Deliverable 1.9: Improved algorithms to acquire and process gravity and deformation data

DigiMon

Digital monitoring of CO_2 storage projects

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1 Introduction

The work presented in this deliverable is part of the efforts to meet the following sub-objectives of the DigiMon project:

- Prepare for integration of DigiMon system by developing and lifting individual components of the system to a common, high TRL.
- Secure optimal performance of the DigiMon system by optimization and validation of processing software for DigiMon system components
- Develop and implement efficient techniques for data acquisition and processing of gravity, seafloor deformation and seismic data.

More specifically, deliverable D2.1 summarizes contributions to the development of two individual technologies, microgravity at the seafloor and seafloor deformation monitoring for applications within CCS.

In total, four individual developments are described in this deliverable. The developments contribute to reducing the cost of gravimetry and seafloor deformation monitoring to make them more feasible for CO_2 sequestration applications, which are more price-sensitive than for the case of oil and gas. In addition, they aim at improving the accuracy of the data to facilitate refined quantitative estimates of the properties of the storage unit and improve CCS management.

Definitions

A **station** is a unique location on the seafloor at which gravity and pressure are measured.

A **concrete platform** (CP) is a seabed station monument made of concrete.

A station **visit** denotes the period during a survey from arriving at a station with an ROV until transit to the next station.

gWatch is OCTIO's new generation of equipment for seabed gravity and seafloor deformation monitoring. It was introduced in 2018 to reduce HSE exposure, improve operational efficiency and improve the data quality in gravity and seafloor deformation surveys.

A **Gravity Monitoring Unit (GMU)** denotes the pressure vessel containing a gravimeter, a vertical-alignment system and a temperature stabilisation system.

DepthView software package for standalone acquisition of seafloor deformation data

A **TSP** is the temperature-stabilised pressure reading system, which contains two pressure containers, one with three Paroscientific Digiquartz pressure sensors and heater elements and one which contains the electronic elements.

The **instrument frame** is the frame that rests on top of the concrete platform during a measurement. It contains three GMUs, a TSP, and a support frame.

A **Gravity Monitoring Platform (GMP)** is the platform installed on the ROV at which the instrument frame rests during transits between concrete platforms.

A **measurement** is a period when the instruments record data at a station for a given station visit.

A **field station** is a station located inside the field, at which gravity and seabed depth are expected to be affected by fluid changes in the storage unit or wider storage complex.

A **zero-level station** is a station located outside the field at which gravity and seabed depths are assumed to be negligibly affected by CO_2 injection.

A **base station** refers to a reference station centrally located in the field which normally is more frequently visited than the rest.

A **tide gauge** refers to one or more tide sensors mounted on a SeaGuard logging platform that is deployed at selected reference stations at the field during data acquisition.

A **reference station** is a station at which one or several tide gauges are deployed.

The **reference pressure** is pressure data recorded by the tide sensors at the reference stations.

2 Method

2.1 The gravity and seafloor deformation monitoring technology

Monitoring of time-lapse gravity changes at the seabed and seabed deformation caused by CO_2 injection into the subsurface provides valuable information on key properties of the storage unit and the fluid dynamics (Furre, Eiken, Alnes, Vevatne, & Kiær, 2017). Time-lapse gravity is sensitive to mass changes in the storage unit driven by CO_2 migration. Seabed deformation is an observable effect compaction/expansion of the storage unit, which is a function of the pressure change caused by injection.

These monitoring technologies rely on periodical surveys in which relative gravity and pressure are measured at a set of locations at the seabed. Seawater pressure is used as the starting point of the processing that allows for accurately measuring vertical seafloor deformation. The measurement locations are defined by concrete platforms (CPs) that are deployed before the first survey to provide repeatability in the measurement position. During each survey, an instrument frame containing three relative gravimeters and three pressure sensors is sequentially positioned on top of the CPs deployed on the field.

The spacing between CPs on the seabed is chosen based on the expected lateral resolution with which gravity and deformation signals can be related to changes caused by CO_2 migration or pressure buildup during the injection. This resolution is in turn mostly determined by the depth of the storage complex and the typical spacing equals the vertical distance between the injected CO2 and the seafloor. However, different phases of the CCS project may call for different survey layouts with a gradual increase of the acquisition area and coarsening of the measurement points.

During a survey, each measurement location is visited at least twice. Each measurement lasts traditionally for 20 minutes. Halfway into the measurement, quality control is performed by the team onboard the survey vessel. If increased noise levels are identified on the gravity or pressure series, the measurement can be extended by a couple of minutes to ensure excellent data quality.

To remove the effect of tides from the gravity and pressure data, tide gauges are deployed in the vicinity of a subset of the CPs at the beginning of each survey and retrieved at the end of the survey. By subtracting tidal effects from the pressure and gravity measurements, all of them are referred to a mean reference sea state and can be compared between consecutive surveys.

Several CPs are deployed at a distance from the field rim and are called zero-level stations. They are of key importance to obtain accurate measurements of the changes in relative gravity and pressure, hence seafloor deformation. By using the constraint that no time-lapse signals are expected at the zero-level stations, one can remove from the time-lapse differences the contribution of effects not related to CO_2 migration within the storage unit or storage complex, like different average sea levels or small differences in sensor calibrations in the different surveys.

The gWatch instrumentation

In 2018, OCTIO introduced gWatch, a new generation of instrumentation for gravity and subsidence measurements (Ruiz, et al., 2020). gWatch consists of an instrument frame containing three gravity monitoring units (GMUs) and one temperature-stabilised pressure measurement system (TSP) as displayed in Figure 2-1. Each GMU contains a state-of-the-art gravimeter, a temperature-stabilization system and a levelling system that ensures verticality of the gravimeter during measurements.

Compared to the gravimeters used in the older-generation equipment, the new gravimeters have smaller recovery effects after sensor tilting and largely reduced sensor drift. The TSP contains three Paroscientific Digiquartz pressure sensors in a temperature-stabilised environment. This temperature stabilisation removes the effect of temperature variations at the seabed from the pressure data.

gWatch has reduced the overall operation cost due to more efficient surveys and the fact that smaller ROVs and vessels can be utilised for the survey.

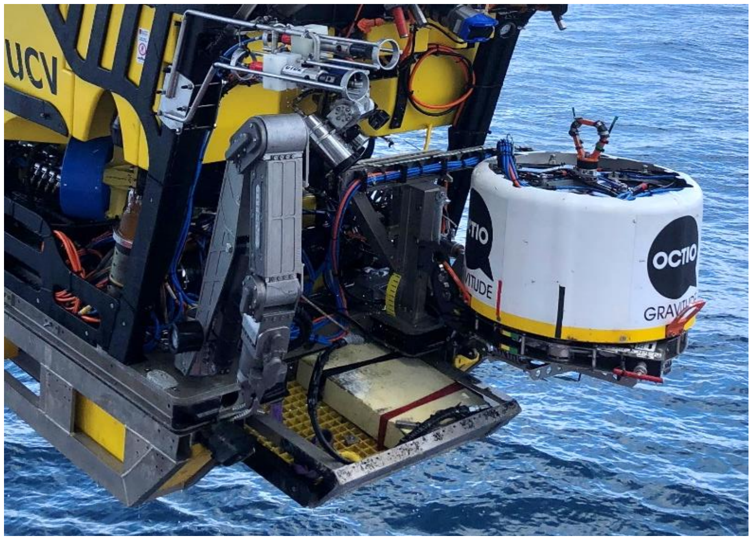

Figure 2-1. The instrument frame on an ROV during an OCTIO survey offshore Norway. The instrument frame is the white cylinder with the OCTIO logo. The instrument frame rests on top of the GMP when transported by the ROV.

The introduction of the gWatch has resulted in more efficient surveys and enhanced data quality, through a combination of improvements in the instrumentation like reduced gravimeter drift, temperature stabilisation and reduced sensitivity to tilt during transits.

These improvements in the instrumentation facilitate new algorithms to acquire and process gravity and deformation data for further improvements in the data accuracy and reductions in the acquisition times.

In the next sections, the developments introduced through the DigiMon project and their impact on improving monitoring technologies for CCS projects are described.

3 New developments

3.1 Validation of standby mode for operating the gravity sensors

A stable gravity series throughout the measurement is a necessary condition for minimizing measurement times and, hence, reducing the overall acquisition times. Stability in the gravity readings is best achieved by keeping the instrumentation in mechanical and temperature equilibrium throughout the survey. This development addresses both these issues.

During operations, the gravity sensors are subject to large tilts and accelerations and the electronics works actively to balance the test mass in the spring. This introduces local heating in the electronics, that propagates to the thermometer used for temperature-stabilizing the core of the sensor. As a result, the temperature correction on gravity is slightly off for some minutes after the measurement starts at the concrete platform. This self-heating effect is seen in the gravity measurements as an initial stabilization time, lasting typically from 1 to 5 minutes.

As a fix to the self-heating problem, the manufacturer of the gravity sensors, Scintrex, introduced a new standby mode, designed to be activated during transits between measurement locations. When set on that mode, the electronics do not aim to balance the effect of acceleration and tilt of the test mass. Therefore, no self-heating is expected, and internal thermometer readings are expected to be correct from the beginning of the measurement.

The new standby mode will be activated automatically between measurements in all the new CG-6 units produced by Scintrex when they are operated through the standard console used on land. Offshore, however, the standard of data quality is higher, and cost implications make it critical that conditions are stable during surveying. Hence, before implementing this development offshore with the potential benefit of significantly reducing the measurement times, extensive testing was required.

Through the DigiMon project, a dedicated test schedule for the implementation of the standby mode to the gWatch equipment for operations offshore was conducted before the first year of operation.

The tests included extensive measurements in the lab, in addition to the validation of the standby mode through a direct comparison of the performance of the sensors with and without standby mode enabled in an onshore calibration campaign.

The calibration of the gravimeters was performed in Jondal between the 2nd and 5th of June in 2020 by Gravitude AS. The calibration range lies in Jondal and consists of two stations. The lower station is close to sea level by the Hardanger fjord. The upper station is at the Folgefonna ski resort, 1200 m above sea level. The stations are 25 min apart by car. In the calibration, in addition to studying the performance of the sensors with and without standby mode activated, an updated scale factor is computed for each gravimeter based on comparison with measurements performed with an absolute gravimeter at the same calibration site in 2018 and 2020.

The data acquired were processed using the gView software package. In the assessment of the calibration data, the effect of standby mode was evaluated by utilizing high-quality measurements where the whole measurement could be analyzed, in total nine measurements. To assess the impact of elevated tilts during transits, only measurements preceded by a van transit were included.

The stabilization time is quantified by computing for each measurement the time it takes for the cumulative average of gravity to stabilize to a value within 0.5 µGal of the average in the whole measurement. The time it takes to reach this measure gives information on both the amplitude of the initial offsets in the gravity readings and the rate at which the time series converge. Results are presented in Table 1 and show that there is a clear improvement when the standby mode is utilized.

Table 1: Time passed (number of samples) before gravity cumulative average stabilizes to within 0.5 µGal.

	GMU 201	**GMU 202**	**GMU 203**	**GMU 204**	**GMU 205**
Stand-by enabled	3300 (5.5 min)	1500 (2.5 min)	2000 (3.3 min)	3400 (5.7 min)	2100 (3.5 min)
Stand-by disabled	8800 (14.7 min)	5400 (9.0 min)	3800 (6.3 min)	4800 (8.0 min)	4700 (7.8 min)

Another key performance factor for microgravity at the seafloor is the magnitude and stability of the gravimeter drift during operations which determines the overall stability in the gravity readings during a survey. From the calibration data, it was seen that the drift of the GMUs shows similar magnitudes and signs with and without standby mode enabled, with one sensor showing a slightly higher drift without standby mode activated.

An overall assessment of the data quality from all the sensors did not disclose any issues as a result of activating the standby mode during the transits. The calibration campaign, therefore, resulted in a clear recommendation that standby mode should be enabled during all transits for the offshore gravimetry surveys.

With the gWatch instrumentation and the implementation of the standby mode, the measurement time required to obtain a high-quality gravity measurement has decreased from 20 to 15 minutes. For a survey with 300 measurements, this gives a total saving of 25 hours of survey time.

3.2 DepthView software package for standalone acquisition of seafloor deformation data

The equipment required for measuring seafloor deformation (pressure sensors) is significantly smaller and lighter than that required for measuring relative gravity. While gravity needs to be acquired in dedicated surveys that ensure careful handling of the sensitive gravimeters, the measurement of seafloor deformation has a good potential of being combined with other measurements in any survey utilizing an ROV or AUV.

The lower deployment cost and operational synergies can make it beneficial on some occasions to measure seafloor deformation independently from gravity. Within the DigiMon project, a new variant of the gView software has been developed to efficiently support the acquisition and processing of seafloor deformation data in realistic field applications. The software is called DepthView and provides the functionality required for both combined surveys and surveys aiming exclusively to obtain vertical seafloor deformation measurements.

During gravity and subsidence surveys, the measurement time at each location (defined by a CP) is determined by the time required by the gravimeters to provide a stable and robust measurement. This time is typically 15 minutes with the new gWatch instrumentation including the developments described above. On dedicated seafloor deformation surveys or combined operations not aiming for gravity measurements, it will be important to reduce the time required for measuring water pressure at each location to the minimum, to reduce total survey time and cost.

In particular, OCTIO has demonstrated that 2-mm accuracy can be obtained with a measurement time of five seconds. Thanks to the patented temperature-stabilized TSP technology, this is regardless of whether the ROV/AUV has recently transited through the temperature gradient in the water column. In order to allow for this high resolution, the DepthView software has been developed to:

- Be completely based on water pressure measurements and remove any dependency on gravity data
- Automatically identify from the pressure and tilt series the stable period corresponding to the stable measurement on the CPs, without the need for dedicated logging
- Automatically introduce corrections if tilt series have some time delay compared to pressure series
- Produce information that allows characterizing the quality of individual measurements (e.g. duration of stable peak and size of tilt corrections)
- Base the drift estimation and uncertainty estimates in a reduced number of repeat measurements, as coming back to the same measurement location can be problemàtic in combined surveys.

The DepthView software developed under this project has been successfully tested in real field operations in which seawater pressure has been measured in a combined operation with Seismic node retrieval (Hatchell, Ruiz, Libak, Nolan, & Agersborg, 2019).

3.3 Reduce sensitivity to off-axis placement of the sensor frame on the concrete platforms

For concrete platforms with tilts reaching the tolerance limit, deviations in the positioning of the centre of the sensor frame relative to the centre of the CP can introduce a sizeable error in both depth and gravity. For a tilt of 5 degrees, positioning the sensor frame 2 cm off the CP centre introduces an effect of 1.7 mm in depth and 0.4 µGal in gravity.

The sensor frame is equipped with a central camera. Under DigiMon, OCTIO has developed the software that allows reducing this source of error (see Figure 2), by providing a measurement of the distance between GMF and CP symmetry axes, that can be combined with the accurate tilt measurements. The correction opens for a more time-efficient operation, as the requirement on centred positioning of the frame on the concrete platform will be less stringent.

This development is estimated to have an average impact of reducing the operational time during positioning of the instrumentation by on average a minute per measurement. In addition, it can be useful for the initial phases of the development of fully unmanned gravimetry surveying, as it will allow loosening the requirement on the accuracy of the placement of the sensor frame on the CP. Finally, this processing based on automatic image processing is considered to be a first step towards future autonomous operations, that will require an automatic identification of the right position to deploy the frame.

Figure 2: A picture that was taken during a measurement by the central camera at the frame. This image, together with measured tilt, can be processed to obtain a correction for both gravity and subsidence.

4 Summary and conclusions

Through the Digimon project, developments for enhancing the applicability of 4D gravity and seafloor deformation monitoring for CCS are implemented. The developments are directed along two main fronts: facilitating cost reductions and improving data accuracy.

In this report, three main developments are described. The first one is the validation of new functionality to reduce the thermal disturbances on the gravity sensor during data acquisition (standby mode) for offshore operations. The second is the development of a new DepthView software package to facilitate standalone services for measuring seafloor deformations. And, as the last one, new functionality for image recognition to measure the placement of the frame at the concrete platform during measurements.

Each of the developments provides value for CCS monitoring campaigns. Through increased accuracy in the data, the sensitivity to subtle changes in the subsurface is improved. With a linear relationship between the data and the property to be monitored (4D gravity depends linearly on mass changes and seafloor subsidence has a linear relation to pore compaction to the first order) a 30% improvement in the data accuracy, corresponds to a 30% improvement in the sensitivity.

Cost reductions are mainly achieved through the implementation of measures to stabilize the instrumentation throughout the survey. Activating the standby mode was observed to reduce the stabilization time of the gravimeters providing high accuracy data earlier in the time series. This again facilitates a reduction in measurement time per station by more than 15% which significantly reduce the survey duration and costs.

Still, in a gWatch campaign, acquiring gravity and seafloor pressure measurements in combination, it is the requirements on the accuracy in the gravity data that drives the measurement times and, hence, survey costs. Developments within the DigiMon project has contributed to making seafloor deformation monitoring available as a standalone service or a service that can be implemented in combination with other measurements utilizing ROV or AUV. For CCS these developments are important in facilitating a cost-efficient monitoring supplement in cases that reactivation of faults and mapping the pressure plume are significant uncertainties in the management of the CCS storage site.

The final development (an accurate measure of frame placement through image analysis) is motivated by the ambition to improve data accuracy in addition to progress towards more autonomous operations were placing the instrumentation on the concrete platform are based on image analysis.

The Snøhvit gas field monitoring case demonstrates the enhanced data value to our customers with the improved gravity and subsidence monitoring accuracy obtained from the novel data processing algorithms in part developed through the DigiMon project (Ruiz, et al., 2020). During the 2020 survey at the Ormen Lange gas field, OCTIO reduced per station measurement time by 15% and the overall number of measurements by 13%. Further, OCTIO delivered the lowest total station uncertainties to date on the field: 0.61 µGal for gravity and 3.7 mm for seabed depth (www.octio.com).

5 References

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