Description of and Results from a Novel Borehole Gravity Gradiometer

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SUMMARY

Gravitec Downhole Instruments Ltd. is in the final stages of adapting its gravity gradiometer technology for deployment in the borehole environment for use in exploration as well as for time-lapse reservoir monitoring. The project, named Scorpius, is in cooperation with partners Kenda Capital and QinetiQ Ltd.

Laboratory testing of the sensor has produced gravity gradient measurements. Work has also been done to forward model the effects of gravity gradient measurements in the borehole environment.

Key words: Gravity Gradiometer, Borehole, Scorpius

INTRODUCTION

A production or exploration borehole is a challenging environment in which to deploy any form of gravity gradiometer. Though the seismic environment is relatively benign, the pressure, temperature, and most importantly limited space place severe restrictions on the designs of gradiometers that can realistically be developed for use in boreholes. Yet there is considerable interest in development of gravity gradiometers for use in borehole monitoring and surveying (Nekut, 1989; Pawlowski, 1998). Gravity gradiometer data, with gravimeter data or on its own, offers more accurate interpretation of near and far field features. For instance, borehole gravity gradiometer data can be used to correctly calculate the density of non-horizontal strata (Nekut, 1989). Because of the $1/r^3$ relationship gravity gradiometers are more sensitive to near-field mass anomalies while gravimeter data is more sensitive to more distant large body anomalies. Forward modelling of a typical oil-water-gas interface shows that the borehole gravity gradiometer has the potential to detect the water-gas/oil-gas interface at distances up to 1 km away.

BOREHOLE GRAVITY GRADIOMETER

Gravitec Downhole Instruments Ltd (GDI), a joint venture between Gravitec Instruments Ltd and Kenda Capital (formerly Shell Technology Ventures), in conjunction with QinetiQ Ltd, is developing the Scorpius borehole gravity gradiometer employing Gravitec's advanced string gravity gradiometer technology.

The sensor builds on the design discussed by Veryaskin in 2000. It comprises a 38 cm long thin ribbon of metallic material held between two fixed end points. Inductive readouts mounted at the ¼ and ¾ positions along the length of the ribbon detect ribbon perturbations of as low as 10^{-14} m caused by the local gravity gradient. Any variations in the uniform gravity field along the ribbon cause the ribbon to deflect in an S shaped mode with minima at the end points and in the centre. In a borehole the sensor is able to directly measure the off diagonal gravity gradient components (Txz and Tyz), where the axis system is defined with respect to the borehole.

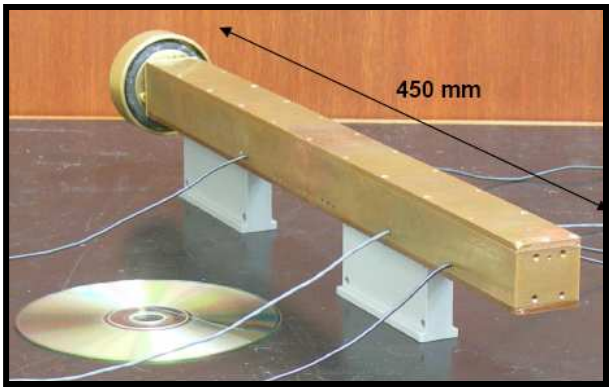

Figure 1. Gravitec Gravity Gradiometer sensor head. The sensor measures 30×30×450 mm and weighs ~1.3 kg.

Gravitec's design represents a radical departure from current technology and has the following key competitive discriminators which make in suitable for a wide range of applications:

- Very low unit cost;
- Small size;
- Lightweight;
- Unique configuration, with single sensing element;
- Ability to take both gravimeter and gravity gradiometric measurements, and
- Low deployment cost

Prototype Laboratory Testing

This design has been tested as a lab prototype with encouraging results. The prototype sensor was mounted vertically in a platform so that the base of the sensor was 40 mm from the top of a lead test mass. The platform was suspended from the ceiling of the laboratory at the University of Western Australia, partly to reduce seismic noise but mainly to ensure deformation of the floor as the test mass moved would not tilt the sensor and produce gravity gradient like signals.

The test mass was placed on a floor mounted automated track so that it moved the test mass back and forth beneath the sensor. The total sweep length was 1300 mm and the sensor was positioned roughly at the centre of the sweep. The position of the test mass was recorded and logged along with sensor output data, allowing personnel to vacate the laboratory and run recordings continuously overnight, when the building was most quiet. It should be emphasised that the testing was done in “strap-down” mode, with no isolation from acoustic noise, vibrations, or other environmental noise.

The test mass consisted of a centre disc and 2 outer rings, allowing one to vary the mass from 40–120 kg in 40 kg steps. Data from each night’s recording was averaged and filtered to reduce noise and aid in identifying the gravity gradient signal. This was repeated several times to ensure the results were consistent and repeatable.

Figure 2 shows representative results for the sensor with 40, 80 and 120 kg test masses. The red curve is the theoretical calculated gravity gradient signal.

Borehole Forward Modelling

QinetiQ Ltd. is a leading international defence and security company dealing with commercial and military contracts. Their experience has included modelling gravity gradient responses from mobile platforms, and their models were easily adapted to borehole modelling as part of the feasibility study of the sensor.

Forward numerical modelling completed by QinetiQ in 2006-2007 in cooperation with GDI has confirmed that the proposed in-hole measurement components will be sufficient to define changes in reservoirs caused by depletion over time. Further, the modelling has shown that the target sensitivity of the sensor will be suitable for detecting the expected changes in reservoir density. The sensor has been demonstrated in laboratory tests, and is now undergoing further engineering prior to being deployed in a tool suitable for the petroleum borehole environment.

The modelling was divided into two areas of interest, the effect of near-field variations (such as rugosity of the borehole wall) on the sensor and monitoring of gas/oil/water interfaces.

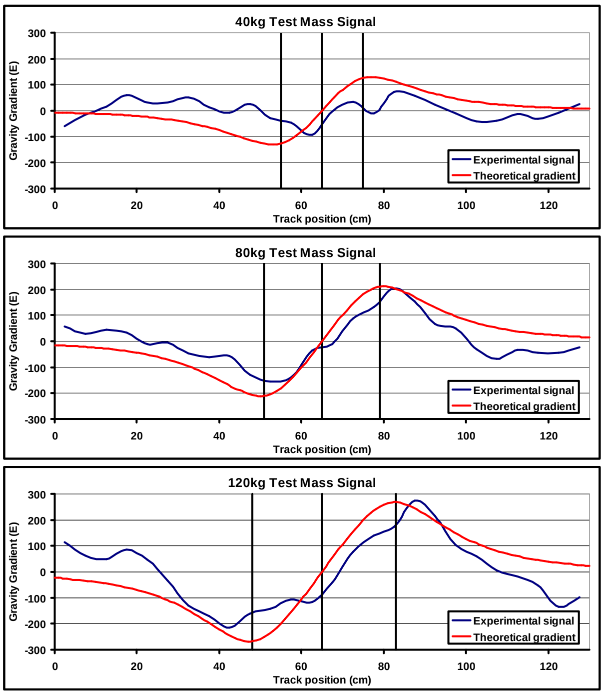

Figure 2. Gravity gradient response from Gravitec’s gravity gradiometer in the presence of 40 kg, 80 kg and 120 kg test masses. The vertical lines indicate the incidence of the leading and lagging edges and centre of the mass. The red curve is the theoretical gravity gradient for the test mass and ribbon sensor dimensions. Visual comparison between theory and experiment allowed calculation of a scaling factor to Eötvös. The same scaling factor was used in all subsequent recordings without adjustment.

The near field modelling showed that non-uniformity in the borehole wall produced a worst-case random spatially varying signature with standard deviation of ~2.5 Eö. For production boreholes where the tool would be removed between measurements this limits the sensitivity of the gradiometer to ~5 Eö (2σ) in a 15 cm diameter borehole and ~2 Eö in a 6 cm borehole.

For the far field case horizontal ingress of a water-oil and water-gas interface was modelled to determine at what distance the interface would be detectable. A gravity gradient of 5 Eö was used as the limitation to the sensitivity of the sensor.

The modelling showed that the water-oil interface is detectable a few meters away due to the low density contrast of oil and water. For a sensor permanently installed in a borehole and averaging over hours rather than minutes and using more advanced filtering techniques the distance could be extended out to hundreds of metres.

The gas-water and gas-oil interfaces the interface is detectable out to hundreds of metres due to the much higher density contrast. With permanently installed sensors and advanced filtering this distance could be extended to ~1 km.

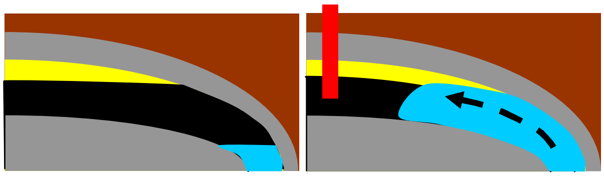

Figure 3. An illustration of water ingress along strata. As oil (black) is extracted it is replaced by water (blue) from the permeable source rocks.

CONCLUSIONS

Testing in the laboratory as well as numerical modelling have been an encouraging part of the development process of Gravitec's borehole gradiometer tool for petroleum applications. As engineering and manufacturing continue, the tests have indicated that such a tool is feasible in terms of functionality and with respect to its usefulness to detect changes in oil/gas/water pore space in a reservoir environment.

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