A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration

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Abstract

At the Sleipner gas field, excess CO_2 is sequestered and injected underground into a porous saline aquifer 1000 m below the seafloor. A high precision micro-gravity survey was carried out on the seafloor to monitor the injected CO_2. A repeatability of 5 μGal in the station averages was observed. This is considerably better than pre-survey expectations. These data will serve as the baseline for time-lapse gravity monitoring of the Sleipner CO_2 injection site. Simple modelling of the first year data give inconclusive results, thus a more detailed approach is needed. Work towards this is underway.

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Executive Summary

This document is a report detailing the work that is has been done under DOE Award DE-FC26-02NT41587, which started September 19, 2002. The work is the quantification of gravity change associated with the sequestration of CO_2 at the Sleipner gas field in the North Sea. At this site, about 1 Mton of excess CO_2 is extracted from the natural gas each year and then injected into a porous saline aquifer (the Utsira formation) at about 1000 m below the seafloor (Baklid et al. 1996). Because CO_2 has never been compressed and injected underground for sequestration before, it is important to monitor what happens as time passes.

As this gas is injected into the storage reservoir, the overall density of the rock and pore space decreases. This decrease in density has an effect on the local strength of gravity. By monitoring how the local gravity field changes with time, we can assess the extent to which the gas is successfully contained and we can put constraints on the density of CO_2 within the reservoir. The monitoring is carried out by making high precision gravity measurements on the seafloor.

A feasibility study for monitoring the CO_2 bubble expansion by repeated gravity measurements (Williamson et al. 2001) modelled various scenarios for CO_2 at either high density (700 kg/m^3 corresponding to temperatures in-line with the single existing well measurement) or low density (350 kg/m^3 corresponding to slightly higher temperatures). If the migration of high-density CO_2 is controlled by topography, such that it fills up the low-relief closures of about 10 m height in the area, a maximum gravity decrease of 12 μGal from production start-up until 2001 was calculated. If the CO_2 has a low density in the reservoir and accumulates at several vertical levels, a gravity decrease of 60 μGal was calculated. If significant amounts of CO_2 penetrate above the top seal, density will be further reduced and the gas will be closer to the observation points, thus gravity changes could well exceed 100 μGal.

Gravity was measured on the seafloor above the Sleipner CO_2 injection site from the15th to the 21st of August, 2002. Measurements were made on top of 30 concrete benchmarks, which were permanently deployed on the seafloor in an area spanning about 7 km E-W and 3 km N-S. Each location was visited at least three times, which gives good control on instrument drift and other error terms. Single observation relative depth estimates have a repeatability of 0.5 cm (standard deviation), which makes monitoring of small vertical seafloor movements in the area possible. Single observation repeatability is estimated to be 4 μGal (standard deviation), and about 2.5 μGal for station mean values. These data will serve as a baseline for future monitoring of changes in gravity caused by increasing amounts of CO_2 in the underground formation. For time-lapse measurements, there is additional uncertainty associated with the reference null level, determined from stations outside the CO_2 area, of about 1-2 μGal. The final detection threshold for time-lapse changes may be about 5 μGal. This is considerably better than the pre-survey expectations (which was about 10 μGal for station averages) and gives good hope for detecting time-lapse changes, depending on in-situ densities and distribution of CO_2.

Without time-lapse data only a limited amount of information about the injected CO_2 can be obtained. Initial modelling, done by making simple Bouguer corrections to the seafloor gravity data, are inconclusive. Further modelling based on updated seismic

results, borehole measurements, and seafloor bathymetry are underway. A future repeat gravity survey will provide an independent and more reliable means to quantify the CO_2.

Experimental

Time-lapse gravity studies have been used onshore for monitoring hydrothermal energy reservoirs (e.g. Allis and Hunt 1986, San Andres and Pedersen 1993) and magma chambers on active volcanoes (e.g. Rymer and Brown 1986). In these and other microgravity surveys on land, accuracy of 10 μGal or better has been achieved by careful use of standard gravimeters. Offshore, ship-borne measurements have uncertainties of several hundred μGals and are not accurate enough for such detailed surveying. Observations at the more stable seafloor could potentially give better precision, but seafloor gravimeters are rare.

A new development of the method and instrumentation of seafloor gravity monitoring has been carried out by Scripps Institution of Oceanography and Statoil (Sasagawa et al. 2003, Eiken et al. 2000) in which results are comparable to land surveys. In this method, concrete seafloor benchmarks serve as reference locations and stable platforms for the measurements. The relative gravity meters are carried by an ROV which places the instrument on the benchmark for a 10-30 minute measurement at each site. Water pressure is also measured on both the gravity meters and on separate stationary reference pressure gauges deployed for the survey period. Differential pressures between these and the instrument-carried sensors are used for high-accuracy relative depth estimates. Time-lapse changes in depth can then be corrected for anomalous tidal signals.

In the version of the instrument (ROVDOG II) used in the 2002 baseline survey on Sleipner, one gravimeter (Scintrex CG-3M) and one pressure gauge (Paroscientific 31K) was housed in each pressure case, and altogether three pressure cases were mounted on a frame (Figure 11). The instrument has been described in more detail in Sasagawa et al. (2003).

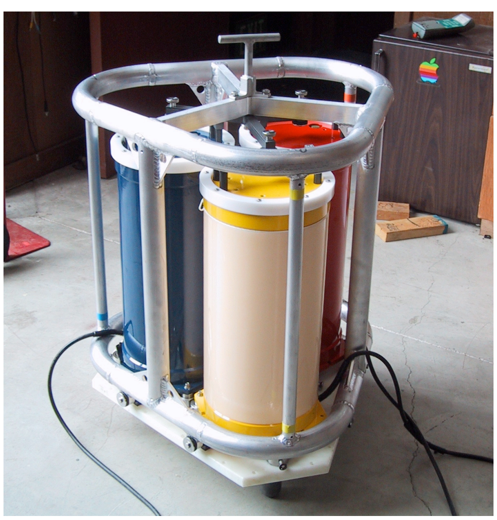

Figure 1: ROVDOG II

Benchmarks were deployed with a wire and acoustic release hooked onto a small chain, which fell into the central hole after release. The deployment operation lasted 10 hours for all 30 benchmarks, and was done just before surveying, on 16th August 2002. 20 of the benchmarks were placed in a 7.3 km long WNW-ESE profile across the injection point (Figure 2). The distance between stations increases from about 300 m near the injection point up to 500 m towards the ends. Another 10 locations span the orthogonal dimension and cover the extent of the CO_2 accumulation in 2002.

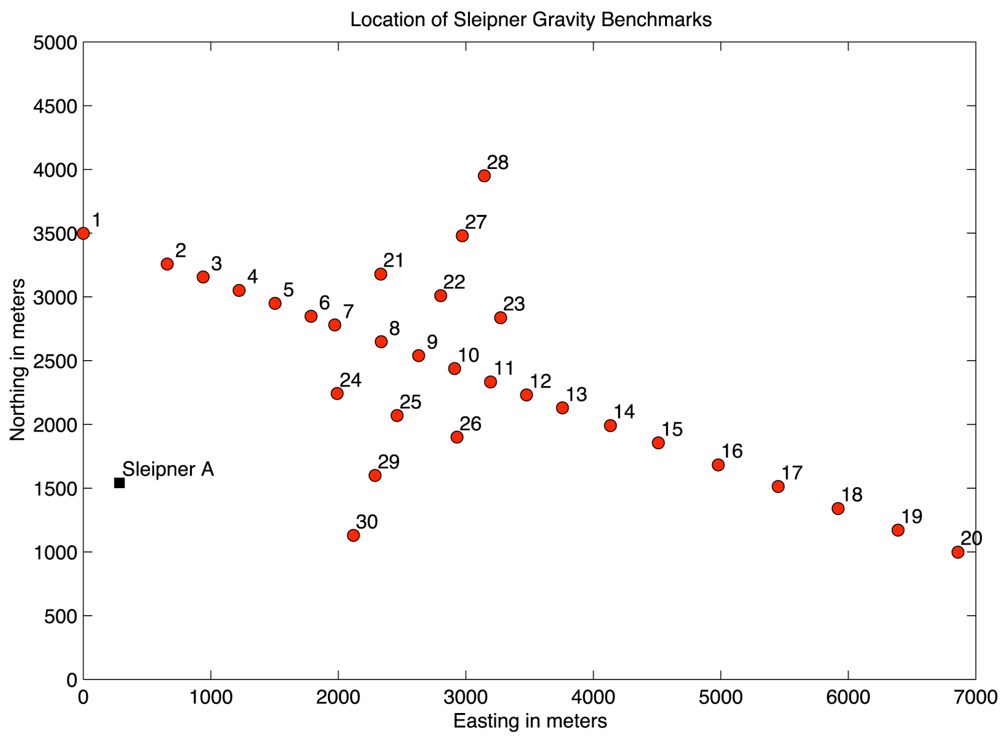

Figure 1. Sleipner gravity benchmark locations are shown in red.

Figure 3: Survey vessel Edda Freya

Figure 4: ROV and gravimeter during recovery.

Marine operations

The supply vessel *Edda Freya* which has been converted for ROV/Subsea operations was used for the survey (Figure 3Figure). It has a length of 87.1 m, breadth of 17.5 m and tonnage of 3476 tons dwt. The vessel carries a HIROV 3000 Mk II (Figure). This is a work class ROV equipped with a 5-function arm and a 7-function manipulator arm. The ROV is launched and recovered with an A-frame on the side of the ship. In addition to DGPS and the standard navigation system showing the ROV position relative to the ship, the NaviPac system was rented for this work, to secure an effective transit from site to site.

Gravity measurements were carried out in the period from the 16th of August 2002 (day 228 in the year) at 18:00 (UTC) until the 20th of August (day 232 in the year) at 15:00 hours. 115 measurements were made (about 30 per day). All stations were visited at least 3 times, for the purpose of redundancy and drift corrections. Survey loops were made with station #9 as the central location. This site was visited 15 times during the four days, giving a loop duration of about 7 hours. The sequence of stations within each loop was varied, to separate time correlated errors from spatially correlated errors. The six stations with largest scatter (based on the onboard processing) received a fourth visit, and the easternmost station (#20), which is likely to be well outside the area of CO_2 influence and hence serve as a reference location for future gravity changes, received five visits. At the end of the survey, five closely spaced locations without benchmarks (22m, 22m, 20m, 44m and 105 m separation) were measured (named #31-35), to investigate short-wavelength variations in gravity.

Weather was good during benchmark deployment and at the start of the surveying, while wind and waves increased during the survey. This can be observed in the noise level (RMS sample scatter) of the gravity time series (Figure 5). Significant wave heights were about 3 meters towards the end of the survey.

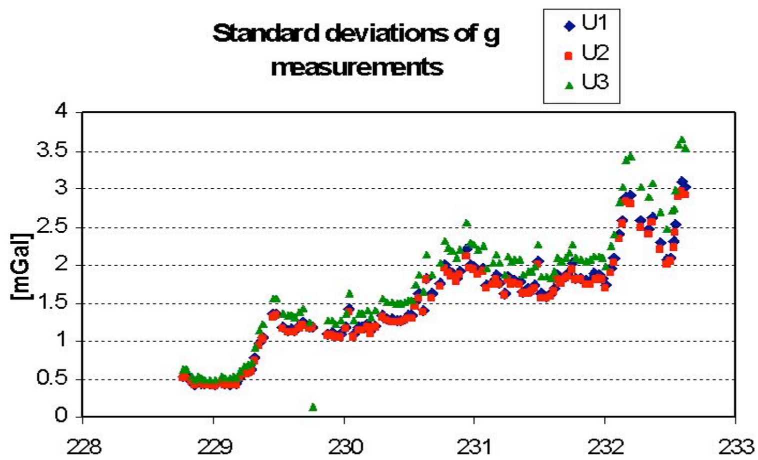

Figure 5: Noise level (RMS 1 s sample scatter) in the gravity time series during the survey. X-axis shows day number in the year.

Reference environmental data

Seafloor pressure gauges

Water bottom pressure was measured continuously during the survey at location #9. Altogether, four reference gauges were deployed (Table 1). They were strapped together in pairs.

Type	WLR 7 (Statoil)	WLR 7 (Sintef)	WLR 8 (1497)	WLR 8 (1687)
Owner	Statoil	Sintef	Geoconsult	Geoconsult
Depth range	0-340 m	0-290 m	0-1370 m	0-1370 m
Time of deployment	16.8 at 07:20	16.8 at 18:05	16.8 at 18:05	16.8 at 07:20
Sampling interval	2 min.	2 min.	5 min.	5 min.

Table 1: Reference water pressure gauges.

Figure7 shows the difference between the pair of sensors. We note that the two WLR 7 pressures are in good agreement. In contrast, the 1687 gauge has about 10% lower tidal amplitudes and the 1497 gauge about 10% higher tidal amplitude. The mean values of the WLR 7 were 912 and 920 kPa, while the WLR 8 gauges deviated about 20% from these values, and were clearly incorrect. They were not used in the further analysis.

We are mainly interested in the time-varying deviations from the average value, and here the two WLR 7 gauges agree to within 36 Pa (standard deviation), see Figure 6. This corresponds to depth variations of only 3.6 mm. A somewhat larger variation is seen in the first few hours of deployment, due to transient effects.

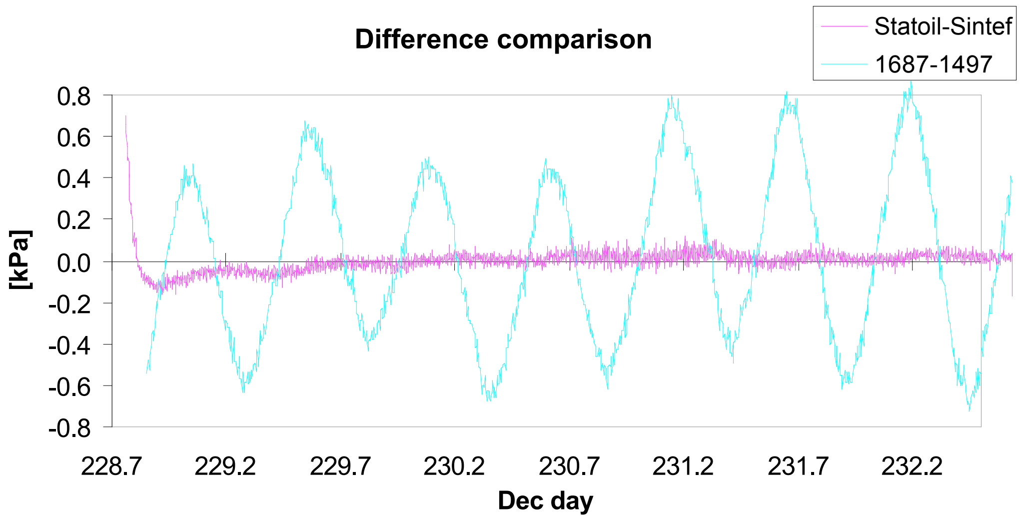

Figure 6: Difference between the two WLR 7 pressure series (Statoil-Sintef) and the two WLR 8 pressure series (1687-1497).

Seawater density

A CTD cast attached to the ROV transmitted data through the ROV umbilical. This was used to measure density profiles at launch and recoveries, two at the start and two at the end of the survey, all at location 9. The first three measurements were made while the ROV was diving, and the last value was obtained after the ROV had been in the water for 15 minutes. This value may be less susceptible to transient temperature effects, as the sensor had time to equilibrate to seawater temperature. The density profiles are shown in Figure 7. Average water density in the four profiles range from 1026.93 kg/m^3 and up to 1027.21 kg/m^3. The last measurement gave the highest average density, and we put most confidence in this measurement. Water densities close to the seafloor were about 1027.85 kg/m^3, with variations between measurements of about 10.03 kg/m^3.

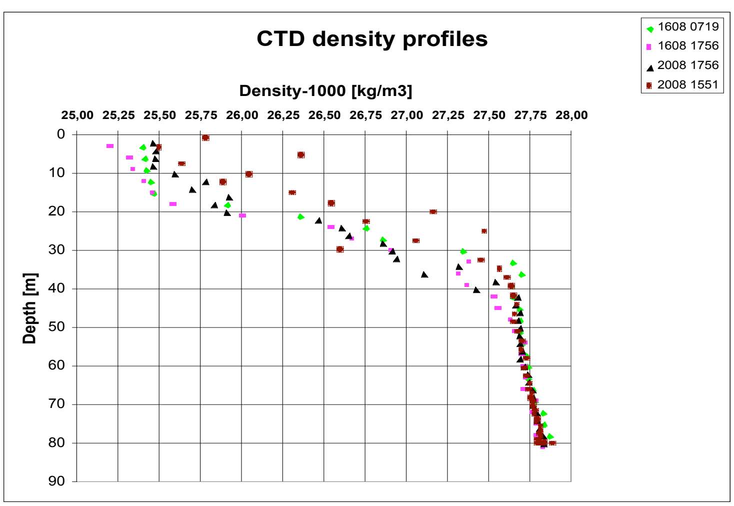

Figure 1: CTD density profiles.

Air pressure

Air pressure was read manually from the barometer onboard *Edda Freya* every hour, at 1 mbar resolution (Figure 8).

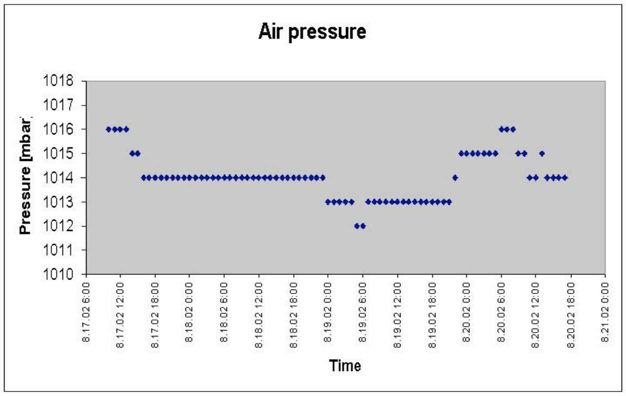

Figure 2: Air pressure as recorded onboard Edda Freya during the survey.

Results and Discussion

Depth estimates

Processing of depth and gravity time series was done in collaboration with Ola Eiken and Torkjell Stenvold at Statoil using in-house developed Matlab code. Average values for each 20 minute record were imported into a spreadsheet where further processing (averaging between records, network and other corrections, analysis) took place.

The averages of each 20 minute time series were compared for the three units. The scatter is about 30 Pa (standard deviation), see Figure 9. There are some time-coherent variations for the first measurements, probably related to transient effects in the gauges during dives (going from ~100 kPa air pressures to ~900 kPa water pressures).

After the mean of the three sensors was extracted for a site visit, the recorded reference pressure (which is adjusted to zero mean) was subtracted and the result converted to depth using a density of 1028 kg/m^3, gravity 9.82 m/s^2 and air pressure 101 kPa. The depths vary between 79.5 m and 83.6 m. The position of the pressure gauges, near the bottom of the pressure case, is about 20 cm above the top of the benchmark, which again is 30 cm above the seafloor. Approximately one half meter could therefore be added to get seafloor depths. The uncertainty in relating these values absolute depth is probably well above 10 cm. However, for monitoring relative changes, depths are referenced to locations outside the area of gas injection, such as station #20. Agreements of station repeats are shown in Figure 10, plotted versus recording data. The standard deviation is 0.5 cm. Apart from three outliers, all values are within 0.8 cm.

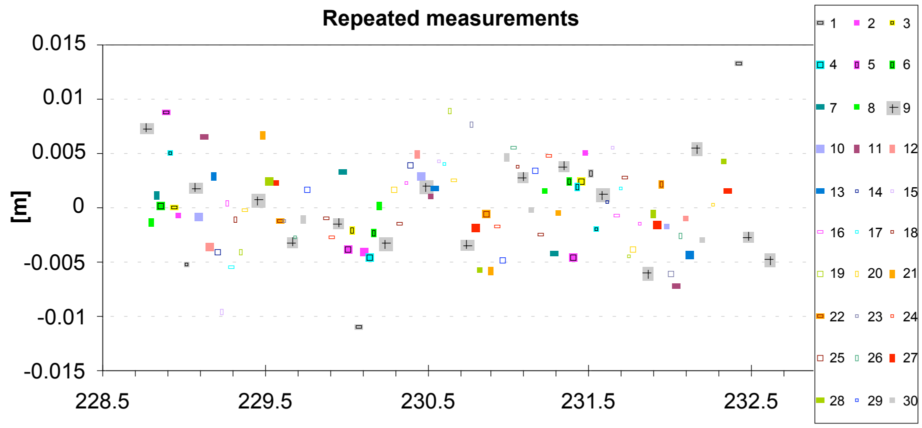

Figure 9: Difference between the pressure gauges after editing and adjustment of the gauges to the average drift of gauge one and three.

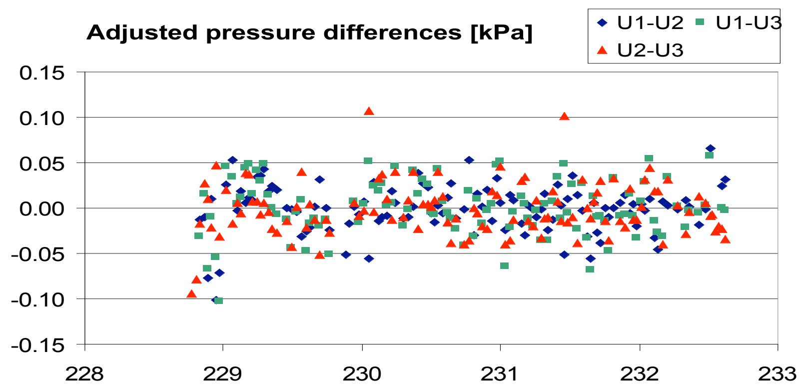

Figure 10: Deviations from station means. The repeatability is 0.5 cm.

Gravity estimates

Processing of the gravity data was done in collaboration with Statoil colleagues Ola Eiken, Torkjell Stenvold, and Havard Alnes. The quality of the data is evident in the repeatability of the measurements. Quality control was thus done by comparing repeated observations in three ways: 1. Multiple measurements made at each benchmark were compared. 2. Agreement among the three meters was examined for each measurement. 3. Stability of each measurement was examined by comparing the first and second half of each 20 minute gravity record.

For each 20 minute long gravity record, noisy samples were edited out and the time range of good data selected, prior to calculating the average. Narrow-band seafloor accelerations (mostly at 2-3 s period) originate as an interference phenomenon between ocean waves from different directions (Longuet-Higgins 1950, Babcock et al. 1994). Amplitudes were up to 3.5 mGal during the survey (Figure), but due to the periodic nature a 20 minute average effectively reduces the noise to acceptable levels. Visco-elastic relaxation of the quartz spring causes recovery effects; transient changes in gravity readings before it levels out. The size of such effects is indicated by comparing the mean of the first half and second half of a 20 minutes record (Figure 11). The recovery phenomenon is smallest on Unit 3, and for some records only the second half of unit 1 was used.

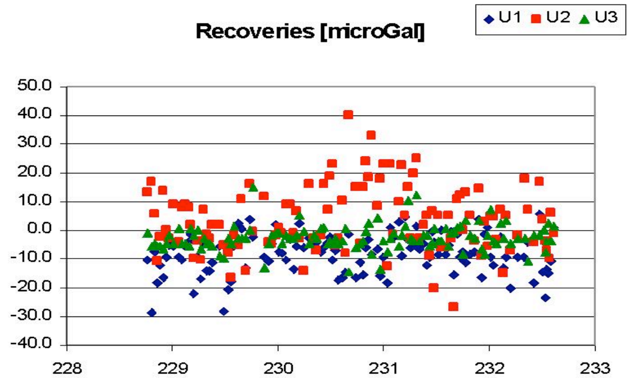

Figure 11: Gravity difference between first half and second half of each measurement.

Gravity values were corrected for solid earth tides and the ocean loading term by using a world-wide model (Agnew 1996). The varying gravity attraction from water tide was compensated for by sea level height estimates based on reference pressures (no extra correction for air pressure, as the bottom pressure may see such variations as well).

Instrument drift was estimated by inverting all repeat measurements using the method of least squares individually for each unit. A change in drift rate occurred for Unit 2 (U2) and Unit 3 (U3) at the time when U3 failed and was recovered to surface (at decimal day 229.7). Therefore, separate drift polynomials are used before and after the failure incident (Table 2) for U2 and U3.

	Linear term [mGal/day]		2. Order term [mGal/day^2]		Split time
	1. Half	2. Half	1. Half	2. Half	
U1	0.55648		-0.001704		
U2	0.36277	0.44239	0	-.000103	229.7
U3	0.17792	0.19274	-.030647	0.000598	229.8

Table 2: Drift coefficients for the three gravity sensors.

The repeatability of the units are 8.8 μGal (U1), 9.9 μGal (U2) and 4.7 μGal (U3). Because of the much better performance of U3, this unit was heavily weighted in the average calculation. After weights of 0.396 (U1), 0.264 (U2) and 2.261 (U3) were given, the repeatability is down to 4.3 μGal (Figure 12).

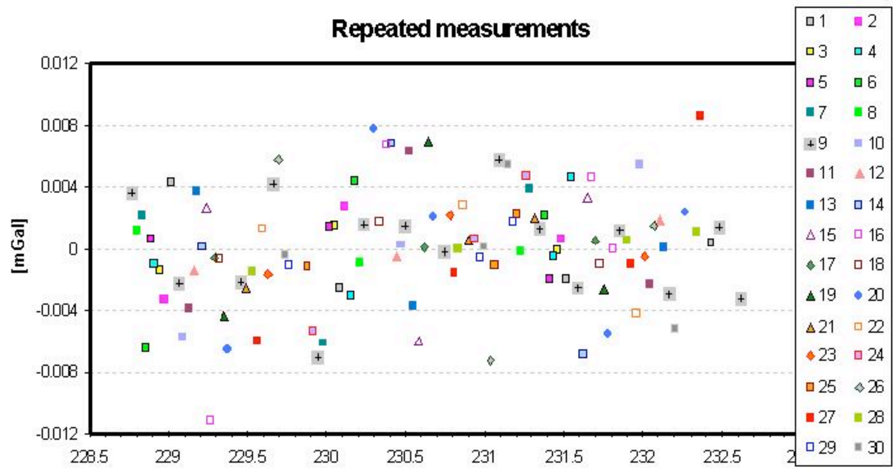

Figure 12: Repeatability for weighted unit averaged measurements. Standard deviation is 4.3 μGal.

The drift correction can be quality controlled by plotting unit differences as a function of survey time (Figure 13). There are no apparent trends left in the plot, which suggest the drift has been removed. We also note that the seafloor measurements during the day interval 232.5-232.6 show larger scatter.

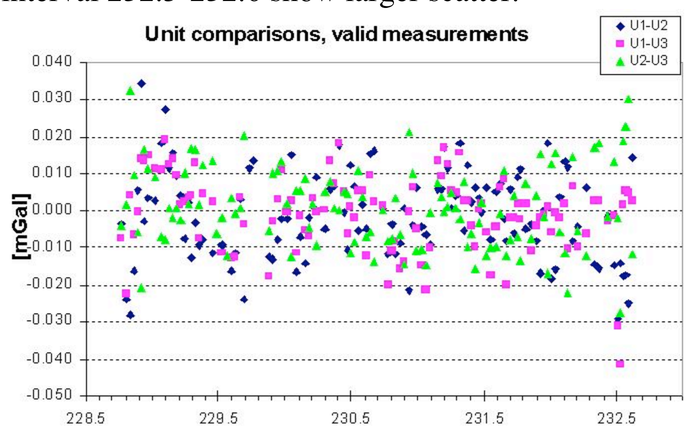

Figure 13: Differences between unit averages after residual drift correction.

With three or more visits at each station, the precision of the station averages is better than the 4.3 μGal repeatability. If remaining error sources are random, station repeatability should be about 2.5 μGal (4.3 μGal/sqrt(3)). For time-lapse changes, additional uncertainty is related to determining the reference zero-level, by using stations outside the area of influence from the gas injection. The southeastern most station (# 20) has with its five visits a standard deviation of 1.9 μGal, and if more stations are used for defining the reference zero-level, this uncertainty will be further reduced. This error will add to all stations.

Gravity Modelling

To gain information about the CO_2 bubble from the gravity data, some modelling must be done. The terrain in the Sleipner region is very flat, changing by less than 5 meters over the area of the survey. Therefore, a simple Bouguer correction was done to the data as a first pass at modelling. A regional gravity signal was also subtracted from the data (Figure 14). However, the resulting anomalies were not consistent with the expected anomalies from modelling the CO_2 bubble. Therefore a better subsurface density model is needed for the region.

In order to build a detailed subsurface density model pre-injection seismic data, core samples, and other regional data such as bathymetry are needed. We are in the process of obtaining this data. Also, the gravity change due to gas removal for the deeper hydrocarbon reservoirs should be corrected for. Code is also being written that will enable us to use all of these data sets together to build a 3-D subsurface density model of the region. This will enable us to begin to put constrains on the CO_2 density and mass.

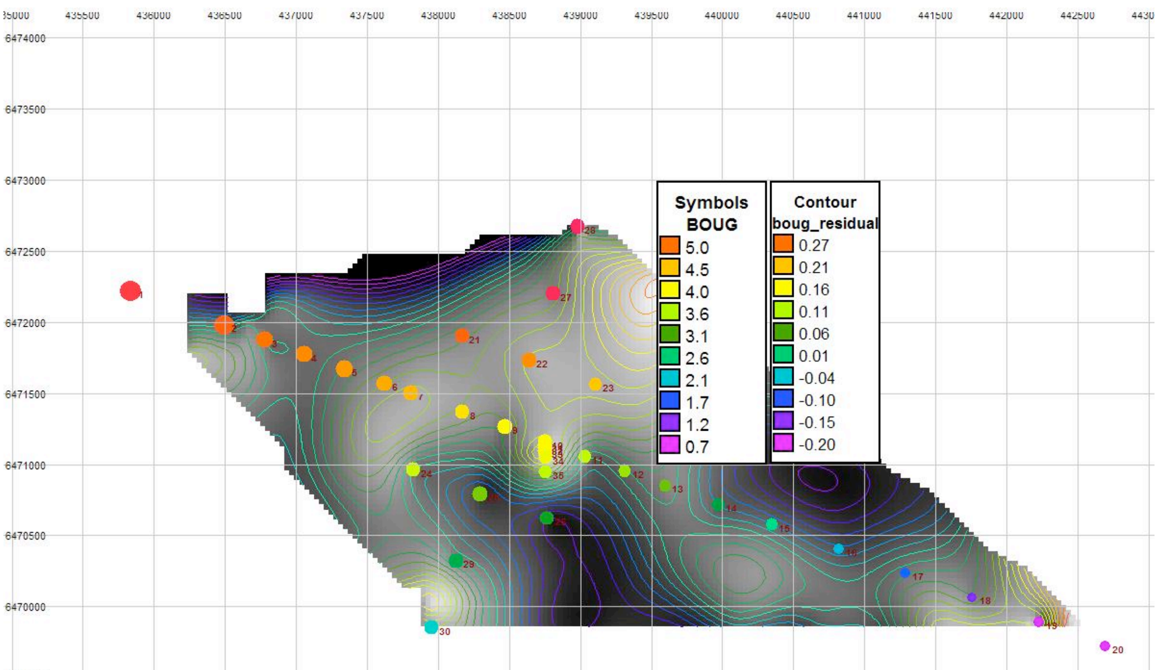

Figure 14. The circles show the benchmark location and the value of the Bouguer anomaly before a residual correction was made. The contours show the value of the anomalies after the subtraction of a regional signal. Note that the contours only have meaning near the location of the benchmarks.

Conclusions Discussion

The seafloor gravity survey at the Sleipner CO_2 sequestration site was very successful. The estimated station uncertainty of 2.5 μGal is significantly better than the

10 μGal accuracy envisioned in Williamson et al. (2001). With a next survey of similar accuracy, and an uncertainty in the reference level of 1-2 μGal, a gravity change of 5 μGal could be detectable, provided currently unknown time-lapse errors do not appear.

Williamson et al. (2001) modeled gravity changes arising from various scenarios of CO_2 in-situ densities and spatial distributions for a two year period. The lowest response, about 10 μGal, was modeled from CO_2 at high density (700 kg/m^3) accumulating in thin layers controlled by topography under the top seal. It is therefore likely that a change in gravity will be detectable in a future survey. While the timing of a repeat survey is subject to debate, note that the uncertainty in the time rate of change will always improve with higher sampling rates. With uncertainties of 5 μGal or less, we expect to be able to observe a gravity change after a two year period.

The ongoing modeling of the baseline gravity measurements will provide an independent check of CO_2 density and mass. Models will also be constructed that will explore lateral spreading of the carbon dioxide, based on time-lapse seismic data.

The highly accurate seafloor depth measurements; relative agreement of 0.5 cm for single station occupations, and maybe as low as 0.3 cm after averaging station visits, open possibilities of detecting small vertical seafloor movements above the CO_2 plume.

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