Introduction

Borehole gravity (BHGM) provides deep density measurements of rock formations surrounding a well through casing. The major applications of the tool in the petroleum industry are :

Reservoir Monitoring

Changes in reservoir fluid saturations and contact depths are monitored in a time lapse logging mode. This application is best suited to gas/oil or gas/water reservoirs.

Remote Sensing.

Borehole gravity data is used in conjunction with seismic and surface gravity data to map geologic structures remote from the well. Salt domes, over-thrusts, reefs, pinchouts and nearby faults are suitable targets.

Formation Evaluation

The densities are practically unaffected by near well influences such as hole rugosity and the presence of casing. The BHGM log is the only porosity log investigating a rock volume as large as the deep resistivity tools.

Other Applications

The tool has also been used for a range of engineering investigations including overburden pressure measurements for gas storage caverns and measurements of large volume ore and overburden rock density in hard rock mining.

EDCON INC.
171 South Van Gordon, Suite A,
Denver, Colorado,
U.S.A. 80228
Phone 303 980 6556 Fax 303 989 3480
edcon@edcon.com www.edcon.com

Andy Black July, 1997

Table of Contents

LIST OF SYMBOLS

ρ_B	BHGM density
ρ_m	Rock matrix or grain density
$\rho_{\gamma\gamma}$	Gamma-gamma density
ρ_h	Hydrocarbon density
ρ_g	Gas density
ρ_o	Oil density
ρ_w	Formation water density
ρ_{mf}	Mud filtrate density
ρ_{xo}	Invaded zone density
ρ_t	Formation density outside invaded zone
R_w	Formation water resistivity
R_t	Un-invaded formation resistivity
R_{xo}	Invaded zone resistivity
R_{mf}	Mud filtrate resistivity
ϕ	Porosity
ϕ_{xo}	Near well porosity.
S_w	Formation water saturation in un-invaded zone
S_{xo}	Mud filtrate saturation
S_g	Gas saturation
S_o	Oil saturation
T	Temperature
R	Universal gas constant
Z	Dimensionless gas compressibility factor
P	Pressure
GMW	Gram molecular weight
a	Tortuosity factor
m	Cementation factor
n	Saturation exponent
G	Universal Gravitational Constant
θ	Latitude
F	Free Air Gradient

1. Physics of Borehole Gravity Measurements

The Earth's Gravitational Field

Between any two bodies of masses m_1 and m_2 located a distance r apart, there exists a force F:

$$F = \frac{G\, m_1 m_2}{r^2} \qquad 1.1$$

where G is the Universal Gravitational Constant and has a value of (6.6726 ±0.0005) x 10^{-8} CGS units.

A unit mass on the surface of a spherical Earth would experience an acceleration g, given by the expression :

$$g = \frac{G\, M}{R^2} \qquad 1.2$$

where M is the mass of the Earth (5.974 x 10^{27} grams) and R is the radius of the Earth (6.37814 x 10^{8} cm). The acceleration g is the quantity measured by a gravity meter. The unit commonly used for gravity measurements is the milligal, abbreviated as mgal.

$$1 \text{ mgal} = 10^{-3}\text{cm.sec}^{-2}$$

In borehole gravity, another unit, the microgal or µGal, is often used.

$$1\ \mu\text{Gal} = 10^{-3} \text{ mgal}$$

The earth is wider at the equator than at the poles and it rotates. Both these factors cause gravity to be greater at the poles than at the equator. The International Gravity Formula of 1967 describes the theoretical variation of gravity at sea level, g, with latitude, θ :

$$g = 978031.85(1 + 0.005278895\ \sin^2\theta + 0.000023462\ \sin^4\theta) \qquad 1.3$$

Sea level gravity ranges from 978,031 mgal at the equator to 983,217 mgal at the poles. Gravity also changes with elevation, h, as this is similar to varying the value R, in equation 1.2. The vertical gradient of gravity, F, is referred to as the Free Air gradient and is also dependent on latitude, θ:

$$F = 0.308768 - 0.000440\sin^2\theta - 0.0000001442h \qquad 1.4$$

where F is in mGal/meter and

$$F = 0.094112 - 0.000134\sin^2\theta - 0.0000000134h \qquad 1.5$$

where F is in Mgal/foot.

Gravity measured on the Earth changes with time due to the attraction of moving astronomical bodies. The sun and the moon have by far the largest effects. Figure 1 shows an example of solar, lunar tidal corrections calculated using an algorithm from Longman, 1959.

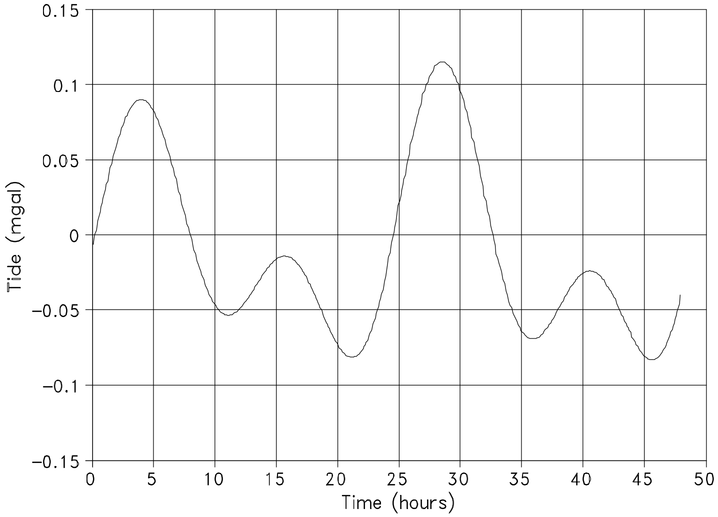


Figure 1.1 Solar Lunar tidal corrections for Denver, U.S.A. December 1 and 2, 1991

Density From Borehole Gravity Measurements

The gravitational attraction, g, due to an infinite horizontal slab of rock of uniform density measured from a point on its upper surface is

$$g = 2\pi\rho G\Delta z \qquad 1.6$$

where ρ is the slab density and Δz is the slab thickness. If measurements are made with a borehole gravity meter above and below this slab, the difference between the two gravity readings will be:

$$\Delta g = -4\pi\rho G\Delta z \qquad 1.7$$

The Free Air Gradient term must also be included for the real earth situation :

$$\Delta g = (F - 4\pi\rho G)\Delta z \qquad 1.8$$

Equation 1.8 can be solved for the slab density

$$\rho = \frac{1}{4\pi G}(F - \frac{\Delta g}{\Delta z}) \qquad 1.9$$

This is the equation used to derive densities from the borehole gravity measurements. When the appropriate constants are inserted in equation 1.9, we obtain :

$$\rho = 3.68237 - 0.005247\sin^2\theta - 0.000001720\bar{z} - 11.92601\frac{\Delta g}{\Delta z} \qquad 1.10$$

when the depth interval is measured in meters and :

$$\rho = 3.68237 - 0.005247\sin^2\phi - 0.000000524\bar{z} - 39.12731\frac{\Delta g}{\Delta z} \qquad 1.11$$

when the depth interval is measured in feet. The gravity change is measured in mgals in both equations.

Corrections must be made if the well is not vertical since the depth interval for the density equation assumes vertical depths. If the deviation of the well from vertical is α, and the slant depth differential is ΔZ_s, then the vertical depth differential used in equation 1.9 is given by :

$$\Delta Z = \Delta Z_s \cos\alpha \qquad 1.12$$

In the situation where the slab density is not uniform, equation 1.9 calculates the density of a uniform slab of rock causing the same gravity gradient as the measured gradient. The borehole gravity density can be termed an *apparent density* in much the same way that apparent resistivities are measured by resistivity tools.

BHGM Density Error

Errors in Borehole Gravity densities result from errors in the depth and gravity differentials.

Present well adjusted LaCoste and Romberg borehole gravity meters produce reading standard deviations of 2.5 µGals in well conditions. The accuracy of depth differential measurements for intervals of less than 2.5 meters obtained with the Shuttle Sonde are less than 2mm.

The total probable error in a BHGM density measurement is calculated by taking the partial derivatives of equation 1.9 with respect to the depth and gravity differentials:

$$\delta\rho_B = \sqrt{\left(\frac{\partial\rho_B}{\partial\Delta g}\delta\Delta g\right)^2 + \left(\frac{\partial\rho_B}{\partial\Delta Z}\delta\Delta Z\right)^2} \qquad 1.13$$

Equation 1.13 yields equation 1.14 when the partial derivatives are evaluated.

$$\delta\rho_B = \frac{1}{4\pi G}\sqrt{\left(\frac{1}{\Delta Z}\delta\Delta g\right)^2 + \left(\frac{\Delta g}{\Delta Z^2}\delta\Delta Z\right)^2} \qquad 1.14$$

We may also evaluate Δg to yield the error in calculated density as a function of the true BHGM density ρ_B.

$$\delta\rho_B = \frac{1}{4\pi G\Delta Z}\sqrt{\delta\Delta g^2 + (F - 4\pi G\rho_B)^2\delta\Delta Z^2} \qquad 1.15$$

When the constant values are inserted in equation 1.15 we obtain:

$$\delta\rho_B = \frac{1}{\Delta Z}\sqrt{(39.12731\delta\Delta g)^2 + ((3.68237 - \rho_B)\delta\Delta Z)^2} \qquad 1.16$$

for Δz in feet and:

$$\delta\rho_B = \frac{1}{\Delta Z}\sqrt{(11.92601\delta\Delta g)^2 + ((3.68237 - \rho_B)\delta\Delta Z)^2} \qquad 1.17$$

for Δz in meters.

It is common to make repeat measurements of the density by positioning the gravity sensor successively above and below the interval. If N measurements of

the interval are made, the error will become :

$$\delta\rho_B = \frac{1}{\sqrt{N}\Delta Z}\sqrt{(39.12731\delta\Delta g)^2 + ((3.68237 - \rho_B)\delta\Delta Z)^2} \qquad 1.18$$

for depths in feet and

$$\delta\rho_B = \frac{1}{\sqrt{N}\Delta Z}\sqrt{(11.92601\delta\Delta g)^2 + ((3.68237 - \rho_B)\delta\Delta Z)^2} \qquad 1.19$$

for depths in meters.

Equations 1.18 and 1.19 are used in survey planning to ensure that sufficiently accurate densities will be obtained for the objective. The number of measurements and the depth interval are normally the controlling factors. Estimates are made of the depth and gravity differential errors based on experience in similar well environments. In quiet conditions, gravity differential errors for N=1 of 3.9 µGals can be used. In noisy conditions such as in a shallow offshore well, the error in the gravity differential may be closer to 20 µGals.

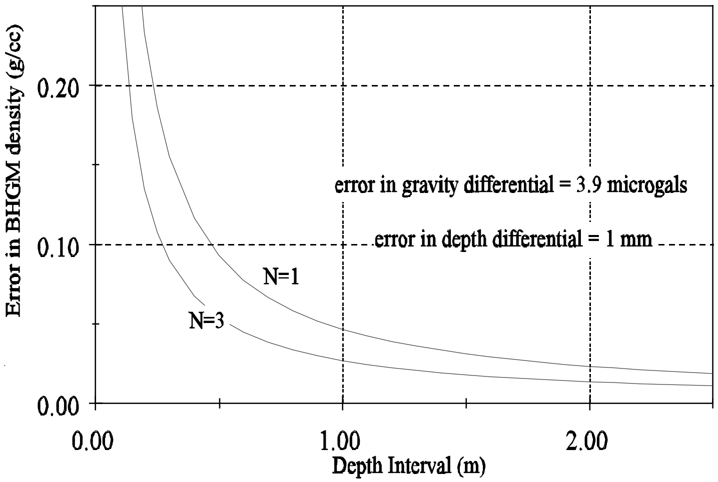


Figure 1.2 BHGM density errors in the shuttle sonde.

The error in Δz for the shuttle sonde is essentially zero. In the range of Δz from 2.5 meters to 10 meters, the Δz errors are normally about 1 cm if the tool movement is unrestricted. In cases where the casing is very small and the mud is very heavy, larger Δz errors will occur. Figure 1.2 shows the errors in BHGM density which can be expected in the shuttle sonde which operates over 2.5 meters. The two lines are for one and three measurements over the same interval. At least three measurements are normally made over the shuttle intervals to enhance density accuracy, provide drift information and allow density accuracy limits to be calculated.

The vertical resolution of a borehole gravity log is effectively limited by the increasing error with decreasing station intervals. If for example, the required accuracy in a water saturation problem required a density accurate to 0.01 g/cc, the smallest station interval able to provide this density accuracy given the parameters shown in the lower curve of Figure 1.2, is 2.69 meters.

Depth of investigation of BHGM densities.

Unlike most other logging measurements, borehole gravity is purely passive. The borehole gravity tool samples the existing gravitational field which is a function of the distribution of mass about the well. The borehole gravity field variation due to a body depends on the distance of the body from the well, its shape and density. Bodies close to the well cause high spatial frequency field variations whereas distant bodies cause low spatial frequency field variations.

The survey station spacing used dictates the highest gravity field spatial frequency which can be measured. The act of increasing the station spacing does not increase the depth of investigation, it merely limits the ability of the survey to detect small bodies close to the well.

In the well bore environment, a mud filtrate invasion annulus develops around the well in porous, permeable rocks. It is important to know if a tool response comes from inside or outside this annulus. For example, the gamma gamma density tool response is normally from inside the invasion annulus while the borehole gravity density response is normally from outside the annulus.

The normal way to define the radius of investigation of a logging tool is to calculate that radius within which 80% of the response is generated for a cylindrical distribution of the property being measured. To do this for borehole gravity we first calculate the gravitational attraction of a vertical cylindrical body centered on the well. The BHGM density response is the vertical derivative of the gravitational response multiplied by $1/4\pi G$.

The BHGM density in the case of a unit density cylinder of radius R and height T surrounded by empty space is :

$$\rho_B = \left(1 - \frac{1}{\left(\left(\frac{R}{T}\right)^2 + 0.25\right)^{0.5}}\right) \qquad 1.20$$

It is useful to refer to the density calculated in this way as the geometric factor, G_f. This is shown in Figure 1.3. G_f is related to actual density values by :

$$G_f = \frac{\rho_B - \rho_t}{\rho_{xo} - \rho_t} \qquad 1.21$$

where ρ_B is the BHGM density
ρ_{xo} is the invaded zone density

ρ_t is the density of material outside the invaded zone

A value of 0.8 for the Geometric Factor corresponds to 80% of the density response being generated from the material immediately surrounding the well. From equation (1.20), this corresponds to an R/T of 2.45. So for a 10 feet thick bed, the radius of investigation is 24.5 feet.

The depth of investigation is purely dependent upon the physical dimensions of the invaded zone and the density contrast it presents to the reservoir. It is not possible to see deeper into the reservoir by varying the BHGM station spacing.

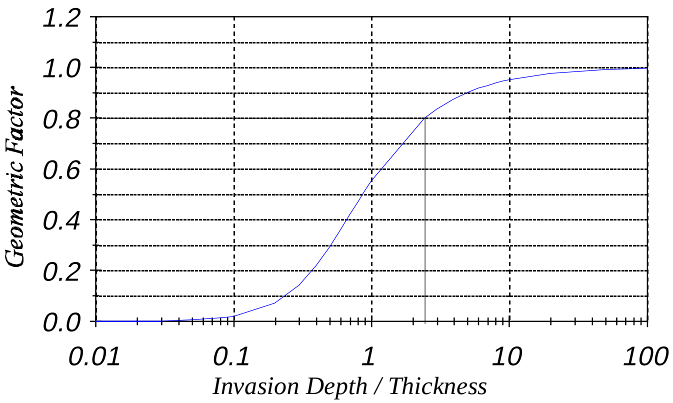


Figure 1.3 Geometric Factor for invasion model.

For a practical example of the use of the Geometric Factor to estimate the response of the BHGM to and invaded gas reservoir, take the case where a 15 foot thick limestone bed with porosity 0.28 is invaded to a depth of 4 feet with mud filtrate having a density of 1.2 g/cc. The gas saturation in the invaded zone is 0.1. In the undisturbed zone, the gas saturation is 0.95 and the water density is 1.05 g/cc. The gas density is 0.08 g/cc. The density of the invaded zone is 2.256 g/cc and the density of the un-invaded reservoir is 2.001 g/cc.

For this invasion geometry, the geometric factor is 0.1177. A gamma-gamma density type measurement will record a density of 2.256 g/cc and the BHGM will record a density given by

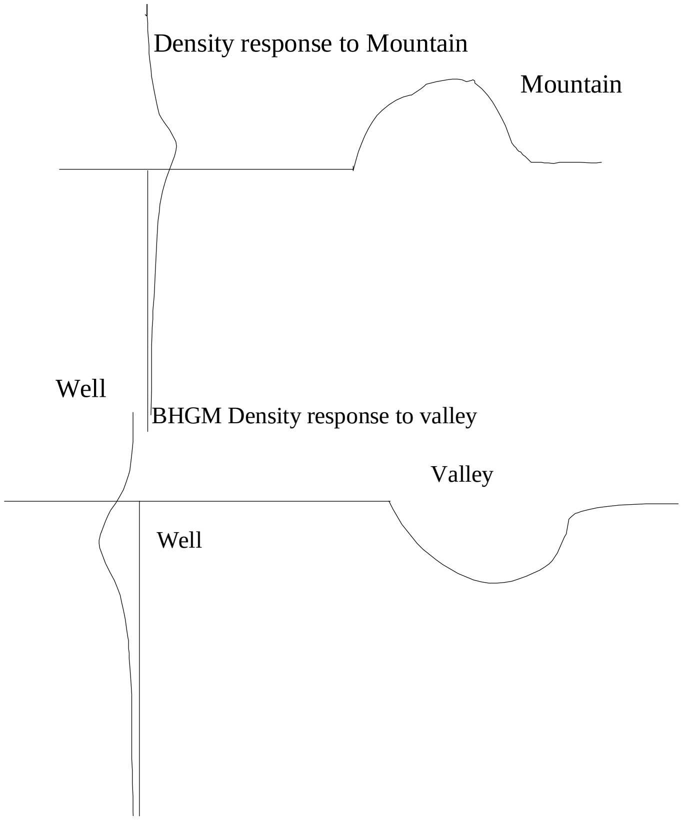
$$\rho_B = \rho_t + G_F\,(\rho_{xo} - \rho_t) \qquad 1.22$$

ie., 2.031 g/cc. For the case of 1 foot invasion into the same 10 foot thick bed the BHGM density would be 2.006 g/cc.

Terrain Corrections

In some cases, the gravitational field due to nearby terrain can disturb BHGM densities. This effect is largest near the surface and decreases with depth and distance from the terrain feature. In flat areas such as West Texas, the terrain effect is normally small and can often be ignored. In hilly or mountainous areas it is advisable to make terrain corrections to the gravity values before calculating densities.

Terrain effects can be visualized by considering the BHGM density responses to nearby masses. The BHGM density response to a positive mass is a positive density maximum opposite the center of mass decreasing in amplitude above and below. A nearby mountain therefore causes a positive density terrain effect somewhere above ground level which decreases with increasing depth in the well. A valley, which can be thought of as a negative mass, has a maximum negative density effect somewhere below ground level after which it decreases in amplitude with further increases in depth.



To calculate the terrain effects for an actual survey, a standard surface gravity technique is used with slight modifications. The terrain centered on the well is divided into concentric rings or zones, which are further divided into compartments. of equal area The following table is the Hayford Bowie scheme :

Zone	Outer Radius (m)	Number of Compartments
A	2	1
B	68	4
C	230	4
D	590	6
E	1280	8
F	2290	10
G	3520	12
H	5240	16
I	8440	20
J	12400	16
K	18800	20
L	28800	24
M	58800	14
N	99000	16
O	166700	28

The average elevation of the terrain in each compartment above a datum plane, which is generally placed at well head ground elevation, is then used to calculate the gravitational attraction of the compartment at each gravity station in the well. The gravitational attraction of compartment j in zone i is :

$$g_{i,j} = \frac{2\pi G\rho_t}{N} \left(\sqrt{r_1^2 + h^2} - \sqrt{r_1^2 + h_1^2} - \sqrt{r_2^2 + h^2} + \sqrt{r_2^2 + h_1^2} \right) \qquad 1.23$$

where	N	is the number of compartments in zone i,
	ρ_t	is the terrain density
	r_1 & r_2	are the inner and outer radii,
	h	is the elevation of the compartment minus the reading elevation.
	h_1	is the ground level elevation minus the reading elevation.

To correct for the curvature of the earth, the compartment elevations are decreased by :

$$\left(\frac{r_1 + r_2}{2}\right)^2 A$$

where	A	is 7.48×10^{-8} for elevations in meters and 2.39×10^{-8} for elevations in feet.

Compartment elevations are computed from a grid of digital terrain data which are then used in field data processing. Terrain elevations out to zone L are generally used. More rings and compartments are used if the Hayford Bowie scheme does not provide enough detail in rugged terrain.

The choice of terrain density is sometimes problematic. A density of 2.67 g/cc is often used in igneous or metamorphic terranes. Much lower densities are warranted in sedimentary environments. For subsea wells, the terrain density, ρ_t in equation 1.23 is decreased by the density of sea water, or 1.03 g/cc if an actual water density measurement is unavailable.

The significance of terrain corrections to BHGM surveys varies with survey objective. When absolute rock densities are important, terrain corrections should be performed. Distant mountains in otherwise flat terrain may change the BHGM density equivalent to a few saturation units. In time lapse measurements, the terrain effect will be constant and subtract out of the density differences.

Errors in terrain corrections are due to errors in the terrain density and differences between the zone and compartment terrain model and the actual terrain. Likely errors may be estimated by varying the assumed terrain density through a reasonable range.

A difference between BHGM densities and the corresponding gamma-gamma densities may remain after performing terrain corrections. These differences are generally subscribed to geologic structures or local Free Air Gradient anomalies. In these cases a comparison of BHGM and gamma-gamma densities over a tight or water saturated sand or lime section can provide a calibration offset.

Measurements of vertical gravity gradient in the air above the well will also help to determine better values for terrain density and Free Air Gradient. This can be a difficult measurement to perform without advance preparation.

2. BHGM Density Formation Response.

The Wellbore Environment

The hydrostatic pressure of the column of drilling fluid during the drilling process is maintained above the formation pressure. This pressure differential causes drilling fluid to invade a porous and permeable formation. As it invades, solid particles in the fluid are left on the side of the well bore as mud-cake. Mud filtrate penetrates the formation and displaces the natural formation fluids away from the well bore. The zone near the well where the formation fluids are practically all displaced is the called the flushed zone. Outside the flushed zone, a region of mixed mud filtrate and formation fluids often forms a transition zone. Outside the transition zone the formation fluids are undisturbed.

The differences in fluid constituents and hence rock bulk density between the invaded and un-invaded zones are important because the gamma-gamma density tool often responds solely to the invaded zone, whereas the BHGM density response is practically unaffected by the invaded zone.

The measured BHGM density response in terms of formation parameters is given by the mass balance equation :

$$\rho_B = \rho_m(1 - \phi) + \phi(S_w\rho_w + (1 - S_w)\rho_h) \qquad 2.1$$

Note that the formation water density and the undisturbed formation water saturation S_w, are used in this relationship. The BHGM density could be used alone to calculate porosity and water saturation by solving for ϕ and S_w in Equation 2.1:

$$\phi = \frac{\rho_m - \rho_B}{\rho_m - \rho_h - S_w(\rho_w - \rho_h)} \qquad 2.2$$

$$S_w = \frac{\rho_B - \phi\rho_h - \rho_m(1 - \phi)}{\phi(\rho_w - \rho_h)} \qquad 2.3$$

The accuracy of these calculations depends on the accuracies of the parameters used. BHGM density measurements can be repeated to within .003 gm/cm^3 over intervals as thin as 10 feet. More typically BHGM densities are accurate to about.01 g/cm^3. This can produce porosities accurate to about 0.5% and water saturations to about 8%.

Gamma-Gamma Density Response

The gamma-gamma density response is dependent on the depth of invasion of the mud filtrate as the tool only investigates about six inches from the well. For deep invasion equation 2.4 is appropriate:

$$\rho_{\gamma\gamma} = \rho_m(1 - \phi_{xo}) + \phi_{xo}(\rho_w S_{xo} + \rho_h(1 - S_{xo})) \qquad 2.4$$

Note that the BHGM and gamma-gamma densities will not always measure the same matrix density since the gamma-gamma density tool is actually measuring electron densities. Table 2.1 compares the tool responses for different rock matrixes.

Table 2.1 BHGM and Gamma Gamma Density Responses for Different Minerals

Mineral	BHGM Density (g/cc)	Gamma Gamma Density (g/cc)
Anhydrite $CaSO_4$	2.963	2.977
Dolomite $CaMg(CO_3)_2$	2.866	2.876
Halite NaCl	2.163	2.032
Calcite $CaCO_3$	2.710	2.710
Quartz SiO_2	2.648	2.648
Carnalite $KMgCl_3.6H_20$	1.610	1.570
Sylvite KCl	1.987	1.863

The gamma-gamma tool is also very sensitive to hole rugosity and will produce a low density in rugose holes. The caliper log and the density correction curve are normally good indicators of this problem occurring. The BHGM densities are practically unaffected by hole rugosity.

Density Difference Value

The density difference is defined as the BHGM density less the gamma-gamma density averaged over the same depth interval. This value is often an indicator of moveable hydrocarbons. In formations in which porosity varies laterally, it is also an indicator of changing porosity.

From equations 2.1 and 2.4:

$$\rho_B - \rho_{\gamma\gamma} = \begin{array}{l} \phi_{xo}(S_w(\rho_w - \rho_h) - S_{xo}(\rho_{mf} - \rho_h)) \\ + \\ \Delta\phi(S_w(\rho_w - \rho_h) + \rho_h - \rho_m) \end{array} \tag{2.5}$$

where $\phi = \phi_{xo} + \Delta\phi$

This equation is arranged into two terms. The first term is the effect of fluid invasion and the second term is the effect of changing porosity.

The magnitude of the first term can be up to -0.2 g/cc in a gas reservoir and up to -0.03 g/cc in an oil reservoir. Larger values of density difference are generally due to increasing porosity away from the immediate vicinity of the well. Combining density and resistivity log responses will allow values for near and far porosity to be calculated.

The density difference value may be negative, zero or positive:

A **negative density difference** may imply that

1. Porosity is on average higher than measured at the well.

2. The mud filtrate has displaced a fluid of lower density. This could be gas, oil or formation water. The density of formation water is normally too close to that of the mud filtrate to cause a measurable negative density difference.

3. A formation of lower density than the formation surrounding the well is being detected.

A **zero density difference** may imply that

1. The formation is tight and no invasion has taken place.

2. The invading mud filtrate has the same density as the reservoir fluid, e.g., water invading water or oil based mud filtrate invading oil.

3. There is no additional porosity within range of the tool.

4. Offsetting effects from the BHGM and gamma gamma densities.

A **positive density difference** may imply that

1. Porosity decreases away from the well.

2. A higher density fluid is displaced by the mud filtrate.

3. Hole rugosity has caused the gamma-gamma density to produce values which are too low.

Density differences due to changing porosity are often recorded in carbonates with fracture and vuggy porosity systems. Note that the density difference is not dependent on matrix density except in the case of varying porosities.

Care must be taken when using density differences that the density difference values are not influenced by remote structure or calibration effects. A base density difference level should be established through the formation of interest by identifying tight and/or water zones, preferably above and below that formation. This should be allowed for in the BHGM survey plan.

Approximate values for water saturation may be calculated by simplifying equation 2.5 assuming that the mud filtrate density is the same as the formation water density.

$$\rho_B - \rho_{\gamma\gamma} = \phi_{xo}(S_w - S_{xo})(\rho_w - \rho_h) \tag{2.6}$$

Fracture Detection

Borehole Gravity Deep Density logs, in conjunction with open hole logs, have the ability to detect and quantify fracture porosity in formations. This ability is due to the very large volume of investigation of the BHGM measurement in comparison to the very localized volume investigated by the normal gamma gamma density and neutron porosity logs.

Consider a formation where the fractures have a sub vertical orientation and are spaced 3 feet apart. The probability is high that the volume investigated by the nuclear density tool which has a radius of investigation of about 4 inches on one side of the hole, will not include fracture porosity. The radius of the BHGM volume of investigation is on the order of 24 feet in a 10 foot thick bed. This volume will definitely include the fracture porosity.

The response equations for the two tools are :

1. Gamma Gamma Density Tool :

$$\rho_{\gamma\gamma} = \rho_m(1-\phi_m) + \phi_m(S_{xo}\rho_{mf} + (1-S_{xo})\,\rho_h) \qquad 2.7$$

2. Borehole Gravity Deep Density Tool :

$$\rho_{BHGM} = \begin{aligned} &\rho_m\,(1-\phi_m-\phi_f\,) && \textit{grain contribution} \\ &+ \\ &\phi_m\,(S_{wm}\rho_w + (1-S_{wm})\rho_h\,) && \textit{intergranular porosity} \\ &+ \\ &\phi_f\,(S_{wf}\rho_w + (1-S_{wf}\,)\rho_h\,) && \textit{fracture porosity} \end{aligned} \qquad 2.8$$

Logging with both density tools through the above fractured formation results in BHGM densities less than gamma gamma densities due mainly to the lighter fracture porosity taking the place of the rock grains. This difference can be calculated by taking the difference between the two tool responses ie. equation (2.7) minus equation (2.8) :

$$\rho_{\gamma\gamma}-\rho_{BHGM} = \begin{aligned} &\rho_m\,\phi_f && \textit{grain contribution} \\ &+ \\ &\phi_m\,(S_{xo}\rho_{mf} - S_{wm}\rho_w + \rho_h(S_{wm}-S_{xo})) && \textit{intergranular porosity} \\ &- \\ &\phi_f\,(S_{wf}\rho_w + (1-S_{wf})\rho_h) && \textit{fracture porosity} \end{aligned} \qquad 2.9$$

Figure 2.1 shows fracture porosity in a carbonate reservoir from 8970 feet to 9250 feet. The reservoir has the following parameters :

Matrix density, ρ_m	2.75 g/cc
Mud filtrate density, ρ_{mf}	1.01 g/cc
Water density, ρ_w	1.01 g/cc
Hydrocarbon density, ρ_h	0.80 g/cc
Matrix porosity, ϕ_m	0.098 pu
Fracture porosity, ϕ_f	0.037 pu
Average $\gamma\gamma$ Density	2.580 g/cc
Average BHGM Density	2.489 g/cc

The right hand track shows the BHGM (light) and $\gamma\gamma$ density. The density difference is shown in track 1. Porosity and production is indicated between 8970 and 9250 feet by a negative density difference of up to -0.15 g/cc. The positive spikes on the density difference log are caused by hole washouts which lower the $\gamma\gamma$ density readings.

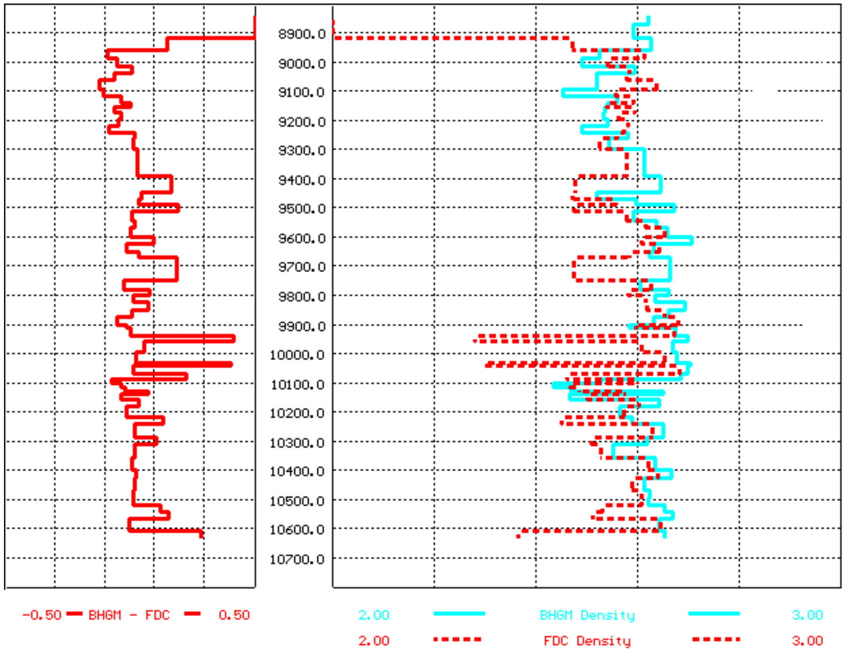


Figure 2.1

3. Calculation of Fluid Saturations using BHGM Densities.

Mass Balance Equation

Formation water saturation may be calculated using the mass balance equation as shown in Part 2 :

$$S_w = \frac{\rho_B - \phi\rho_h - \rho_m(1 - \phi)}{\phi(\rho_w - \rho_h)} \qquad 3.1$$

Independent values for porosity, hydrocarbon density, formation water density and matrix density are required. This information may come from cores and production samples in which case care must be taken that values corrected to the actual formation pressure and temperature are used: Formation water and mud filtrate density may be derived from the water salinity using equation 3.2.

$$\rho = 1 + 0.73p \qquad 3.2$$

where p is the water salinity expressed in ppm NaCl divided by one million. If only the water resistivity is available, p may be found using equations 3.3 and 3.4.

$$px10^{6} = 10^{\left(\frac{3.562 - \log(R_{75} - 0.0123)}{5.3^{0.955}}\right)} \qquad 3.3$$

where R_{75} is the water resistivity at 75° F.

$$R_{75} = R_t\left(\frac{T + 7}{82}\right) \qquad 3.4$$

where R_t is the water resistivity at temperature T. Equation 3.4 is the Arps formula.

The hydrocarbon density must also be found at the formation temperature and pressure. In the case of a gas, the gas density may be derived from Equation 3.5 which has been derived from the equation of state:

$$\rho_g = \frac{P\ GMW_{av}}{R\ Z(T + 273.15)} \qquad 3.5$$

where: P is the gas pressure in the formation in PSIA.

GMW_{av} is the average gram molecular weight of the gas.
R is the Universal Gas constant (1206 for these units)
T is the temperature in degrees Centigrade.
Z is the dimensionless gas compressibility factor.

e.g. for methane at 60° C, 2890 PSI and Z = .865, the gas density is .1134 g/cc.

If the required values for equation 3.1 are not available from samples, then other logs may provide them.

Formation water density may be found from formation water resistivity values, R_w, derived from SP logs and mud filtrate resistivity, R_{mf}. Alternately, R_w may be estimated using the apparent water resistivity calculated from the Archie equation, or from the Pickett plot of porosity against formation resistivity, R_t.

It is extremely useful to include at least one and preferably several water zones in a survey to establish good values for R_w and formation water density.

BHGM Density and Formation Resistivity,

This log combination is applicable to both oil and gas reservoirs. It is more accurate in gas reservoirs. This method involves first establishing accurate BHGM densities and formation resistivities for the same depth interval. The BHGM survey plan should be based upon the deep resistivity log. The BHGM reading locations should enclose regions where the resistivity does not vary rapidly since this will avoid averaging widely varying lithologies and porosities.

The deep resistivity log values should be corrected for invasion and thin bed effects to obtain a reasonable value for formation resistivity, R_t.

The calculation of S_w is performed by simultaneously solving the Archie equation, 3.6 and the BHGM density response equation, 3.7 . This may be done using Newton's iterative method.

$$S_w^n = a\phi^{-m}\frac{R_w}{R_t} \qquad 3.6$$

$$\rho_B = \rho_m(1 - \phi) + \phi(S_w(\rho_w - \rho_h) + \rho_h) \qquad 3.7$$

We can eliminate the S_w term by combining equations 3.6 and 3.7 to obtain a function in porosity, F, given by equation 3.8. The derivative of F with respect to porosity is given by equation 3.9.

$$F\ (\phi) = (\rho_w - \rho_h)(a\frac{R_w}{R_t})^{\frac{1}{n}}\phi^{(1\ -\ \frac{m}{n})} + \phi(\rho_h - \rho_m) + \rho_m - \rho_B \qquad 3.8$$

$$F^{/}(\phi) = (1 - \frac{m}{n})(\rho_w - \rho_h)(a(\frac{R_w}{R_t})^{\frac{1}{n}}\phi - \frac{m}{n} + \rho_h - \rho_m \qquad 3.9$$

$$\phi_{i+1} = \phi_i - \frac{F(\phi)}{F^{/}(\phi)} \qquad 3.10$$

An appropriate value is chosen for porosity which is then updated using equation 3.10 until two successive porosities are less than 0.1% apart.

$$\rho_{\gamma\gamma} = \rho_m(1 - \phi_{xo}) + \phi_{xo}(S_{xo}(\rho_{mf} - \rho_h) + \rho_h) \qquad 3.11$$

$$S_{xo}^n = a\ \phi_{xo}^{-m}\frac{R_{mf}}{R_{xo}} \qquad 3.12$$

The gamma gamma density and micro-resistivity logs can be used in the same way to solve for invaded zone porosity, ϕ_{xo} and invaded zone water saturation, S_{xo}.

The accuracy of water saturations calculated using this method can be less than 2%. Inclusion of several water zones in the BHGM survey will help establish accurate parameters for use in this procedure.

Effect of Variations in Porosity on Sw Calculations.

The calculation of Sw and porosity from deep resistivity and BHGM density avoids the problem where near well porosity values are used to represent the large volume investigated by the resistivity tool. If the porosity is in error by $\Delta\phi$ the calculated value for water saturation S_{wa} will be in error according to:

$$S_w = S_{wa}(\frac{\phi_{xo}}{\phi_{xo}+\Delta\phi})^{\frac{m}{n}} \qquad 3.13$$

For example, in a fractured carbonate situation, the well has penetrated a fractured zone which is well sampled by both the deep resistivity and BHGM densities but undersampled by the nuclear porosity logs at the well. The nuclear porosity logs indicate a porosity of 5% and the average porosity of the region investigated by the deep resistivity and BHGM logs is 10%. The average oil saturation calculated using BHGM and deep resistivity logs is 50%. However, if the porosity from the nuclear logs is used with the deep resistivity logs, an apparent oil saturation of 0% will be calculated.

Time Lapse Monitoring of Hydrocarbon Saturation

If water saturation is determined using BHGM density and formation resistivity as described in the previous section, a change in water saturation due to production may be measured at a later date by measuring the change in BHGM density which has occurred. This technique promises enhanced accuracy because errors due to structural effects and matrix density accuracy or variations are eliminated. The initial BHGM density is :

$$\rho_B = \rho_m(1 - \phi) + \phi(S_w(\rho_w - \rho_h) + \rho_h) \qquad 3.14$$

and the after production BHGM density response ρ_B' is :

$$\rho_B' = \rho_m(1 - \phi) + \phi(S_w'(\rho_w - \rho_h) + \rho_h) \qquad 3.15$$

Subtracting equation 3.15 from equation 3.14, we obtain :

$$\rho_B - \rho_B' = \phi(\rho_w - \rho_h)(S_w - S_w') \qquad 3.16$$

and rearranging terms:

$$S_w' = S_w - \frac{\rho_B - \rho_B'}{\phi(\rho_w - \rho_h)} \qquad 3.17$$

Equation 3.15 is used to calculate the water saturation after production allowing residual hydrocarbon saturation levels, S_{hr} to be calculated:

$$S_{hr}' = 1 - S_w' \qquad 3.18$$

Location of Bypassed Production Behind Casing

The BHGM tool is especially suited to finding bypassed hydrocarbon production and in particular gas behind casing set in old wells. Wells cased before the advent of modern porosity logs will often have a suite of old resistivity and SP logs available. An older form of neutron porosity log may also be available. Modern neutron porosity logs may also be run through casing. If gas is present in the formation, the neutron log will read less than the true porosity due to the absence of hydrogen ions in water or oil and the excavation effect. A valid calculation of water saturation in a gas zone in this case requires additional porosity information which can be provided by the BHGM tool. Values for porosity and water saturation can be calculated as outlined above if the fluids have not moved since the electric log was run. .

4. BHGM Response to Remote Structures

Geologic structures in the vicinity of a well often have rocks of contrasting densities adjacent to each other. These distributions of contrasting densities can often be detected using BHGM density measurements. The magnitude of the density effect depends upon the size of the body, its distance from the well and the density contrast it presents to the rock lying between it and the well.

BHGM density effects from remote structures can normally only be recognized if a base density log such as a gamma-gamma density log has been recorded in the same well. This base log is used to show what the BHGM density log would record if the structure were not present. The difference between the BHGM densities and the gamma-gamma density log, known as the density difference log, $\Delta\rho_a$, is used in the interpretation of these structural effects.

The ability to recognize small density differences is dependent upon the quality of both logs. When both logs are of good quality, density differences accurate to 0.015 g/cc are obtained over 10 foot intervals. Wider depth intervals will produce higher accuracy $\Delta\rho_a$ measurements.

The density difference is also strongly affected by mud filtrate invasion into the formation as described elsewhere in the manual. This effect may be distinguished from structural effects since invasion is evident on the resistivity logs. Invasion effects are also dependent upon the permeability of particular formations so a smooth density difference anomaly crossing several bed boundaries is probably caused by structure.

The only structural effect which is confined to single beds is the effect of dipping beds. This may be recognized by positive density differences in the low density beds flanked by negative density differences in the relatively high density beds.

In some places in the world, large regional gravity anomalies exist which can produce local variations of the Free-air gradient. This is normally recognized as a constant density difference throughout the well. In these cases, it is necessary to establish the magnitude of this regional density difference before formation analysis work can be performed. The magnitude of these regional effects can be established by selecting either tight or water filled formations in which the density difference due to invasion should be zero.

Structural Modelling.

BHGM structural responses can be modelled relatively easily with graphical interactive modelling programs. A common situation is to model the BHGM response to a surface or downhole seismic interpretation and note any discrepancies with the BHGM field response. The interpreted structure is then modified until a fit is achieved to both seismic and gravity data.

Models are often constructed before a survey is run to determine if the BHGM response can resolve the expected range of structures. Pre-survey modelling provides templates which are used in rapid onsite interpretations. EDCON crews also have the capability of performing modelling on site.

A model is built in section view by creating polygons which extend normal to the section plane. The extent of the polygons normal to the section can be specified. Gravity response calculation points may be placed any where in the model.

The response is normally shown as a density, purely because this is a more intuitively useful quantity to most users than a gravity response. There are some arguments for modelling responses in gravity since the accuracy of the gravity measurements are higher than can be shown with normal density displays. The problem is that the Bouguer gravity measurements used in gravity modelling must be calculated using the gamma gamma density values and the BHGM gravity values. There is therefore no gain in accuracy using gravity modelling unless the application is independent of the gamma gamma density. One such application is time lapse monitoring of flood fronts.

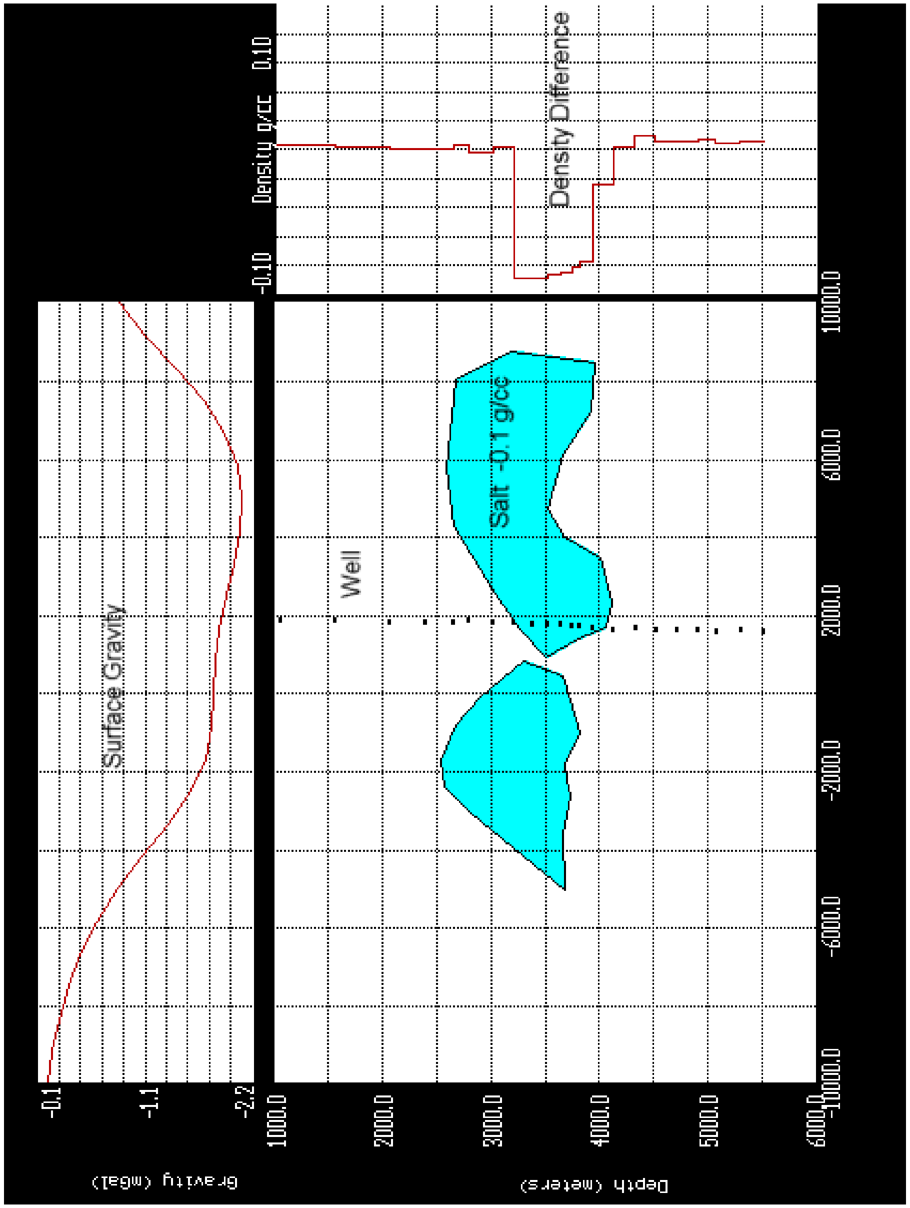
Salt structures are the most common structural targets for BHGM surveys. The most common questions concern distance to salt flanks and extent of overhangs. It must be emphasized that BHGM has very poor resolution of long continuous vertical flanks but horizontal extensions can be resolved.

Surveys run within salt have a large advantage over surveys run outside the salt structure. Within the salt, salt density is often uniform over large distances. Variations of the BHGM density from the salt density are direct reflections of the structure. Outside the salt the BHGM densities must be compared to gamma gamma densities which are subject to many disturbing influences.

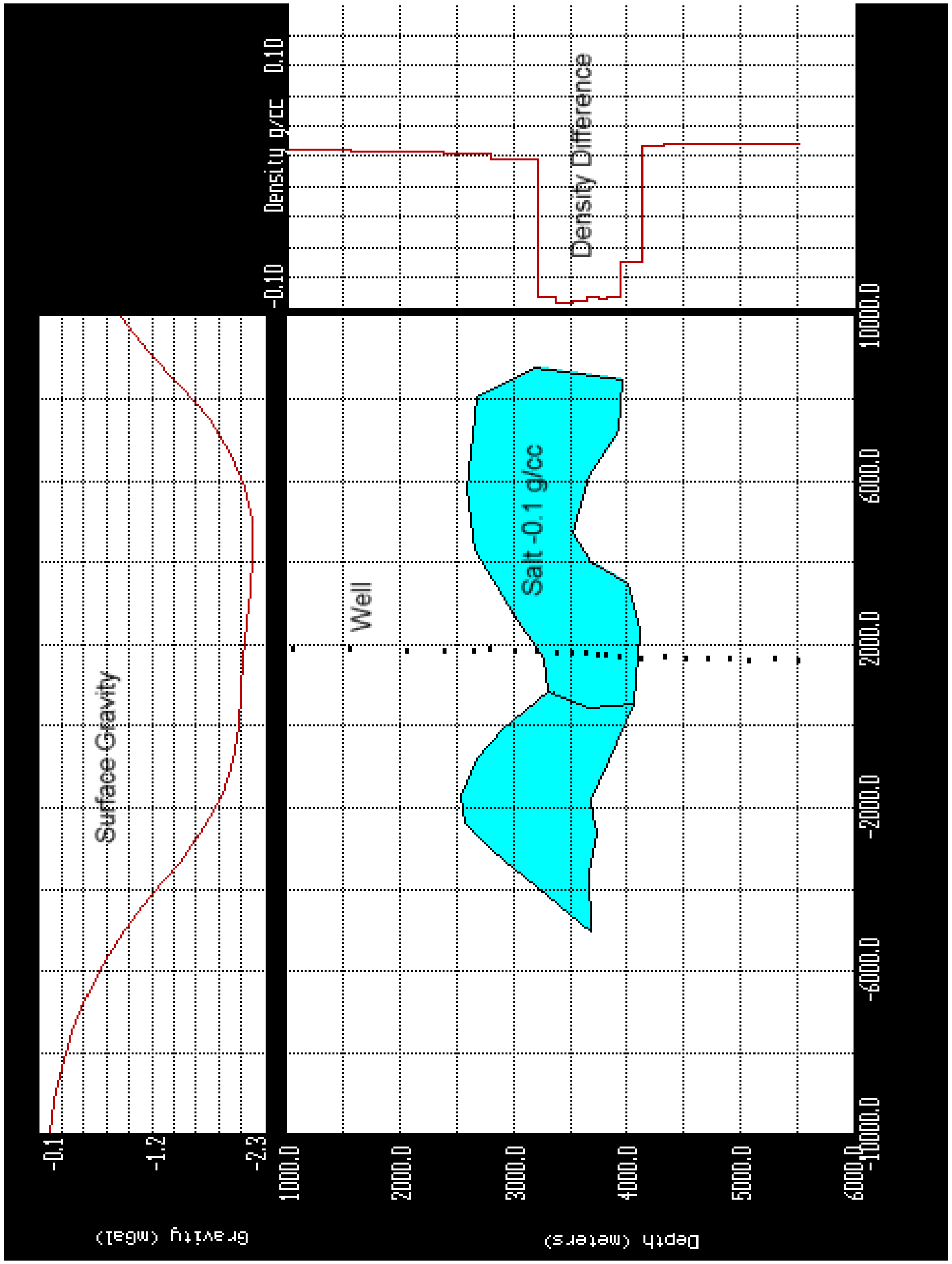
The next three figures show models through salt sills. The second model shows the two independent sills from the first model joined. The density difference response through the salt shows a sloping response in the first model compared to a vertical response for the second. The sloping response is due to the proximity of higher density sediments between the sills in the first model.

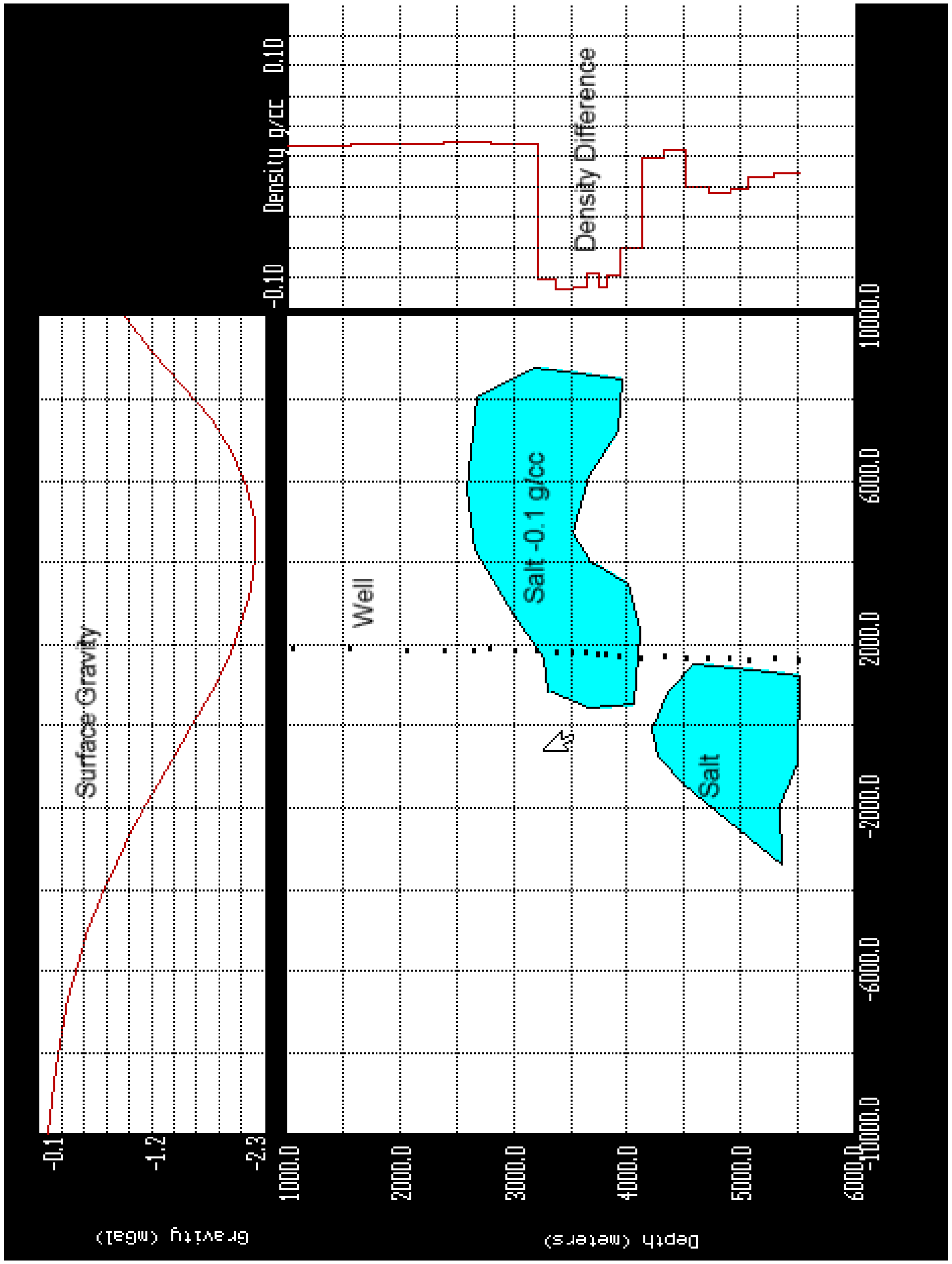
The third model shows a deeper sill with the well adjacent within the sediments. The presence of the salt is indicated by the negative excursion of the density difference curve opposite the salt.

Remote Structures 4.3



Remote Structures 4.4




Density g/cc
0.10
-0.10
Density Difference
Surface Gravity
Well
Salt -0.1 g/cc
Salt
-0.1
-1.2
-2.3
Gravity (mGal)
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
Depth (meters)
-10000.0
-6000.0
-2000.0
2000.0
6000.0
10000.0

5. The Borehole Gravity Meter

The borehole gravity meter is basically a sensitive spring balance in which the weight of a hinged beam with a mass on its free end is balanced by spring tension. As the gravitational acceleration and hence the weight of the beam changes, the tension of the spring must be changed to maintain the beam in a stationary horizontal position. The spring tension is controlled by a measuring screw. The gravitational acceleration is indicated by the number of turns of this screw. Figure 5.1 shows a simplified diagram of the meter element.

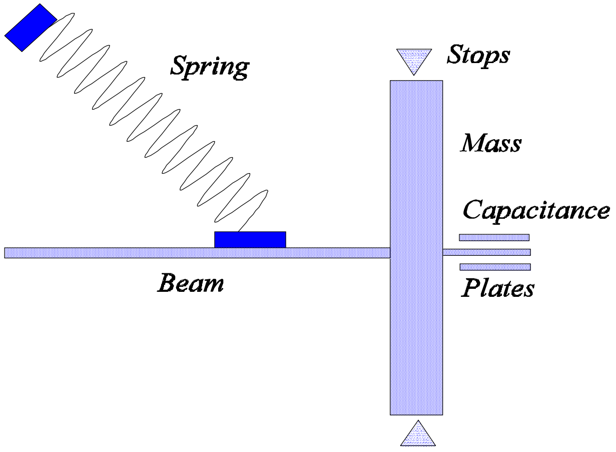


Figure 5.1

The meter has a mechanical clamping mechanism which immobilizes the beam for transportation and movement between gravity stations. To make a gravity reading in a well, the meter is first brought up hole to the desired depth and is then held stationary by the wireline. The meter is then levelled by rotating and tilting the element. When the element is level, the beam is unclamped and the measuring screw is adjusted until the beam balances at the horizontal position. The beam is then clamped and the tool is moved to the next station.

Most borehole gravity meters have a range of about 2500 Mgals corresponding to a certain range of latitudes. A few meters have world wide ranges.

The borehole environment imposes quite rigorous design requirements for a useful borehole gravity meter and consequently only two designs have been used operationally to this date. Vibrating string systems were developed by both Shell and Esso in the 1960's (1,2). A LaCoste and Romberg (L&R) borehole gravity meter was first field tested in 1966. This first meter and the two following it had a 5.5 inch outside diameter, an operating temperature of about 95 degrees C and a deviation limit of 7 degrees. The current borehole gravity meters were manufactured by LaCoste Romberg of Austin, Texas.

Borehole Gravity Field System.

The EDCON Borehole Gravity tools use identical sensors which are interchanged between different pressure housings to match particular hole conditions. The high temperature sondes contain Dewar flasks and fusible metal heat sinks for operations above the sensor thermostatting temperature. The CCL and natural gamma tools are used to locate the BHGM tool in the well with respect to previous logs.

Sonde	Maximum Pressure (PSI)	Maximum Temp. (^{o}F,^{o}C)	Outside Diameter (in./cm)	Length (ft/m)	Weight (lb/Kg)	Volume (ci/cc)
Large	20,000	400	5.25	11.17	472	2,789
High Temp.		204	13.34	3.40	215	45,695
Small	15,000	400	4.75	10.56	354	2,249
High Temp.		204	12.07	3.22	161	36,844
Large	12,000	230	4.125	8.15	158	1,743
Low Temp.		110	10.478	2.49	72	28,560
Shuttle	20,000	230	4.125	18.38	310	2,925
		110	10.478	5.60	141	47,935
Small	8,000	230	3.875	8.40	76	1,189
Low Temp.		110	9.843	2.56	39	19,478
High	20,000	400	3.625	3.04	64	351
Resolution		204	9.208	0.93	29	5,740
CCL Tool						
Gamma	20,000	400	3.625	5.71	112	760
Tool		204	9.208	1.74	51	12,460
Wall	20,000	400	4.000	5.58	150	

Lock	204	10.160	1.70	68

The large high temperature sonde may be operated at temperatures to 260 C with special O-ring seals. The immersion time will decrease with higher well temperatures.

Wireline Connections and Lines

All sondes connect to the wireline with a standard Schlumberger 10 conductor cable head with a coarse thread. When run below a Schlumberger telemetry tool, the BHGM tools connect to an AH-63 sub.

The BHGM tool wireline conductor usage varies with the tool :

When operating below a Schlumberger telemetry tool such as a natural gamma tool or a VSP tool, the BHGM system uses line 7 for FSK style bi-directional telemetry and takes power 200 VAC from lines 1 and 4.

When run without third party tools, the system uses lines 2, 3, 5 and 7 for 440 VAC power and serial telemetry.

These conductor assignments are not altered when the CCL and gamma systems are run above the BHGM sonde. When the wall-lock tool is run as the top tool of the string, 150 VDC power is supplied on conductor 1.

Downhole System

There are two modules housed in the gravity pressure sonde. The lower module contains the actual gravity sensor. The upper module contains most of the control electronics.

Gravity Sensor Module

The gravity sensor module contains the gravity meter element mounted in a gimbals system. The gimbals allow the sensor to be rotated and tilted with respect to the pressure sonde to make readings in deviated wells.

The gravity sensor is enclosed in insulating material to moderate temperature changes. A temperature sensor is attached to the outer wall of the sensor box inside the insulation. This sensor provides the MTemp telemetry value used to monitor the sensor temperature.

There are two pendulum type levels mounted on the bottom of the sensor. One of these levels swings parallel to the sensor beam and is called the long level. The other level is normal to the beam and is called the cross level. The voltage outputs

from these levels are known as the long and cross level (LL and CL) values.

The sensor is tilted along the beam axis and normal to the beam axis by the movement of supports along a worm screw. The position of the sensor supports along theses two worm screws are known as the long and cross positions (LP and CP).

There are two circuit boards below the meter sensor. The temperature control circuit board, in conjunction with the heater coils wrapped about the heater or element box, thermostats the sensor at a temperature near 120 °C. The capacitive position indicator circuit board, known as the "CPI" board, monitors the position of the sensor beam and the electronic levels.

The space above the gravity meter is mainly occupied by electric motors. Two of these motors are used to move the worm screws that tilt the sensor as described above. A third motor rotates the bottom 3/4 of the module with respect to the sonde. A fourth motor is used to adjust the sensor measuring screw and the fifth is used to operate the beam clamping mechanism.

Electronics Module

The electronics module contains several circuits with distinct functions:

The electronics power supply provides power to all other circuits. Power is also available for other tools which may be mounted above the gravity sonde.

The telemetry circuit accepts commands from the uphole system electronics. It also sends data to the uphole system.

The relay circuitry accepts the commands from uphole and activates the requested motors in the meter module. It also switches power and commands to the other tools mounted above the gravity sonde.

The A/D circuit converts analogue voltages indicating the gravity meter condition to digital signals for transmission uphole. It also converts selected circuit voltages as an aid to uphole quality control and remote electronic trouble shooting. Analogue signals from other tools are also converted.

The beam control circuit provides the electrostatic reading capability.

Uphole System

The uphole system consists of an uphole power supply with a telemetry interface, a depth encoder system and a personal computer. The computer controls the entire uphole and downhole electronic system. The uphole electronics module provides power to and data telemetry to and from the downhole system. The depth encoder accepts the data output from an optical encoder mounted on the wireline, converts this data for input to the computer where it is converted to wireline depth.

Gravity Meter Element

The gravity meter sensing element is housed in an aluminum box surrounded by a heater coil. Two electronic pendulum levels are attached to the bottom of this heater box.

The element mechanism (Figure 5.1) consists of hinged horizontal beam with a mass at its free end which is free to move up and down. Changes in gravity change the weight of the mass and vary the clockwise torque about the hinge. A spring is attached to the upper surface of the beam. A balancing counter clockwise torque is produced by adjusting the spring tension until the beam is nulled. This adjustment is made by turning a measuring screw which is connected by a linkage system to the top of the spring. The spring and measuring screw have been calibrated over known gravity ranges so that the position of the measuring screw when the beam is at level rest indicates the gravity reading.

A mechanical calibration table is supplied by LaCoste and Romberg with each meter. The calibration table for BHGM #10 is shown in the following table. It relates the measuring screw reading, or counter reading, to the equivalent relative gravity reading. The range of the meter is given as 0 to 2747.713 mGals. A counter reading of 0.0 corresponds to approximately 980,510 mGals on the International Gravity Standardization Net 1971 (IGSN 71). The absolute gravity range of BHGM #10 is from 980,510 to 983,257.7 mGals. As the spring ages its strength changes and the equivalent gravity range also changes. The meter calibration is checked bi-annually on a range in the mountains west of Denver.

Table 1

Counter Screw Calibration table for Borehole Gravity Meter #10.

Counter Reading	Gravity Reading	Counter Reading	Gravity Reading
0.000	0.000	1500.000	1370.769
50.000	45.730	1550.000	1416.509
100.000	91.447	1600.000	1462.252
150.000	137.152	1650.000	1507.999
200.000	182.848	1700.000	1553.749
250.000	228.535	1750.000	1599.500
300.000	274.217	1800.000	1645.254
350.000	319.895	1850.000	1691.009
400.000	365.572	1900.000	1736.767
450.000	411.246	1950.000	1782.527
500.000	456.919	2000.000	1828.288
550.000	502.591	2050.000	1874.050
600.000	548.263	2100.000	1919.814
650.000	593.936	2150.000	1965.578
700.000	639.608	2200.000	2011.343
750.000	685.282	2250.000	2057.107
800.000	730.956	2300.000	2102.870
850.000	776.632	2350.000	2148.630
900.000	822.309	2400.000	2194.388
950.000	867.989	2450.000	2240.143
1000.000	913.672	2500.000	2285.895
1050.000	959.359	2550.000	2331.643
1100.000	1005.051	2600.000	2377.384
1150.000	1050.746	2650.000	2423.118
1200.000	1096.447	2700.000	2468.844
1250.000	1142.153	2750.000	2514.560
1300.000	1187.864	2800.000	2560.265
1350.000	1233.582	2850.000	2605.956
1400.000	1279.305	2900.000	2651.630
1450.000	1325.035	2950.000	2697.288
		3000.000	2747.713

An individual gravity reading is obtained from the meter reading by extrapolating between the corresponding gravity readings. For example, a counter reading of 1657.234 corresponds to a relative gravity reading of 1514.618 mGal. This corresponds to an approximate absolute gravity reading of 982,024.62 mGal. An accurate absolute gravity reading cannot be obtained without tying the gravity reading to a network reading.

There are other auxiliary components of the system. An air damping system is provided by two opposed systems of canisters. The vertical and horizontal motion of the mass is restricted by mechanical stops. Two vertical arrestment rods clamp the beam to lower stops to minimize the effects of vibrations during transportation. The action of these rods ensures that the length of the spring while clamped is the same as the length of the spring in its reading position. A mechanical bladder is provided to balance the changing buoyancy of the mass if the air pressure inside the element box should change.

The position of the beam in a borehole gravity meter is monitored using a capacitance position indicator system (CPI). This consists of two capacitance plates placed above and below the beam and a capacitance plate on the beam itself. Square wave signals with a 90 degree phase shift are applied to the lower and upper plates. The signal detected by the beam plate is amplified and transformed to an analogue voltage, referred to as the beam signal.

The capacitance plates are also used to force the beam to the horizontal or reading line position. This is done by placing a DC voltage bias on either the upper or lower plate which electrostatically forces the beam up or down. The beam signal is the input to the Electrostatic Positioning Voltage, or EPV circuit, which compares the beam position with the known reading line position and places a DC voltage across the capacitance plates which will force the beam to the reading line.

In practice, the spring tension is adjusted to apply a net upward torque equivalent to between 0.1 and 1.4 mGals on the beam. The EPV circuit applies a DC voltage to the plates which automatically provides the correct electrostatic force to keep the beam horizontal. The spring calibration provides the equivalent gravity reading for the measuring screw position. The magnitude of the EPV signal must then be converted to a gravity value and subtracted from the spring tension derived gravity value to obtain the true gravity reading.

The advantage of the electrostatic system is that readings may be taken automatically in noisy environments. Any acceleration of the downhole tool will displace the beam from the reading line. This is instantaneously counteracted by the EPV system and the EPV value used in the gravity calculations is an average over a certain time interval.

The first stage of the EPV calibration is done using the measuring screw as a reference. The measuring screw is varied through a range which causes the cheat voltage to vary from zero to maximum amplitude. This range, expressed in equivalent mGals, is referred to as the dynamic range of the EPV system. The electrostatic calibration equation is of the form:

$$G_{EPV} = A.EPV + B.EPV^{2}$$

For comparison between meters, A and B are most usefully expressed in units of microgals / mVolt and microgals / mVolt^2. The following are the calibration factors for BHGM meters 8 and 10:

BHGM	A microgal / mVolt	B microgal /mVolt
8	-2.13 x 10^{-2}	22.2 x 10^{-6}
10	-1.76 x 10^{-2}	18.5 x 10^{-6}

It is possible to achieve a linear EPV voltage to gravity relationship. This is done by pulse modulating a constant DC voltage according to the beam offset from the reading line as opposed to simple amplitude modulation of the DC voltage.

At a pulse amplitude of 15 volts, BHGM #8 has a linear calibration factor of 0.311 microgal / mVolt.

The EPV calibration is further checked by recording solar lunar tides and comparing these to theoretical calculations. This is done over a period of several days. The counter position is changed during this calibration to ensure the complete EPV range is checked.

The electrostatic feedback reading methods allow digital sampling of the gravity several times per second. However, it is necessary to record over a number of minutes to obtain high accuracy readings. The length of the reading time is dictated by the hysteresis effect, the background noise level and the sample resolution.

The hysteresis or ooze effect is seen directly after the beam is unclamped. It is the recovery of spring strength due to the spring being slightly stretched when the beam is clamped for tool movement. The gravity reading will normally increase over a range of 3 to 20 microgals before assuming a constant level. The effect typically lasts for 2 to 5 minutes. The hysteresis duration and amplitude can be adjusted by adjusting the clamping movement of the beam.

Background noise occurs over a wide range of frequencies and amplitudes. It includes seismic noise and noise transmitted to the meter down the wireline cable. It is normally necessary to record over times corresponding to several periods of the dominant noise component and then use a digital filter. The dominant noise period in many wells is often in the range of 8 to 15 seconds.

The sample resolution is dictated by the digital word size output by the A/D converter used in the electronics module. An 8 bit word corresponding to a dynamic range of 1.4 mGals has a sample resolution of 5.5 microGals. This implies that 121 samples must be stacked to achieve a resolution of 0.5 microgals. A 12 bit word already has a .4 microgal resolution over a dynamic range of 1.4 mGals.

Gravity Readings

A BHGM gravity reading is made by balancing the beam in a horizontal position with a combination of spring tension and electrostatic force. An equation for this balance may be written as :

g = Spring tension - Electrostatic force + Tide Correction.

The spring tension and electrostatic force are derived from the position of the counter screw and the electrostatic positioning voltages respectively. Both are calibrated in terms of gravity equivalents.

Borehole Gravity Meter Settings

There are several essential settings required for accurate readings :

1. The sensor mechanism must be vertical in the cross level plane.

This position is found by first tilting the sensor normal to the beam until a maximum gravity reading is obtained. The corresponding cross level output is noted. This is also the position least subject to gravity errors due to small cross level tilt errors. The Cross Level is angle β in Figure 5.2.

2. The long level and reading line settings must be optimized.

The position of the beam in Figure 5.2 in the XZ plane with respect to the OX axis is known as the reading line. The meter is read with the beam in a horizontal position. At this position, gravity varies least for a change in the long level angle.

The long level angle is the angle between vertical and a line passing through the upper spring support and the beam hinge. This is angle α in Figure 5.2. At the correct long level value, a displacement of the beam from the reading line will not result in a mechanical restoring or displacing force, ie. the beam exhibits neutral static stability. This position is also called the position of infinite sensitivity.

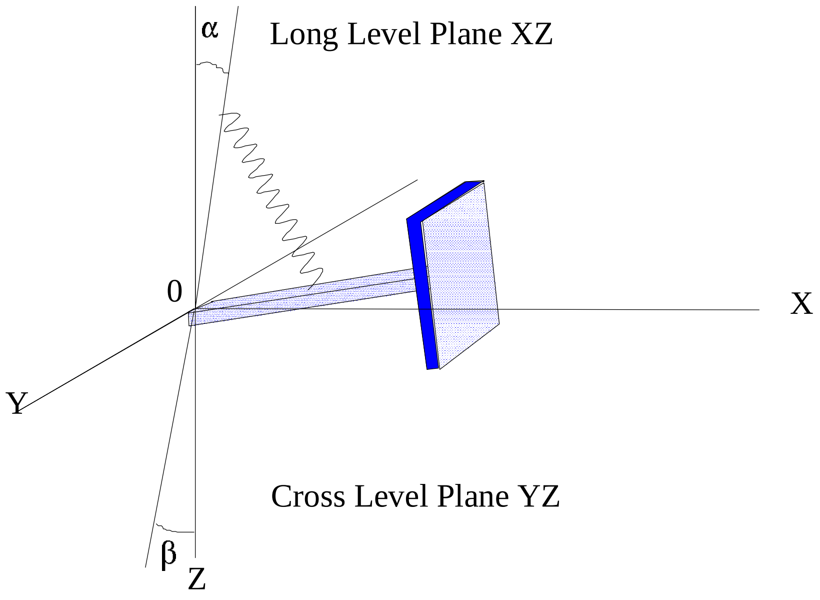


Figure 5.2

The reading line remains constant over time unless there are changes to the internal mechanical system. The long and cross level settings as read by the system electronics are subject to variations in the mechanical attachment of the levels to the sensor box caused by transportation shock. The long and cross level settings are always checked in the well before starting a survey.

The sensitivity of the levels must also be adjusted to enable gravity readings to be made with the required accuracy. The level sensitivity of 5 arc seconds corresponds to 0.5 microGals.

Temperature Control

The operating temperature of the meter mechanism must be kept constant to prevent variations in the spring strength. The mechanical design of the sensor produces a gravity reading minimum with varying temperature. At this gravity reading minimum, the gravity reading is least prone to temperature variation errors. The sensor is therefore thermostatted at this minimum gravity reading producing temperature which is commonly known as the "nose" temperature.

It is important that the temperature control system be able to maintain the temperature at the nose with changing external temperatures. A system is used which relies on insulating material placed around the sensor and measurement of the sensor temperature and the temperature just outside the insulation. The system is tested by making gravity readings while heating the gravity meter and electronic modules within an oven. The oven temperature is typically raised from about 20ºC up to 110ºC. The variation of gravity reading with temperature change is adjusted to be less than 1 microGal / degree C.

The temperature of the meter mechanism may also vary if it is tilted to make a reading in a deviated well. The temperature control circuit also ensures that the effect of this source of temperature change is minimal.

Uphole System

The Uphole system consists of a PC computer, a telemetry interface, a power supply and a depth system..

Power Supply.

Both EDCON power supplies operate on input power of 110 VAC or 240 VAC.

The standard system supplies 440 VAC downhole.

The shuttle system supplies 270 VDC to the downhole electronics.

When the BHGM is operated below a Schlumberger telemetry tool such as the CSAT downhole seismic tool, power is supplied from the Schlumberger downhole tool as 220 VAC on lines 1 and 4.

Both AC and DC power supplies incorporate the uphole telemetry interface electronics.

Depth System

A quadrature decoder pc board installed in the PC accepts the depth signals from the wireline truck optical encoders installed at the rear of the truck. The depth signals are used to drive the gamma and CCL recording software in the EDCON PC. The display of the depth on the PC is to 3 decimal places which is normally higher than the display resolution of the wireline truck software.

The signal from the optical encoders is split off from the wireline truck signal so the same signal is used by EDCON and the wireline truck depth displays.

Borehole Gravity Meter Software.

There are five separate, data compatible software programs written by EDCON to acquire, process, display and interpret BHGM data.

Data Acquisition Software

The data acquisition program (B7.EXE), controls and accepts data from the downhole gravity meter, gamma and CCL tools. It also accepts depth signals from the wireline truck optical depth encoders via a quadrature decoder board in the PC backplane.

The computer communicates with the gravity meter via 8 bit serial telemetry at a 2400 baud transmission rate. 14 distinct signals are received from the gravity meter and commands can be sent to 5 downhole motors. Data is sampled at 8 samples per second, enabling high resolution CCL data collection and efficient control of critical motor functions from up hole. This rate is higher than needed for the gravity signal so 8 EPV samples are averaged to give a 1 second EPV sample which is recorded to disk.

The system is designed to operate manually or automatically. The manual control setting allows the operator to drive any of the downhole motors. This is required in some test situations or some survey situations which the automatic system has difficulty handling efficiently. In automatic mode the gravity meter levels and records data automatically. Batch programs can also be executed by the B7 program to perform unattended gravity meter tests.

Solar lunar tides are calculated in real time and recorded along with the EPV samples.

Data storage format.

The data is stored in ASCII format on a floppy disc. The data records made at each station consist of a header and a record. The header contains all information which does not change during the recording. This includes the station depth, counter reading, temperature, date, cross level position, long level position, rotation position and the record start time. The record start time is the time at which a signal generated by the beam arrestment mechanism shows the beam is first unclamped. The record contains the information which changes over the reading time. This includes the EPV voltage, TCG or Tide Corrected Gravity, the cross and long level readings and the sensor temperature. At the end of each record an average TCG value is recorded.

Gamma and CCL Recording.

The gamma and CCL recording is performed within the data acquisition program. The data is written to a separate file. The operator will normally record gamma and CCL when the tool is moved to a new station during depth critical surveys. Casing collar positions allow the depth to be checked to better than 1" resolution.

Data Reduction Software.

The field data files is read into the data reduction program (R7.EXE) which outputs final gravity and BHGM density values. R7 outputs several files.

The reading file (*.RDG) contains a summary of each gravity recording showing all the gravity meter settings, the depth, the tide correction, temperatures and record noise statistics.

The reduction file (*.RED) displays the drift correction processing and the repeat statistics of the gravity readings and the final density values.

The density file (*.DEN) contains the final drift corrected density values which can be input to the log display and reduction programs.

Log Display Software

The display software (G7.EXE) displays well logs on screen in the field allowing checks of depth ties and comparisons of different logs. The log scale is unrestricted allowing very small details to be shown. Logs can also be printed to a number of different printers as single page displays or to continuous feed printers at normal well log scales. G7 also accepts the BHGM density data files (*.DEN) from the data reduction program, R7.

Interpretation Software

There are two interpretation software packages. The first is a 2.5 dimensional structural modelling package which is described in Section 4 of this manual. The second is a well log interpretation package that performs standard well logging calculations for porosity and water saturation determinations.

Gravity Meter Testing

When a borehole gravity survey is planned, it is normally possible to define a specific survey objective. To fulfill the survey objective, a survey plan should be specified which includes the required depth sample spacing and the corresponding accuracy of the gravity measurements. It is necessary to ensure that the gravity meter system is capable of achieving these accuracy levels in the survey environment before undertaking the survey. The following items are routinely checked before mobilizing the tool.

Well deviation capability.

The gravity reading must not vary significantly with deviation. This may be checked in the laboratory by making gravity readings with the meter module vertical and tilted. The temperature control circuitry should be adjusted so the gravity reading will vary by less than less that 1 microGal for each degree of meter module deviation.

Well temperature sensitivity.

A gravity meter is exposed to extreme temperature variations during the course of a survey. Survey readings may be made at meter module temperatures ranging from below 0 degrees Celsius to 120 degrees Celsius. The gravity meter should be exposed to the expected temperature range in a laboratory oven to ensure that a variation of less than a microGal occurs for each degree Celsius change in temperature.

A rapid change of temperature is likely to momentarily change the temperature of the meter from the nose temperature. The time taken for the system to reestablish the nose temperature should be minimized. If a sufficiently short stabilization time cannot be achieved, the survey should be run using the Dewar system.

Sensitivity to Magnetic Fields.

The spring of the gravity meter is very slightly magnetic. Small bar magnets are attached to the beam by the manufacturer to compensate for this. The meter and electronic modules are also surrounded by Mu-metal shrouds. The casing in a well may be accidentally or deliberately magnetized. If the magnetic field produced by the casing is larger than the natural magnetic field, the gravity reading will be disturbed. This situation may be recognized in the well by taking readings with the meter oriented to different directions. A magnetized casing will cause the gravity reading to change with the meter's orientation to the magnetic field.

This effect may be minimized by performing a magnetization check in the laboratory. The variation in gravity reading with orientation to the natural magnetic field of less than ten microGals should be seen.

Background Noise.

Background noise can be grouped into noises due to cable motion, seismic energy and noises with sources in the well itself. They may be impulsive or continuous. The degree to which they affect the gravity reading accuracy depends upon their frequency and amplitude.

The gravity meter and certain parts of the electronic circuits act as low pass filters. Since the EPV voltage is digitally recorded over time, a digital record of instantaneous tide corrected gravity with noise superimposed is recorded. Digital filters may be applied to the recorded data. Noise spikes can be removed as long as there is sufficient time between the spikes to allow undisturbed data to be recorded.

The system cannot record if the amplitude of the noise is larger than the dynamic range of the system. This dynamic range can be adjusted by varying the maximum cheat voltage used and the range of the digitizer. The EPV voltage cannot be increased beyond a certain level at which the system becomes unstable. The dynamic range of the instrument should be optimized for reading accuracy under the expected survey noise levels. In severe noise conditions such as in shallow wells and surveys run from offshore floating platforms, a wall lock device should be used to prevent cable noise.

Shuttle System

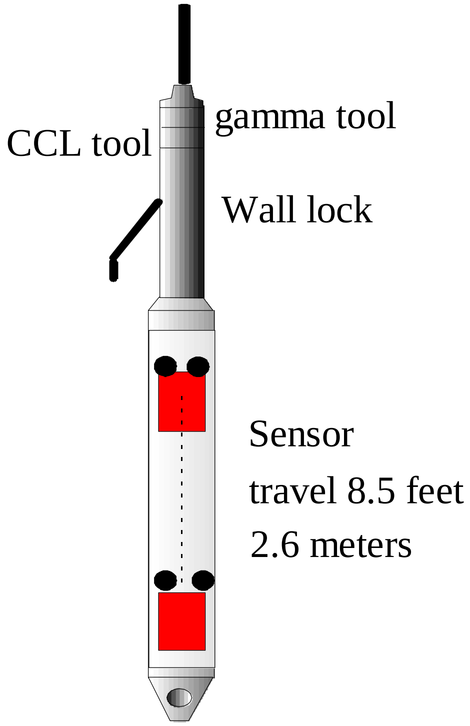


Figure 5.3 Shuttle System diagram

The shuttle system provides more accurate BHGM densities over short vertical intervals by eliminating errors in depth difference measurements. It is particularly suited to the following applications :

1. Investigating bypassed production in thin beds.

In many older wells, many potentially productive zones may have been bypassed in favor of the main producing zone. As the main zone is depleted, fluid saturation information is sought for the bypassed zones which are now behind casing. In a shaley sand sequence, the bypassed zones can normally be located by gamma or self potential logs run open hole when the well was originally drilled.

The shuttle system is moved from below the zone of interest logging with the gamma and CCL tools. The string is stopped when the gravity sensor is at the top of the zone of interest. The gamma trace made while the string is moving shows the exact boundaries of the zone. The gravity sensor is then moved with the internal winch to the exact zone boundaries recorded by the gamma system a moment earlier.

2. Monitoring fluid saturations or fluid interface movements in thin bedded reservoirs.

This application normally requires the tool to return to the same location in a well several months or years after the first log. The EDCON high resolution CCL tool provides a means of relocating the tool within 0.5 inches or 1 cm according to nearby casing collars. In one case, the tool string has been stopped at particular locations by locking into small gaps in between casing pup joints. (Alixant & Mann, 1995).

The gravity sensor is raised and lowered with a high tensile strength cable wound on a winch which is driven by a stepper motor. The actual position of the sensor within the pressure housing is given by the optical encoders attached to the sensor package. These encoders measure the rotation of wheels pressed against the inside of the pressure housing. The resolution of this internal depth system is better than ± 1 mm. This is much better than can be achieved using a surface depth measuring system.

6. BHGM Survey Planning and Operations

Introduction.

The manner in which a borehole gravity survey is undertaken will dictate the operational economics and the ultimate data quality and usefulness. The planning stage of the survey should identify potential problems before mobilization. The preparation of the gravity meter before the survey and rigorous attention to depth control during the survey will ensure good data quality.

Sequence of events:

a. A theoretical study of the expected benefits of running borehole gravity is made and station spacings are defined.

b. The practical aspects of running the tool are investigated.

c. The operational aspects of mobilization and demobilization are planned.

d. The survey crew is notified of the survey time, well characteristics and the need for any particular acquisition and processing requirements.

e. The crew mobilizes to arrive at the well site ready to survey at the time advised by the client company.

f. The crew rigs up and is ready to commence the survey immediately when the preceding work or survey in the well is finished.

g. The survey is made paying particular attention to quality control and well safety. The client representative is kept informed of the survey progress, expected survey duration and any unusual features affecting data quality.

h. The gravity tool is removed from the well and rigged down in an efficient and safe manner.

i. The survey data is processed and a preliminary data and logistics report is prepared for the client in case immediate well testing is required.

j. The crew demobilizes.

k. The final data report is produced. A detailed interpretation is made if required.

Survey Planning.

Geologic Objectives.

The study of the well geology will dictate the needed station spacing for the survey objective. This will indicate the required gravity reading accuracies and the sequence in which the stations should be occupied. Small station spacings will require longer reading times and possible repeat occupations to gain sufficient accuracy and define the gravity meter drift.

The planning of a BHGM survey starts with a concept of what information is needed, proceeds through a consideration of the measurement resolution for the existing conditions and ends with a listing of station locations and the number of readings to be made at each.

For example, if the position of a gas water interface behind casing is needed, a method is first required to distinguish between gas and water. One method is to combine the BHGM density through casing with the open hole gamma-gamma density and neutron porosity information. The open hole log combination will allow a density, matrix density log to be established. This information, combined with the BHGM density allows fluid density or water saturation value to be calculated over each BHGM interval.

The errors involved in this calculation must then be evaluated. These will be influenced by the error level in the open hole porosity information and the BHGM density. The BHGM density error will vary according to the gravity reading and depth interval measurement accuracies. See section 1 of this manual for error calculations. The gravity reading accuracy will be dictated by the well conditions, ie. the ambient noise level which may be expected to be much higher at shallow depths and offshore in stormy weather.

Estimating a reasonable gravity reading and depth interval error level will allow the error in the calculated fluid density as a function of reading interval to be calculated and preferably graphed. The maximum acceptable error in calculated water saturation can then be associated with a gravity station spacing. If this station spacing is too coarse, means of reducing the primary error levels must be sort for the survey to be of use. The gravity reading error levels can be lowered by taking repeat measurements. The depth interval error level can be lowered by running with the Shuttle System.

Once the station spacing and number of readings per station has been established, the existing logs, if available, should be examined to establish optimum station positions. If one is attempting to find the gas water contact in a shale sand sequence, it does not make sense placing stations at even intervals since station pairs straddling sand layers make best use of the methods accuracy.

At this stage, the number of readings to be collected during the survey can be established and an estimate can be made of the survey duration. The cost of the survey can also be estimated with reasonable accuracy at this point.

In the case of time lapse survey applications, care must be given to planning the absolute depth establishment method.

Practical survey aspects.

It must first be established whether the tool can fit in the hole.

The 5.25 inch high temperature sonde will fit in clean 7 inch casing. It may become stuck if this casing has not been well cleaned out after a cementing job.

The 4.125 inch low temperature sonde will just fit in a 5.5 inch casing. Again if this is not cleaned out, the tool risks becoming stuck at some depths with a subsequent loss of depth control accuracy.

If the casing planned will be too narrow for the tool, it may be possible to run the tool in open hole. In some cases this can be advantageous as the depth control is better when the tool moves more freely.

The highest deviation normally possible is about 14 degrees. The tool may be lowered through a hole with higher deviations so long as the well is deviated at less than 14 degrees in the survey region. The tool deviation depends upon the amount of insulation placed around the meter element. If a high deviation survey is planned the survey contractor should be informed ahead of time so the actual deviation capability can be checked for the survey tool.

It is impractical to have a wireline cable devoted to borehole gravity operations given the present scattered locations of the surveys. The tool must be matched up to the most convenient local wireline cable. A standard 7 conductor cable is used although the gravity meter, natural gamma tool and CCL combination can be run using only 4 conductors. The EDCON tool is configured to be compatible with the standard Schlumberger ten pin cable head with a coarse thread.

The well temperature at the survey depth dictates the sonde which can be used as shown by the table in the Gravity Meter chapter of this manual. The high temperature tool has the added benefit of effectively insulating the gravity meter from temperature changes outside the pressure sonde. Surveys can thereby be made in wells with unusually high temperature gradients without loss of accuracy. For example, the rapid temperature change across the water air interface in a well during a winter survey can produce large drift effects when the low temperature sonde is used but does not affect the meter in the high temperature sonde.

Highly magnetic casing is not normal but its effect has been seen in about one percent of the wells surveyed with the borehole gravity meter. One effect of magnetized casing on the data can be to cause small local inaccuracies which can be identified by making readings at different azimuths. Another effect is to permanently magnetize the gravity meter spring so strongly that it must be returned to the manufacturer to be demagnetized. There are some well tools which deliberately magnetize the casing, for example to ensure that the well can be located from a relief well in the case of loss of control. The gravity meter should not be run after these tools.

When the wireline cable supporting the meter moves, the gravity meter is accelerated. This acceleration adds to the gravitational acceleration acting on the meter beam producing a noisy signal. This type of noise may be filtered if it is of sufficiently low amplitude or of sufficiently high frequency.

There are several sources of cable noise. Some are due to ground surface sources while others are generated down hole. The amplitude of the surface generated noises decrease with depth due to the weight of the wireline and tool in the hole and the elasticity of the cable. A heavy tool and a stretchy cable are helpful when surveying with surface generated noise. A stretchy cable is a compromise since it is not good for accurate downhole depth control and checks must be run with a gamma or CCL tool continually.

Some well situations are inherently noisy and high accuracy surveys will be difficult to obtain in them. Offshore floating platforms are naturally noisier than jack up platforms. Numerous successful surveys have been made from floating platforms in sea states up to force 5. The wireline cable and gravity tool act like a damped spring and the motion of the rig transmitted to the cable at the surface diminishes in amplitude with increasing depth, tool and cable weight and decreasing Young's modulus of the cable. In certain sea states there will be a cut off depth above which it is not possible to make gravity readings without clamping the tool to the inside of the casing. At force 4 sea state that depth appears to be about 7000 to 10000 feet. At this level the peak to peak noise amplitude of the vertical tool acceleration exceeds the dynamic range of the recording system which is normally set between 1.7 to 5 mGals. Tests on clamping systems do show a decrease in noise, but this may only allow another 500 to 1000 feet to be surveyed. The motions of the floating platforms are also different depending upon the prevailing direction of the sea. Some survey locations and the depths at which gravity readings have been obtained from floating platforms are:

1. Mediterranean offshore Spain 8,000 feet calm seas

2. Gulf of Mexico 18,000 feet to 6,000 feet Sea state 3

3. Navarin Basin 12,000 to 7,000 feet Sea state 4 to 5.

4. Enewetak atoll lagoon drill ship 250 to 80 feet casing clamp used.

Offshore platform crews tend to hyper-activity when a borehole gravity survey is in progress. Heavy equipment is loaded and unloaded from supply vessels. Large sections of deck have been cut and moved from one side of the rig to another. These activities can sometimes cause jolts and changes in the elevation of the rig at inopportune times, thus prolonging surveys. Good communication between the rig engineers and the survey personnel can save rig time in these situations.

Jack up platforms are not very different from land rigs for the gravity meter operation except when the survey is extremely close to the surface. A tall Jack up in deep water may move a little in heavy seas and certain machinery noise is essential for rig safety. In one exceptional case in the Gulf of Suez, gravity readings were made in the riser pipe of an unoccupied jack-up platform with the wireline unit located on an adjacent barge.

A common source of noise when the tool is shallow is wind moving the wireline cable at the surface where it is stretched from the wireline truck through the sheave wheels to the top of the well. This may be minimized by suspending the gravity meter from the actual rig floor and slacking off on the cable from the rig floor to the wireline truck. Closing the rams in a cable blow out preventer is an effective way to do this.

The noise from machinery operating on the rig floor may be minimized by shutting down inessential machinery.

There are also some downhole sources of noise. In a deep hole, the wireline cable often twists after the tool has been lowered to the bottom. This is a result of the cable being coiled at the surface. If the well is deviated, the gravity meter levels must be continuously adjusted as the tool rotates. This effect eventually stops after a time period dependent upon the cable condition and the tool depth. It is an irritation that should be allowed for, but it is not a survey threatening effect.

If a heavy viscous mud is used in a deep well, care should be exercised not to move the tool up too fast in narrow holes as this may lower the well pressure immediately beneath the tool. The tool will also continue to move downhole in this situation after the winch has stopped at the surface since the cable has been stretched. It may take up to ten minutes for the tool to come to rest during which time irregular vertical accelerations occur and it may be impossible to make a reading. This can be avoided by pulling the tool about an inch past the required station depth and then lowering to the station depth. This removes considerable cable tension allowing a reading to be made almost immediately after the winch stops at the surface.

Gas bubbles produced by the formation will rock the tool as they pass by it. These are normally seen as periodic noise spikes. In the situation where the tool is hanging in a severely washed out zone and the formation is producing gas, the tool may be buffeted to produce considerable continuous noise.

In some situations liquids may be produced into the well. Open fractures are mostly responsible in these situations. When the tool is directly beside the source of the produced liquid, continual noise is seen. Above and below the source quiet readings are virtually always possible. In one situation, ten barrels of sea water per minute were being pumped into a formation to keep it from producing while a gravity survey was in progress. Opposite the fractures where the sea water was entering the formation, readings were extremely noisy. They were free of noise immediately above and below these fractures.

If the well is over-pressured, the survey will probably have to be run through a lubricator or, in some extreme cases, the tool may have to be pumped down the hole. It should be ensured that the necessary safety equipment is available for these wells to fit the gravity meter sonde.

Most borehole gravity meters have a limited range of latitudes at which they can read. The latest meters have a larger measuring screw and can be read all over the earth. The limited range meters can be range adjusted by adding or subtracting weight from the beam mass. This is only done by the manufacturer and normally occupies 2 to 3 weeks. If a planned survey is at an unusually high or low latitude it is wise to check that a borehole gravity meter is available for that latitude some time in advance.

Survey Operations.

Mobilization.

Present borehole gravity operations are based in Denver. Occasionally a set of equipment is based in Europe for several months at a stretch. Most surveys therefore involve non trivial mobilization and demobilization planning.

It is best to inform the contractor of the possibility of a survey at least two weeks ahead of the survey date and preferably more when international shipping is involved. The contractor can then accept the responsibility of ensuring that the equipment is prepared and can be mobilized on time. If scheduling conflicts exist, they can be discussed so all parties are aware of the possible conflicts and alternatives. The mobilization time should be determined so the final request to mobilize can be given to ensure that the crew and equipment is ready at the well site on time without wasted standby days.

The simplest mobilization case is when the crew with equipment can drive from their present location to the drill site. The operation becomes progressively more complex when airfreight, customs clearances and transportation offshore or to remote sites is involved. Normal customs clearances take one to two days. Customs clearances into certain countries and the necessary export licenses and visas can take several weeks to arrange.

It is always possible that the logging equipment will receive a substantial shock during shipment to the well site. It is therefore prudent to allow the crew a day before the survey is run to check the equipment before logging.

The gravity meter itself is always hand carried by the survey crew. This insures that there are no physical shocks and that the meter is kept at the thermostatting temperature for as long before the survey as possible. It also allows the crew to check the gravity meter operation without the heavy equipment which is shipped separately.

Upon arriving at the rig site it is important for the crew to meet with the engineer in charge of the rig and discuss the survey requirements and any limitations imposed by the well condition. .

The crew should ensure that there will be no well delays before the survey start due to long rig up times or equipment malfunctions.

The survey plan must be discussed to be sure that it is safe to use the tool at the proposed survey depths considering the conditions in the well. It may be advisable to run a gauge ring or a wiper trip may be required if cementing operations have left the internal diameter of the well diminished. The location of plugs and packers should be noted.

A very heavy viscous mud will slow the survey and decrease the accuracy of the gravity and depth measurements. Some muds may start to solidify if the survey time is long. If it is possible to substitute a lighter mud given the well pressure constraints, a better survey will be obtained.

The location of any potential bridging zones should be noted and time below those zones minimized. Survey time in open hole in zones which are potentially productive should also be minimized within the constraints of the survey plan.

Well deviation.

Often the survey will be run in a section of the well which has just been drilled. The well deviation survey should be obtained to enable the data to be corrected and to ensure that the planned survey is still possible.

Rig Up

The rig up should be made so that the gravity tool is ready to be placed into the well with as little rig delay as possible. This normally means that the rig up should start about an hour and a half before the expected survey time. If drill pipe is being lowered from the drill floor to the cat walk immediately before the survey, it will not be safe to commence some aspects of the rig up until that activity has stopped.

It will often prove useful to read the gravity meter on the ground close to the drill hole immediately before and after the survey. This can assist with drift calculations and can be used to tie the borehole gravity and surface gravity surveys together. It is important to keep the gravity meter powered up with as little interruption as possible before the survey. This will avoid drift problems due to temperature fluctuations.

Borehole Gravity Survey.

At the start of the survey, it is important to make a surface depth tie and to ensure that the tools are all functioning. The gravity meter is checked when making the surface measurement and after tightening the tool together. It is important to check that the telemetry is working in both directions and that the thermostatting circuitry is functioning. The thermostatting circuit will draw a higher current immediately after the gravity meter is turned on in the sonde as it warms up after being disconnected. After it has reached the thermostatting temperature, the current supplied to the meter will decrease. It is useful to note what that current level is. Fluctuations in the current supplied to the tool may indicate problems elsewhere in the system and should not be ignored. For example, the most catastrophic failure will occur if the pressure sonde somehow lets fluid into the sonde. An immediate increase in the current would result due to short circuiting of the downhole instruments.

The gamma and CCL tools can be checked on the cat walk before they are moved to the rig floor. A metallic mass should be moved beside the CCL tool and a small gamma radiation source such as Cs 137 may be moved near the gamma crystal. If the gamma data is to be used for anything apart from depth ties, the calibration should be checked by placing the gamma source at predetermined distances which produce certain standard API radiation levels.

Depth control.

It should be established before rig up which of the previously run logs will be used as a depth tie for the survey. The reference elevation for that log must also be known. This will normally be the rig floor or ground level. If a work over rig is being used instead of the original rig an allowance should be made.

It is generally most convenient if all the different tool traces are displayed at the depth of the gravity meter element. This helps avoid painful and error prone adjustments to determine actual tool depths. The distances between the gravity meter element and the other tool sensing positions must be known. These may have to be measured when the tool is on the cat walk if the tool configuration has been changed from that which is normally run.

The wireline odometer should be set to zero when the gravity meter element is level with the reference elevation. It is important that this odometer is working well.

The tool is then lowered to a position about 50 meters below a locatable gamma or CCL feature near to the survey start depth. This ensures that the cable tension during the depth tie will be similar to the tension when the survey is run. A short gamma and CCL survey is performed across the locatable feature and the odometer depth is adjusted so that the depth of the locatable feature is the same on the reference log and on the tie in log just run. This should be rechecked by at least one more logging pass. Note that the wireline odometer will often be shallow by two or three meters after travelling downhole 3000 meters.

When the depth tie has been made, the tool should be placed at least 30 meters below the first station location and then pulled up to the station depth. The pre survey checks should then be run.

These checks should include a cross and long level check and a drift check. The cross and long level checks are described in the gravity meter section of this manual. The drift check allows the operator to see when the gravity meter drift rate has slowed down to an acceptable level for the survey to start. An acceptable level is generally under +/-1 microGal per minute. When the drift rate is acceptable, the survey reading at the first station can be made.

The order in which the survey stations are occupied will depend upon the accuracy desired. If the survey plan requires stations every 500 meters from TD to surface, it is not worth while repeating readings at stations to calculate drift rates. This is because the accuracy with which the depth of the station can be repeated will be poor after travelling at least 1000 meters and the densities calculated without drift rates will be of sufficiently high accuracy unless something extraordinary has happened to the meter. It is sufficient to obtain an estimate of the drift rate while reading each station in this situation.

If the survey is over an isolated zone in the well with close stations, it may be advisable to loop back to the start of the zone for a drift closure or to repeat several stations to obtain repeat statistics taking actual depth variations into account.

Quality control while the survey is in progress can be effected by monitoring the gravity meter drift rates and comparing the calculated borehole gravity densities to other sources of density information. If the gravity meter drift remains within reasonable limits, such as +/- 1 microGal per minute, the calculated densities will be reliable. Abnormal densities may require more stations to define the geologic source.

Depth control should be checked regularly. One method of doing this is to run the gamma and CCL tools between gravity stations. After arriving at the station according to the odometer, the correspondence with the reference log should be checked. If this is in error, the odometer should be corrected and the correction made noted for use in data processing. It is not advisable to make repeated up and down trips to run repeated gamma surveys since this has the effect of drastically changing the cable tension.

The speeds at which the wireline moves should be as slow as reasonable and stops and starts should be made without jerks. This will help to prevent depth accuracy problems. When first moving into or out of the well speeds up to 10,000 feet per hour are reasonable in unimpeded casing. The speed should be decreased when moving into narrower casings or in open hole. When moving between stations that are within 6 meters, the speed should not rise above 10 feet per minute. 20 feet per minute is an appropriate speed for longer moves. When approaching a station, it is necessary to progressively lower the speed so the winch can be stopped smoothly exactly at the depth required. The lowest winch gear must be used for this. The gravity survey data quality will often indicate the time intervals during which a smooth or rough wireline operator was driving the winch. *A careless winch operator can mean the difference between excellent and useless data.*

When the tool stops at a station, it is worthwhile marking the cable at a position adjacent to some solid object so the position of the mark can be measured to an accuracy of half a centimeter. When a station is reoccupied, the distance from the original mark should be noted. In high accuracy surveys, it is normal to measure out the station distances and mark the cable ahead of the gravity readings. This method is often more reliable than the odometer readings by themselves.

Copious notes should be made of anything that may affect the survey. Times should be included to allow events to be checked against the data. Any changes to the odometer setting, such as the wireline truck engineer adjusting the odometer with the adjustment wheel while moving between stations should be noted. Changes in travel direction should also be noted.

The odometer depth should be rechecked at the end of the survey by again placing the gravity meter level with the reference elevation. A gravity reading at this point or level with ground surface can also be useful.

The engineer in charge of the rig should be kept informed of the survey progress at regular intervals. A conservative estimate of the survey finish time should be given and updated as needed. If an optimistic estimate of the survey end time is given, there will often be rig crew personnel waiting who will drive machinery and produce noise when the need to reduce noise is greatest.

Rig Down

The survey rig down operations should be conducted as quickly and safely as possible. It is useful to repeat the surface gravity reading to get an overall drift for the survey. The time the meter is disconnected should be minimized to prevent temperature drift.

A preliminary data report should be prepared for the client within a reasonable period from the survey end. This should include copies of the survey notes and raw data and a preliminary listing of the borehole gravity densities. Well logs of the borehole gravity densities may also be needed in many cases.

Demobilization.

Most of the potential problems involved in demobilizing the equipment will already have been dealt with during the mobilization stage. In some cases the

equipment can only be moved by the client company from a remote or offshore site. The point where the client hands the responsibility for the equipment over to the contractor should be established before demobilization. A fast operation here minimizes survey costs and ensures the availability of the equipment for the next survey.

Summary.

Borehole gravity operations have been made in a wide variety of wells in many different onshore and offshore locations. It is possible to predict the likely well environment for the gravity meter ahead of the survey allowing potential problems to be avoided. The survey itself should be conducted in a safe and efficient manner with particular attention accorded to depth control and gravity meter drift. Good survey notes are extremely useful during subsequent data reduction and good communications must be maintained between the survey crew and the engineers responsible for the rig operations.

References

Adams, S.J.:"Gas Saturation Monitoring in North Oman Using a Borehole Gravimeter", SPE paper 21414 presented at the 1991 Middle East Oil Show, Bahrain, November 16-19.

Alixant, JL, and Mann, E.: "In-Situ Residual Oil Saturation to Gas from Time-Lapse Borehole Gravity", SPE paper 30639, proceedings of the 1995 Annual Technical Conference and Exhibit, Dallas, Texas, Oct. 1995.

Beyer, L.A. :"Analysis of Borehole Gravity Surveys at Oak Crater", U.S. Geological Survey Open-File Report 87-665, 1987

Black, A.J. and Herring, A. T.:"Offset of Borehole Gravity Densities Due to Geologic Structures", Paper presented at the Annual Meeting of CSEG, Calgary, Alberta, April, 1983.

Black, A.J. :"Borehole Gravity Shuttle System for enhanced deep Densities at small Depth Intervals", Paper presented at the 62nd Annual International Meeting of SEG, New Orleans, Louisiana, October 25-29, 1992.

Brown, A. R. and Lautzenhiser, T. V.:"The effect of dipping beds on a borehole gravimeter survey", Geophysics Vol. 47, no. 1, 25-30, 1982

Goodel, R. R., and Fay, C.H.: "Borehole Gravity Meter and its Application", Geophysics, vol. 29, no. 5, 774-782, 1964.

Gournay, L.S. and Lyle, W.D.:"Determination of Hydrocarbon Saturation and Porosity Using a Combination Borehole Gravimeter (BHGM) and Deep Investigating Electric Log," SPWLA paper WW presented at the twenty-fifth Annual Logging Symposium, June 10-13, 1984.

Hearst, J. R.;Schmoker, J. W.;Carlson, R. G.:"Effects of terrain on borehole gravity data", Geophysics Vol. 45, no. 2, 234-243, 1980

Howell, L.G., Heintz, K.O., and Barry, H.: "The Development of a High Precision Downhole Gravity Meter", Geophysics, vol 31, no. 4, 764-772, 1966.

Lines, L.R., Schultz, A.K. and Treitel, S. :"Cooperative Inversion of Geophysical Data", Geophysics Vol. 53, no. 1, 8-20, January 1988.

Longman, I.M.:"Formulas for Computing the Tidal Accelerations Due to the Sun and Moon", Journal of Geophysical Research, Vol. 64, No. 12, 2351-2355, Dec. 1959.

Maute, R.E., and Gournay, L.S.:"Determination of Residual Oil Saturation With the Borehole Gravity Meter", SPE paper 13703 presented at the 1985 Middle East Technical Conference and Exhibit, Bahrain, March 11-14.

Robbins, S. L.:"Bibliography with abridged abstracts of sub surface gravimetry (especially borehole) and corresponding in-situ rock density determinations" USGS Open File Report 8-710, 1980

Robbins, S. L.:"Reexamination of the values used as constants in calculating rock density from borehole gravity data." Short note in Geophysics Vol 46 no.2, Feb. 1981 208-210.

Schultz, A. K.:"Monitoring fluid movement with the borehole gravity meter", Geophysics Vol. 54 no. 10, 1267-1273, 1989.

Smith, N.J. :"The case for gravity data from boreholes", Geophysics Vol. 15, no. 4, 605-636.

Wolfgram, P.A., Casten, U., Gatto, H., Neubauer, F.M., Richter, J.E.T. and Strack, K.-M.:"Interpretation of borehole gravity data from the German Continental Deep Drilling Project", Scientific Drilling Vol. 3, 70-75, 1992

Index

Down hole pressure :

$$P = \mathrm{K}\ \rho_{mud}\ depth$$

where	P	pressure in PSI.
	ρ_{mud}	mud density in g/cc
	depth	in feet.
	K	0.433

when mud density in lb/gallon, K = 0.05189

To derive oil density, ρ_o from API weight, API :

$$\rho_o = \frac{141.5}{API + 131.5}$$