A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO₂ Migration

Technical Progress Report

Reporting Period: 3/19/05 - 9/18/05

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Report Issued: 12/13/05

DOE Award Number: DE-FC26-02NT41587

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Abstract

Since 1996, excess CO₂ from the Sleipner natural gas field has been sequestered and injected underground into a porous saline aquifer 1000 m below the seafloor. In 2002, we carried out a high precision micro-gravity survey on the seafloor in order to monitor the injected CO₂. A repeatability of 4.3 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 CO₂ injection site. This report covers 3/19/05 to 9/18/05. During this time, gravity and pressure modeling were completed and graduate student Scott Nooner finished his Ph.D. dissertation, of which this work is a major part. Three new ROVDOG (Remotely Operated Vehicle deployable Deep Ocean Gravimeter) instruments were also completed with funding from Statoil. The primary changes are increased instrument precision and increased data sampling rate. A second gravity survey was carried out from August to September of 2005, allowing us to begin examining the time-lapse gravity changes caused by the injection of CO₂ into the underground aquifer, known as the Utsira formation. Preliminary processing indicates a repeatability of 3.6 µGal, comparable to the baseline survey.

Table of Contents

ABSTRACT	2
TABLE OF CONTENTS	3
EXECUTIVE SUMMARY	4
EXPERIMENTAL	5
RESULTS.....	7
<i>DATA PROCESSING</i>	<i>7</i>
<i>BENCHMARK LOCATION AND GRAVITY GRADIENT</i>	<i>9</i>
<i>SLEIPNER EAST GAS TAKEOUT CONTRIBUTION.....</i>	<i>11</i>
CONCLUSIONS	11
REFERENCES	12

Executive Summary

This document is a report detailing the continuing work that has been done under DOE Award DE-FC26-02NT41587, which started September 19, 2002. This work, the quantification of gravity change associated with the sequestration of CO₂ at the Sleipner gas field in the North Sea, is a collaborative research effort between US scientists and members of the SACS (Saline Aquifer CO₂ Storage) consortium. At this site, about 1 Mton of excess CO₂ 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 CO₂ 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 CO₂ within the reservoir.

Near predicted reservoir temperature and pressure conditions, CO₂ goes through a critical phase transition in which the density changes from 200 kg/m³ to over 700 kg/m³ over a short range of temperature [Span and Wagner, 1996]. Thus, a slightly higher temperature could result in a much lower CO₂ density. Therefore, a feasibility study for monitoring the CO₂ bubble expansion by time-lapse gravity measurements was done by Williamson et al., (2001). They computed the gravity signals from both a high and a low-density model. The low-density model (350 kg/m³) shows a peak anomaly of -34 µGal, while the high-density model (700 kg/m³) shows a peak anomaly of -7 µGal after 2.268 MT of CO₂ was injected (slightly over two years). If significant amounts of CO₂ penetrate above the top seal, density will be further reduced and the gas will be closer to the observation points, causing gravity changes that could well exceed 100 µGal, making gravity an effective tool for measuring catastrophic leaks.

Gravity was measured on the seafloor above the Sleipner CO₂ injection site from the 15th to the 21st of August 2002, on top of 30 concrete benchmarks, which were permanently deployed on the seafloor. The area spans about 7 km E-W and 3 km N-S. In relative gravity surveys, the uncertainty is given by the repeatability of the measurements, thus each benchmark was visited at least three times. Repeatability for a single gravimeter is estimated to be 4.3 µGal. These data will serve as a baseline for future monitoring of the CO₂ bubble. For time-lapse measurements, there is additional uncertainty associated with the reference benchmark, determined from stations outside the CO₂ area, of about 1-2 µGal. Therefore, the final detection threshold for time-lapse changes is about 5 µGal. This is considerably better than the pre-survey expectations of 10 µGal, and increases the likelihood of detecting time-lapse changes. Single observation relative depth estimates have a repeatability of 0.5 cm, which also makes monitoring of small vertical seafloor movements in the area possible.

Using software developed in house, we have been able to place bounds on the expected time-lapse gravity signal, which depends upon the density of the CO₂ within the reservoir. For low density CO₂, we expect to see a gravity change of 7-9 µGal/year and for high density CO₂ we expect to see a gravity change of 2-3 µGal/year. For a 3-year

span between surveys (2002-2005), this means a maximum gravity change between 27 μGal or 9 μGal (Table 1). By calculating the seismic velocity pushdown (time delay in the two-way vertical travel time), some constraints can be placed on the geometry of the intra-reservoir CO_2 . This work has been included in detail in the Ph.D. dissertation of Scott Nooner, which was completed in June of 2005.

With funding from Statoil, three new ROVDOG instruments were built, using a Sintrex CG-5 as the sensor core. These gravimeters sample at 6 Hz, while the older CG-3M based gravimeters have a 1 Hz sampling rate. Improvements in the mechanical design of the CG-5 help to reduce recovery of the gravimeter spring after transport from benchmark to benchmark. The first repeat survey was carried out from the 2nd to the 6th of September 2005. Mobilization and demobilizations costs were minimized by piggybacking the Sleipner survey onto a survey of the TROLL gas field using the same instruments. Initial processing of the data was done in real time onboard the ship. Preliminary results show a gravity repeatability of about 3.6 μGal .

Table 1. Summary of the maximum magnitude of the gravity change expected per year for each of the different models. The values given for the seismic horizon models with $\rho_{\text{CO}_2} = 350 \text{ kg/m}^3$ and $\rho_{\text{CO}_2} = 550 \text{ kg/m}^3$ are an estimate of the result of redistributing the diffuse CO_2 to match the pushdown and injected mass (see the text).

Model	$\rho_{\text{CO}_2} \text{ (kg/m}^3\text{)}$	Maximum change ($\mu\text{Gal/yr}$)
Seismic horizon	350	~7.4
Seismic horizon	550	4.5
Seismic horizon	700	2.7
Model I	700	2.2
Model IIa	700	2.4
Model IIb	550	4.7

Experimental

In microgravity reservoir monitoring surveys on land [e.g. Allis and Hunt, 1986; San Andres and Pedersen, 1993] accuracies of 10 μGal or better have been achieved by careful use of standard gravimeters. However, ship-borne measurements have uncertainties of several hundreds of μGal , making offshore gravity monitoring difficult. A new seafloor gravimeter (ROVDOG for ROV deployed Deep Ocean Gravimeter) has been developed by Scripps Institution of Oceanography and Statoil [Sasagawa et al., 2003; Eiken et al., 2000]. The collection of seafloor gravity data is desirable because the signal-to-noise ratio is significantly better than that of sea surface data. The primary benefit, however, is that the ROVDOG is placed directly on the seafloor and is connected to the deployment vehicle via only a loose tether, eliminating all accelerations caused by ship and vehicle. Also, by deploying the instrument with an ROV onto seafloor benchmarks, positioning uncertainties related to site reoccupation are virtually eliminated.

Water pressure is also measured in our instrument package for high-accuracy relative depth measurements. Separate stationary reference pressure gauges are also

deployed for the survey period to record tidal signals, which need to be taken out of the relative pressure records.

The primary sensor in the ROVDOG instrument is either a modified Scintrex CG-3M or CG-5 gravimeter mounted in a compact gimbal platform for leveling and enclosed, along with a Paroscientific 31K pressure gauge, in a watertight pressure case. Three pressure cases were mounted on a frame. The instrument is described in more detail in Sasagawa et al. [2003]. With funding from Statoil, three new ROVDOG instruments were built, using a Sintrex CG-5 as the sensor core. These gravimeters sample at 6 Hz, while the older CG-3M based gravimeters have a 1 Hz sampling rate. Improvements in the mechanical design of the CG-5 help to reduce recovery of the gravimeter spring after transport from benchmark to benchmark.

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

Benchmarks were deployed in a 10-hour period just before surveying, on August 16, 2002. 20 of the benchmarks were placed in a 7.3 km long WNW-ESE profile across the injection point (Figure 1). 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 CO₂ accumulation in 2002. The 2002 gravity data were analyzed in collaboration with Ola Eiken and Torkjell Stenvold from Statoil (as discussed in previous technical reports). We found the repeatability of the meters to be about 2.5 μ Gal, making the observable signal size from a time-lapse measurement about 5 μ Gal.

The 2005 gravity survey was carried out from 2130 UTC on September 2, 2005, until 1330 UTC on September 6, 2005. During this time, benchmarks 1, 2, 3, 15, 28, and 30 were measured twice, benchmarks 4, 6-8, 10-14, 16-19, 21-27, and 29 were measured 3 times, benchmark 5 was measured 4 times, benchmark 20 was measured 5 times, and benchmark 9 was measured 12 times (Figure 1). A total of seven recoveries of the instruments to the ship were done, for long transits. Two CG-5 and one CG-3M based ROVDOGS were used for the survey (Unit 4, Unit 5, and Unit 3, respectively).

Five reference tide gauges were deployed, with two at benchmark 20 and three at benchmark 9. At benchmark 20, one gauge was a WLR7 and the other was a WLR8. At benchmark 9, there were two WLR7's and one WLR8. The data from the WLR8's did not agree well ($\sigma = 0.17$ kPa), so only the WLR7 data was used. Disagreement between the WLR7 gauges was 0.04 kPa. The sea state varied from 1 to 4 meters significant wave height, resulting in single measurement scatters ranging from 0.6 to 1.8 mGal (Figure 2). Since most of this noise is periodic, the standard errors on average reduce to 0.001 mGal, 0.005 mGal, and 0.009 mGal for single a measurement for Units 3, 4, and 6, respectively. However, instrument drift, changes in the local water density and temperature, tides, benchmark tilt, mechanical disturbance of the gravimeter springs, and other effects reduce this precision. Therefore the best estimate of measurement precision is given by the repeatability of multiple occupations of each site, after tide and instrument drift have been accounted for.

Figure 2. Standard deviations of single measurements for the raw gravity data. Magnitude of the standard deviation reflects the sea state.

Results

Data processing

The initial data processing was done on board using a Matlab software package developed in house and a Microsoft Excel spreadsheet. The Matlab software was used to edit out bad data, correct for solid earth tides, and account for periodic noise. The results were then pasted into an Excel spreadsheet for further processing. On board, tides were calculated using SPOTL, however, on shore tides were removed using the data from the

reference tide gauges. The steps of processing gravity are as follows: 1.) subtract the water attraction term of the tidal signal, which was calculated from reference tide gauges, 2.) estimate instrument drift using a matrix inversion of all repeated sites, then subtract this drift, 3.) take the mean of all three gravimeters with appropriate weights for each site, and finally 4.) calculate the mean value of gravity at each benchmark. Weights of 0.8, 1, and 0.1 were applied to Units 3, 4, and 6, respectively. Individual measurements were examined for consistency by looking at unit differences and recovery effects for each measurement. Large recoveries prompted the use of the second half of a record, rather than the entire record. Remaining outliers were not included in the final results. The resulting gravity values have a repeatability of $\sigma = 3.6 \mu\text{Gal}$ (Figure 3). A similar processing scheme was used for the pressure analysis: 1.) subtract the reference pressure (tide signal) from the raw pressure, 2.) estimate and subtract gauge drift, 3.) calculate the mean of the three gauges for each site, 4.) convert pressure to depth, and finally 5.) find the mean depth for each benchmark. Once again, data quality was checked by comparing the differences between gauges for each measurement. Extreme outliers were not included in further analysis. The resulting depth values have an uncertainty of $\sigma = 0.54 \text{ cm}$ (Figure 4). Comparing the resulting values for gravity and depth in 2005 to those of 2002 give estimates of the changes in these quantities over the three-year duration. Uncertainties in the absolute values for gravity and depth are much greater. To avoid using absolute values, a reference site is typically chosen that is not expected to change over time. All subsequent measurements are made with respect to this reference site. Therefore, some assumptions have to be made about site stability that introduce some ambiguity into the interpretation.

Figure 3. Scatter of repeated gravity measurements. Each point is the average of the three gravimeters for that measurement, with the proper weights applied

Figure 4. Scatter of repeated depth measurements. Each point is the average of the three pressure gauges for that measurement.

Benchmark location and gravity gradient

The time-lapse gravity and depth data are shown together in Figure 5. The depth changes have a scatter of ~ 7 cm, with no apparent spatial correlation. This result is surprising since little or no subsidence was expected for the area. Changes in the gravity coincide nicely with the changes in depth, providing assurance that the observed depth changes are real. However, this means that there is no evidence of a stable benchmark to serve as a reference. Therefore, there is no method of determining which benchmarks actually moved; furthermore, there is no way to determine the direction of change (uplift verses subsidence) from the data alone. The cause of these spatially uncorrelated benchmark depth changes are something that we would like to understand. There are several pieces of information that can be used to limit the possible sources of benchmark motion. These are explored below.

Trawl fishing in the area is not uncommon. Some benchmark disturbance by trawlers is evident from the fact that benchmark 27 was not located in the position it was in 2002. It was offset to the northeast by about 20 m. Biological evidence also indicated that it had been moved recently. Tracks from the dragged benchmark enabled us to locate it. No other benchmark had been obviously moved in this manner. All were located in the expected place and no biological or morphological evidence suggested movement. Navigation was good to only a few meters, however, so small movements cannot be precluded. In addition to lateral movements, benchmarks could have been tilted by trawlers. Several benchmarks were tilted more than in 2002, but it is unknown whether this was caused by trawlers or by biological disturbances. This is discussed more in the following paragraph.

Benchmark tilt can be estimated using the coarse motor position voltages. Doing this for both 2002 and 2005, it is evident that some of the benchmarks have become tilted since the first survey. Benchmarks 1, 9, 13, and 20 appear to be tilted at angles greater than 2 degrees more than they were in 2002, while benchmarks 10, 18, and 25 are tilted by a lesser amount. The remaining benchmarks are within a degree of the 2002 tilt values. Benchmark 20 also had a few cm tall mound of sediment on one corner. As

Figure 5. Plot showing the correlation between depth changes and gravity changes. The fact that the two are so similar provides evidence that the changes are real.

mentioned above, this could be due to disturbance by trawl fishing. Additionally, under each benchmark lived a family of steinbit (also wolf-fish or Atlantic catfish). These fish are large (up to 1.25 m) and feed on sea urchins, mussels, cockles, and crabs. Surrounding each benchmark was a few square meter area littered with shells from the feeding habits of the steinbit. In order for at least two fish of this size to live under each benchmark, there must be a large cavity (maybe 10 cm deep) underlying each benchmark. It's easy to imagine the benchmarks sinking and/or tilting due to such a large underlying cavity. One possibility is that trawling could disturb a benchmark enough to shift it by a few cm over the underlying cavity, thereby causing it to sink and tilt. Corrections for benchmark tilts were made to the pressure gauges based on an empirical formula. Without this correction, uncertainty introduced by a tilt of 2 degrees is about 9 mm for depth and 2 μGal for gravity.

The predicted vertical gravity gradient in the ocean is 0.220 mGal/m. This changes a small amount with latitude and with depth (by up to ~ 0.002 mGal/m), but at the location and depth of the survey, this value should be correct. The observed gradient also depends to some extent on the local geology. The observed gradient is estimated by spatially high-pass filtering the time-lapse gravity data (subtracting a best-fitting 2nd order polynomial from the dg versus easting data) and then finding the slope of the best fitting line to the dg versus dg data. The result is $dz/dg = 0.16 \pm 0.04$ mGal/m. This value is significantly lower than the value of the expected gradient. A combination of factors may account for this. First, the gradient is reduced by 0.027 mGal/m from the benchmark

sinking into the sediments; however, not more than a few cm of benchmark settling was observed. Second, strong ocean currents in the region could cause advection of sediment surrounding each benchmark, causing a localized depression centered on each benchmark. Concurrent benchmark subsidence would cause a decrease in the observed gradient of 0.038 mGal/m. A 10 cm cavity under each benchmark would cause a decrease in observed gravity by 0.002 mGal, but would not affect the gravity gradient. A combination of these effects could account for the observed gradient. The horizontal gravity gradient in the area does not exceed 1.3 μ Gal/m, meaning that the benchmarks could have moved laterally 5 m at most, assuming that the scatter in the depth gradient corrected gravity data comes from lateral motions. From the above arguments, it seems likely that all benchmark motion was due to some sort of subsidence. However, due to the relative nature of the measurements and the lack of a stable or motionless reference benchmark, it is impossible to rule out the possibility of uplift at some benchmarks.

Sleipner East gas takeout contribution

After corrections for tide drift and depth changes have been taken into account, there remains a long-wavelength increasing gravity trend to the west due to extraction of gas from the Sleipner West field. This trend has an apparent maximum value at benchmark 1 (the western most station) of about 0.03 mGal. The trend is not well approximated by a linear fit. Estimates of the gravity increase due to Sleipner West were done by Torkjell Stenvold and Ola Eiken, however the predicted increase is about 4 times smaller than the observed increase. Therefore, in a first attempt at correcting for this signal, the predicted gravity increase was scaled by a constant, which was determined simultaneously with the best fitting dg/dz by minimizing the residual gravity values when these two parameters are varied. The result is that the constant 4.49 times the predicted Sleipner West signal along with a $dg/dz = 0.16$ mGal/m fit the observed gravity changes the best. Refinements in the Sleipner West prediction are being looked into using updated reservoir data. This should improve our confidence in the model.

Conclusions

We have carried out the first repeat gravity survey at Sleipner from the 2nd to 6th of September 2005. The time between surveys was 3 years. With funding from Statoil, we built three new gravimeters using a Sintrex CG-5 land gravimeter as the sensor. The previous ROVDOG instruments used Sintrex CG-3M land gravimeter sensors. During the 2005 survey, we used two CG-5 and one CG-3M ROVDOG instruments.

Preliminary processing indicates a repeatability of 3.6 μ Gal. This is comparable to the initial survey in 2002, which had a repeatability of 4.3 μ Gal. The uncertainty in the time-lapse values are certain to be significantly greater than what is observed within each survey, due primarily to benchmark instabilities from trawl fishing and sediment scouring.

Further processing and interpretation of the time-lapse gravity and depth data will be ongoing over the next six months. A gravity decrease over the CO₂ reservoir is the primary observable we hope to see. This will allow us to begin to constrain the properties of the CO₂ within the reservoir.

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