

# **A Baseline Gravity Survey over the Sleipner CO<sub>2</sub> Sequestration Site**

**Scott Nooner, Mark Zumberge, Glenn Sasagawa**

Scripps Institution of Oceanography  
University of California, San Diego  
La Jolla, CA 92093

**Ola Eiken, Torkjell Stenvold**

Statoil Research Center  
Trondheim, Norway

## **Executive Summary**

This work, the quantification of gravity change associated with the sequestration of CO<sub>2</sub> at the Sleipner gas field in the North Sea, is a collaborative research effort between US scientists and members of the SACS (Saline Aquifer CO<sub>2</sub> Storage) consortium. At this site, about 1 Mton of excess CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> within the reservoir.

Near predicted reservoir temperature and pressure conditions, CO<sub>2</sub> goes through a critical phase transition in which the density changes from 200 kg/m<sup>3</sup> to over 700 kg/m<sup>3</sup> over a short range of temperature (Span and Wagner, 1996). Thus a slightly higher temperature could result in a much lower CO<sub>2</sub> density. Therefore a feasibility study for monitoring the CO<sub>2</sub> 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/m<sup>3</sup>) shows a peak anomaly of -34 μGal, while the high-density model (700 kg/m<sup>3</sup>) shows a peak anomaly of -7 μGal after 2.268 MT of CO<sub>2</sub> was injected (just over two years). If significant amounts of CO<sub>2</sub> 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.

Gravity was measured on the seafloor above the Sleipner CO<sub>2</sub> injection site from the 15<sup>th</sup> to the 21<sup>st</sup> 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  $\mu\text{Gal}$ . These data will serve as a baseline for future monitoring of the  $\text{CO}_2$  bubble. For time-lapse measurements, there is additional uncertainty associated with the reference null level, determined from stations outside the  $\text{CO}_2$  area, of about 1-2  $\mu\text{Gal}$ . Therefore, the final detection threshold for time-lapse changes is about 5  $\mu\text{Gal}$ . This is considerably better than the pre-survey expectations of 10  $\mu\text{Gal}$ , 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.

Based on the original survey alone, a limited amount of information about the injected  $\text{CO}_2$  can be obtained. Initial modelling, done by making simple Bouguer corrections to the seafloor gravity data, show that detailed models of local geologic features in the surrounding strata are needed to attempt to back out the signal of the injected  $\text{CO}_2$ . Thus, further modelling based on updated seismic results, borehole measurements, and seafloor bathymetry is underway. A future repeat gravity survey is the only way to provide an independent and reliable means to quantify the  $\text{CO}_2$ . We expect that in a second survey, any gravity change will be due to the changing  $\text{CO}_2$  volume, not the presumed stable geologic setting.

## **Experimental**

In microgravity reservoir monitoring surveys on land (e.g. Allis and Hunt, 1986; San Andres and Pedersen, 1993) accuracies of 10  $\mu\text{Gal}$  or better have been achieved by careful use of standard gravimeters. However, ship-borne measurements have uncertainties of several hundreds of  $\mu\text{Gals}$ , 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 on the gravity meters 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 gravity record.

The primary sensor in the ROVDOG instrument is a modified Scintrex CG-3M gravimeter mounted in a compact gimbal platform for leveling and enclosed in a watertight pressure case. A pressure gauge (Paroscientific 31K) was also housed in each pressure case, and altogether three pressure cases were mounted on a frame. The instrument is described in more detail in Sasagawa et al. (2003).

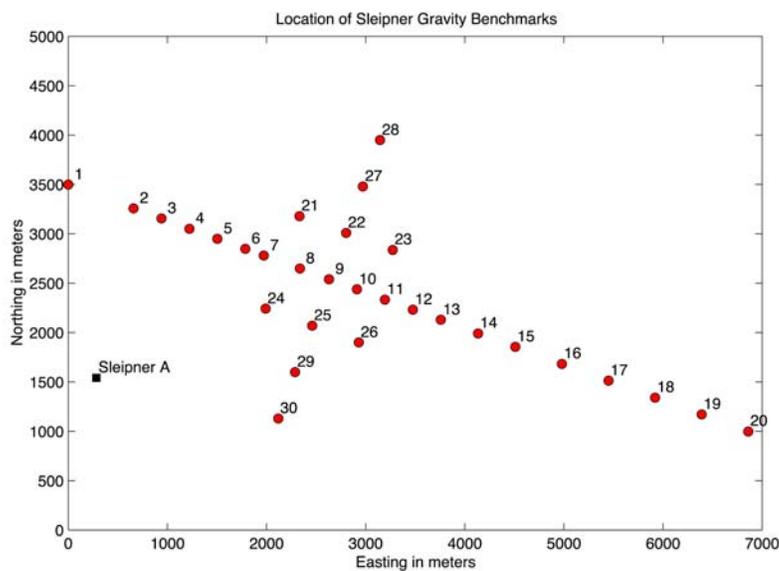
Benchmarks were deployed in a 10-hour period just before surveying, on August 16, 2002. 20 of the benchmarks were placed in a 7.3 km long WNW-ESE profile across the injection point (Figure 1). The distance between stations increases from about 300 m

near the injection point up to 500 m towards the ends. Another 10 locations span the orthogonal dimension and cover the extent of the CO<sub>2</sub> accumulation in 2002.

### ***Marine operations***

The supply vessel *Edda Freya* which has been converted for ROV/Subsea operations was used for the survey. The vessel carries a HIROV 3000 Mk II, which 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.

The gravity measurements were made from the 16<sup>th</sup> of August, 2002, until the 20<sup>th</sup> of August. 115 measurements were made in total, which amounts to about 30 per day. Survey loops of about 7 hours were made with station #9 as the central location. This site was visited 15 times during the four days. All other stations had at least 3 occupations, and the easternmost station (#20), received five visits. This is because it is thought to be well outside the area of CO<sub>2</sub> influence, so will serve as a reference location for future gravity changes.



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

## **Results and Discussion**

### ***Depth estimates***

Processing of depth time series was done in collaboration with Ola Eiken and Torkjell Stenvold at Statoil using in-house developed Matlab code. The mean pressure

from the three sensors was converted to a depth at each site. The depths range from 79.5 m to 83.6 m. For monitoring relative changes, depths are referenced to locations outside the area of gas injection, such as station #20. The standard deviation of station repeats is 0.5 cm. Apart from three outliers, all values are within 0.8 cm.

### ***Gravity estimates***

Processing of the gravity data was also done in collaboration with Statoil colleagues Ola Eiken, Torkjell Stenvold, and Håvard 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.

Visco-elastic relaxation of the quartz springs in the gravimeters causes recovery effects. The size of this effect seen by comparing the mean of the first half and second half of a 20-minute record is -2.3  $\mu\text{Gal}$  on average. Each gravity measurement was about 20 minutes long. This is long enough for this transient effect to pass, as well as reduce the noise from microseisms to acceptable levels.

The gravity values were corrected for solid earth tides and ocean loading using a world-wide tidal model (Agnew, 1996). Sea level height estimates based on reference pressures allowed us to correct the data for imperfections in the tidal model. Instrument drift for each gravimeter was estimated by minimizing the residuals of all repeat measurements in a least squares sense.

The repeatability of the units are 8.8  $\mu\text{Gal}$ , 9.9  $\mu\text{Gal}$ , and 4.7  $\mu\text{Gal}$  for U1, U2, and U3 respectively. Because of the much better performance of U3, the data from this meter was heavily weighted when averaging the three units. After weights of 0.396 (U1), 0.264 (U2) and 2.261 (U3) were used, the repeatability for a single gravimeter is 4.3  $\mu\text{Gal}$ . However, if the remaining error sources are random, station repeatability for all three meters taken together should be about 2.5  $\mu\text{Gal}$  (4.3  $\mu\text{Gal}/\sqrt{3}$ ). For time-lapse changes, additional uncertainty is related to determining the reference zero-level, which is obtained from stations outside the area of influence of the  $\text{CO}_2$  injection. For example, the primary reference station, # 20, was occupied five times with a repeatability of 1.9  $\mu\text{Gal}$ . This error will add to all stations.

### ***Gravity Modelling***

In general the volume that the  $\text{CO}_2$  occupies,  $V$ , is given by

$$V\phi(1 - v_{sh})S = \frac{M_{\text{CO}_2}}{\rho_{\text{CO}_2}} = \frac{M_w}{\rho_w} \quad \text{----(1)}$$

where  $\rho_{\text{CO}_2}$ ,  $M_{\text{CO}_2}$ , and  $\phi$  are  $\text{CO}_2$  density, injected mass, and rock porosity, respectively.

$S$  is the  $\text{CO}_2$  saturation and  $v_{sh}$  is the fractional percent of shale in the formation by volume. Therefore,

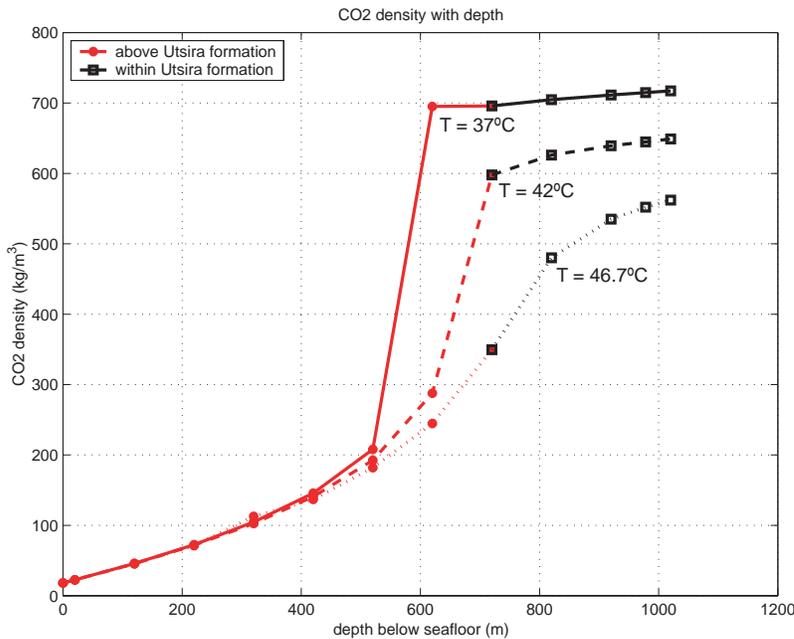
$$\Delta M = M_{\text{CO}_2} \left( 1 - \frac{\rho_w}{\rho_{\text{CO}_2}} \right). \quad \text{----(2)}$$

Near predicted reservoir temperature and pressure conditions,  $\text{CO}_2$  goes through a critical phase transition in which the density changes from  $200 \text{ kg/m}^3$  to over  $700 \text{ kg/m}^3$  over a short range of temperature (Span and Wagner, 1996). Thus a slightly higher temperature could result in a much lower  $\text{CO}_2$  density. Figure 2 shows  $\text{CO}_2$  density with depth for three different temperature profiles to demonstrate this issue.

In order to accurately estimate the saturation, the parameter needed for seismic estimation of mass, a careful treatment of the  $\text{CO}_2$  bubble volume is needed. By inverting  $\Delta g$  while using the seismically determined  $\Delta V$  as a constraint, we can determine the effective density contrast in the bubble. This is related to  $\text{CO}_2$  saturation and density by the following equation:

$$\Delta \rho_{\text{eff}} = (\rho_{\text{CO}_2} - \rho_w) \phi S (1 - v_{sh}). \quad \text{----(3)}$$

The amplitude of the gravity signal will tell us something about the density regime of the  $\text{CO}_2$ . Therefore, making appropriate assumptions about  $\rho_{\text{CO}_2}$ , will give us an estimate for the saturation,  $S$ . In the future, once  $\rho_{\text{CO}_2}$  has been determined, we will be able to directly solve for the change in mass with gravity and seismic volume.



**Figure 2: This shows a plot of CO<sub>2</sub> density with depth for three different temperature profiles, based on the uncertainty in the temperature. The black lines show the location of the Utsira formation in each case. Notice the rapid change in density from 200 kg/m<sup>3</sup> to ~700 kg/m<sup>3</sup>.**

We built a model using the seismically imaged CO<sub>2</sub> horizons in both 1999 and 2001 to constrain the volume of the CO<sub>2</sub>. The total mass of injected CO<sub>2</sub> was taken to be the known value of injected gas. Gravity was calculated from this model at the locations of the seafloor benchmarks by assuming the seismically imaged bubble contains only carbon dioxide in high saturations ( $S = 0.7$ ) and the remaining carbon dioxide was located in a low saturation spherical volume centered at 850 m depth (centered on the seismically imaged bubble). Layer depth was determined using a linear velocity model, and layer thickness was linearly related to reflection amplitude (Chadwick et al., 2002) with the maximum amplitude corresponding to an 8 m thick layer. Porosity was taken to be  $\phi = 0.37$  and the shale volume was taken to be and  $v_{sh} = 0.15$  within the formation. The values for  $\phi$  and  $v_{sh}$  were estimated from tests on core samples (SACS final report, 2000). The change in gravity seen on the seafloor benchmarks in these models depends on the density of CO<sub>2</sub> within the Utsira formation, as discussed above. The maximum change in gravity was calculated to be about  $-6 \mu\text{Gal}/\text{year}$  and  $-2 \mu\text{Gal}/\text{year}$  for  $350 \text{ kg}/\text{m}^3$  and  $700 \text{ kg}/\text{m}^3$ , respectively. This model confirms that we expect to be able to put limitations on the CO<sub>2</sub> density with time-lapse gravity measurements spanning at least 2 years.

To glean information about the CO<sub>2</sub> bubble from the a single year of gravity data, detailed information must be known about the region. 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 preliminary attempt at modelling. A regional gravity signal was also subtracted from the data. However, the shape and size of the local gravity field obscured any obvious CO<sub>2</sub> signature. Therefore, in order to attempt to extract a signal from the single survey, a better subsurface density model is needed for the region.

In order to build a such a model, pre-injection seismic data, core sample data, well logs, seafloor gravity and bathymetry are needed. This data was obtained from Statoil in August/September 2003. Code is 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 and in order to put constraints on the density and mass of the injected CO<sub>2</sub>. Building such a model is not a straightforward task. One problem comes from incomplete data coverage. For example, the density logs are from nearby wells, thus give only an average sense of subsurface density variations. The density logs also all lack information about the upper 500 m of the wells. Small-scale gravity variations, however, can be sensitive to density structure in this upper region. Another problem is that while shipboard gravity data can give us a sense of the long wavelength gravity trends in the area, it is about two orders of magnitude less precise than the seafloor data that we have measured. The seismic records are limited in that it can be difficult to separate noisy data from small wavelength reflectors. Work on interpreting this data and building a subsurface density model is underway.

Reservoir engineers from Scintef have supplied us with the results from their CO<sub>2</sub> saturation and flow models. The models show the results of up to 6 years of injections

for different CO<sub>2</sub> transport scenarios. We have written code that enables us to compute the expected seafloor gravity directly from these models. This will be a useful predictive tool in future seafloor surveys. These models also provide us a good way of visualizing the CO<sub>2</sub> bubble in 3-D.

## Conclusions

The baseline seafloor gravity survey at the Sleipner CO<sub>2</sub> 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). A follow up survey with similar accuracy will allow us to detect a 5 μGal gravity change.

Williamson et al. (2001) modeled gravity changes arising from various scenarios of CO<sub>2</sub> in-situ densities and spatial distributions for a two year period. In the worst case scenario, the maximum gravity change expected would be about -10 μGal for a two-year period of injection. Our modeling, based on the 1999 and 2001 seismically imaged CO<sub>2</sub> horizons, indicate smaller signals (-6 μGal/year and -2 μGal/year for 350 kg/m<sup>3</sup> and 700 kg/m<sup>3</sup>, respectively). It is likely that a change in gravity will be detectable in a future survey spanning two years or more. From the SACS meeting in Trondheim from September 9-10, a repeat gravity survey is tentatively on schedule for 2005. The highly accurate seafloor depth measurements (<0.5 cm) open possibilities of detecting small vertical seafloor movements above the CO<sub>2</sub> plume.

The ongoing modeling of the baseline gravity measurements will provide an estimate of the CO<sub>2</sub> density and mass. The results of time-lapse surveys will be an independent (and perhaps better constrained) check of this. Models that explore lateral spreading of the carbon dioxide, based on time-lapse seismic data, are also being explored. We plan to continue to work in collaboration with reservoir engineers to calculate the expected gravity change for a range of carbon dioxide flow scenarios.

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