
<td>Weighted Mud</td>
<td></td>
<td>12.1–14.6</td>
<td>9.6–10.6</td>
</tr>
<tr>
<td>Type 4</td>
<td>9-12</td>
<td>1675–1900</td>
<td>1275–1400</td>
</tr>
<tr>
<td>Weighted Mud</td>
<td></td>
<td>14.0–15.9</td>
<td>10.6–11.6</td>
</tr>
<tr>
<td>Tool Limits</td>
<td>12 db/cm/MHz</td>
<td>1900</td>
<td>1400</td>
</tr>
</tbody>
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**Vertical Resolution**

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<thead>
<tr>
<th>UBI Speed (KHz)</th>
<th>Logging Speed (ft/hr)</th>
<th>Firing Mode</th>
<th>Mud Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>400</td>
<td>500</td>
<td>0.1, 0.2 (2 upper limits)</td>
</tr>
<tr>
<td>0.4</td>
<td>800</td>
<td>500</td>
<td>0.4</td>
</tr>
<tr>
<td>0.6</td>
<td>1200</td>
<td>500</td>
<td>0.4</td>
</tr>
<tr>
<td>1.0</td>
<td>2600</td>
<td>500</td>
<td>0.4</td>
</tr>
</tbody>
</table>

UBI was run in optimum mud condition, yet image quality somewhat average to poor possibly due to reduced acoustic contrast and sticking.
UBI – Image quality issues: stick-slip

- Tool stick-slip effects – observed as smearing effect on all images, affecting many parts of the logged section.
Honey-comb effect – this is a gain calibration issue

Gain Calibration:
In the UBI tool, the waveform is multiplied by a gain before digitisation. Since the amplitude is divided by the gain before recording, the amplitude is normally corrected for the applied gain. However, the gain applied electronically may not lead to a proportional gain in acoustic amplitude. It is therefore necessary to calibrate the gains, and re-correct the amplitudes. If the gains are not calibrated, the image will appear spotty or ‘honey-comb’ appearance. The artifact is found only on the amplitude image of the UBI (P. Cheung, SRPC, SLB Clamart, France). This artifact is seen mainly in lower half of the logged interval.
UBI – Image quality issues: wood grain effect

- Tool Wood Grain effect: caused by sampling bias – bias in interpolation algorithm. Artifact appears on both amplitude and radius image. Wood grain pattern results where the transit time varies by only a few sampling intervals.
UBI – Image quality issues: reduced acoustic contrast

- Reduction in acoustic contrast between beds or formations would often result in lack of clear bed definition. Bedding contrast is usually subtle and gradual and often difficult to visualize.

Subtle contrast in layering
UBI – borehole quality issues: Tool marks

- These tool marks are non-geological markings on borehole wall possibly caused by other logging tools or BHA.
- Whilst the UBI images show the clear presence of borehole breakouts, the clarity and overall quality of the images becomes degraded for other geological features like beddings.
Image Comparison
Where there is ample contrast in formation resistivity and density (acoustic impedance), the two types of measurements complement each other.
Image Comparison 2 – Fractures

Larger Fractures are clearly distinguishable in both types of images.
Bedding features are clearly observed on FMI images and in some instances on the UBI images as this example shows.
Borehole breakout are clearly visible on both the FMI and UBI images.
Appendix: Borehole resistivity image processing/interpretation options offered by PTS

For more information on specific processing & interpretation products offered by Schlumberger PTS, contact PTS for more details.

Image processing & QC
Image data loading, quality control, image correction/enhancement, static & dynamic normalisation.

1. Dip picking of geological features
Dip picking of planar geological features on image; true dip orientation of bedding, fractures, faults; fracture type/density, etc.

2.a. Structural dip analysis
Structural bedding orientation, structural dip zonation, formation orientation, fault positioning.

2.b. Stress analysis
Identification of geomechanical stress related features (borehole breakout, induced fractures), determination of max/min horizontal stress directions.

2.c. Sedimentary analysis (clastic/carbonate)
Sedimentary bedding/texture analysis, facies identification, depositional environments, palaeocurrent directions, carbonate vuggy porosity.

For more information on specific processing & interpretation products offered by Schlumberger PTS, contact PTS for more details.

Report, Prints, Digital data (image, dips, facies, etc).
Processed image data (dlis format)

PetroTechnical Services
Global Expertise
Appendix: Formation MicroImager – Introduction I

What does it provide?

The FMI tool generates an azimuthally oriented electrical image of the borehole wall in water based mud.

Current is generated from the tool between the pads/flaps and an upper electrode which measures the voltage drop and as a result resistivity is calculated.

FMI image generation

8 Pads & Flaps, each containing 21 sensor buttons, record a total of 192 microresistivity measurements at 0.2-in vertical resolution. These resistivity measurements are allocated to a colour scale & displayed as an oriented resistivity image. Orientation of the image is achieved using survey data measured in the same tool string by the magnetometer & accelerometer of the General Purpose Inclinometry Tool (GPIT).

192 sensors record resistivity at borehole wall

Allocation of resistivity measurements to colour scale

- Vertical & azimuthal resolution of 0.2in
- Borehole coverage: 95% in 6” hole, 77% in 8.5”, 51% in 12.25”
- 4 arms each with one pad & flap, 192 microresistivity buttons

FMI Interpretation Answers

- Structural geology (structural dip, fault & natural fracture identification/orientation/characteristics)
- Sedimentary geology (facies, stratigraphy, depositional environments, palaeoflow directions)
- Geomechanics (drilling induced features, stress field analysis, wellbore stability)
Appendix: Formation MicroImager – Introduction II

### Feature identification

- The images display apparent dip and are affected by well deviation.
- Planar features (e.g. bedding, faults) identified using sinusoids placed over image.
- Software calculates true dip of features & displays on tadpole tracks.

### Static Image vs. Dynamic Image

- **Static Image**: Applies to an entire interval.
- **Dynamic Image**: Applies to a 0.6m moving window.

### Tadpole orientation

- Gridlines are 0-90 deg.
- Dip magnitude of surface indicated by position of tadpole along horizontal grid.
- Dip azimuth indicated by direction of tadpole tail.

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- “Unwrapped” image normally basis of feature identification.
- Image oriented to either North or Top-Of-Hole.
- Resistivity values assigned to colour scale (darker = more conductive).
- Two types of images based upon assignment of resistivity values to colour:
  - Static categorisation using resistivity range over entire log interval.
  - Dynamic categorisation using resistivity range over 0.6m sliding window.
Ultrasonic Borehole Imager

**What does it provide?**

The UBI tool provides high-resolution azimuthally oriented acoustic images of the borehole in water- or oil-base mud.

**The UBI tool**

The UBI has a rotating transducer which emits ultrasonic pulses & measures the transit time & amplitude of the resulting echo reflected off the borehole wall. Transducers come in a variety of sizes to match a range of borehole sizes.

Transit times are converted to borehole radii using mud velocity to produce hole radii with 360deg coverage.

**UBI outputs**

Two images are generated by the UBI: Amplitude and Hole Radius. These images have full 360deg coverage of the borehole wall. Hole radii data can also be output as spiral plots/cross-sections.

**COLOUR SCALE**

- High
- Low

**COLOUR SCALE**

- High
- Low

**UBI Interpretation Answers**

- Structural geology (structural dip, fault & natural fracture identification/orientation/characteristics)
- Geomechanics (drilling induced features, stress field analysis, wellbore stability)