Automatic CO_2 detection based on a modified NRMS coefficient: Example of Greensand.

Introduction

CCS projects are becoming paramount to decrease the CO_2 footprint in the atmosphere and mitigate climate change. In the Greensand Phase 2 project, offshore Denmark and co-funded by EUDP, a pilot injection of CO_2 was conducted into a depleted oilfield in the first quarter 2023. In conjunction with the first injection a new geophysical monitoring approach with a low environmental impact and enabling a higher monitoring frequency than standard 4D seismic, Spot seismic (Al Khatib et al., 2021), has been applied. Reliable, low cost, low impact and lean monitoring approaches are key for public acceptance and delivery of CCS projects. We show that a special processing flow, developed for spot monitoring, can be used to automatically detect the CO_2 in specific location of the subsurface that are targeted to validate or invalidate injection scenario, enabling a predictive maintenance approach.

Acquisition and processing

The seismic acquisition to monitor the CO_2 pilot injection consisted of 3 campaigns, the baseline survey in January 2023 and two monitor surveys, the first after approx. 2000 tons injection (early March), the final monitor after 4000 tons injection in the last week of March.

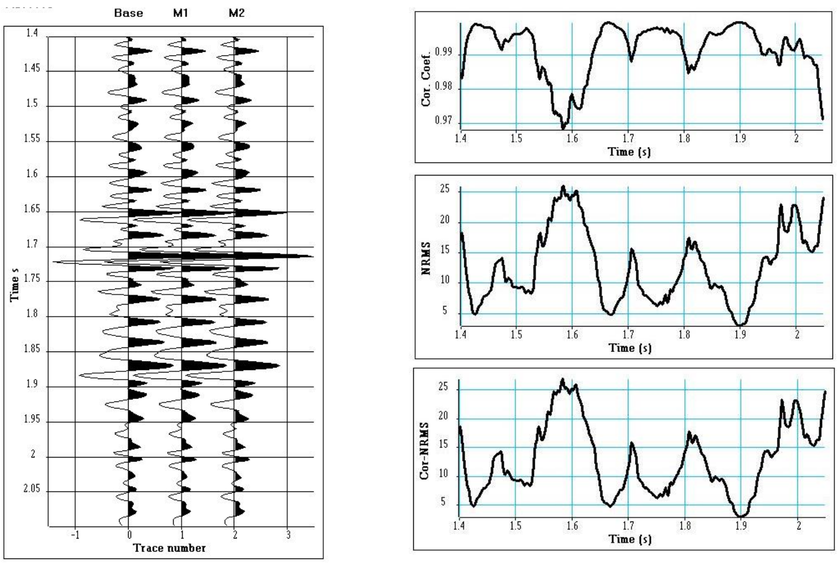
The receivers used had been 25 Mass III™ ocean bottom nodes from TGS at 17 locations, some of the locations had several nodes deployed to test repeatability and for redundancy. Most of the node positions were chosen “optimally” (Mogan et al., 2020) to gain reflectivity information from 7 target spots. A small compressor triple-air gun array with 600in³ total volume was used as source. Multiple shots were fired at a static location for each single source location to evaluate the repeatability of the seismic traces and increase the signal to noise ratio by stacking.
The acquisition provided three seismic data sets for the individual source-receiver pairs A new processing method has been recently developed and implemented to honor the specific data characteristics of these common spot gather (Al Khatib & Mari, 2023).The first steps include a stacking of the spot gathers for the individual spots and campaigns. This results in the MSG (monitoring spot gather) which consists of only three traces per spot and receiver-source combination, one each for baseline and the two monitors. After a spectral balancing a stratigraphic deconvolution is carried out, to derive an operator between the baseline trace of the MSG and the corresponding trace from the vintage 3D migrated cube. For this process a static compensation of receiver and source depth and NMO correction must be applied. The aim of this step is to reduce the ghost and bubble effects as well as other multiples. This operator is only derived for the baseline if no time lapse events had happened between vintage 3D seismic and focused seismic acquisition. The resulting operator is applied to the three traces of the MSG. An example of MSG processing, including stratigraphic deconvolution and long period amplitude compensation, applied to spot 7 can be seen in figure 1a.

Data QC

Before data processing, the repeatability of the seismic traces is evaluated by NRMS coefficients (Kragh and Christie, 2002) computed from a set of shots (40 in average) recorded for each single source location at each monitoring time (base and monitors). Repeatability is good for NRMS values ranging between 0 and 20, medium for NRMS values ranging between 20 and 50 and poor for NRMS values higher than 50. Table 1 gives the results obtained for Spot 7.

Monitoring time	NRMS (average value)	NRMS (Std)
base	24.6	1.74
Monitor 1	20.8	5.6
Monitor 2	27.9	4.8

***Table 1** Spot 7: NRMS versus monitoring time before MSG processing*



a b

Figure 1 Spot 7: MSG processing results (a), time variant attributes: Cor. Coef., NRMS, Cor-NRMS (b, from top to bottom)

NRMS values (table 1) indicates the good repeatability of the raw data, with a weak dispersion indicated by the standard deviation value (Std). As quality control, correlation coefficients and NRMS coefficients are computed between the base and the monitors M1 and M2 at the first step (vertical stack) and at the last step of the MSG processing (fig 1a). The results in table 2 show a good repeatability between the base and the monitors. A high value of correlation coefficient indicates a high similarity between the base and a monitor in terms of phase. A low value of NRMS indicates a high similarity between the base and a monitor in terms of amplitude.

	MSG processing – first step		MSG processing – last step	
Monitoring time	NRMS	Cor. Coef.	NRMS	Cor. Coef.
Base – M1	21.9	0.976	11.8	0.99
Base – M2	19.8	0.98	15.3	0.98

***Table 2** Spot 7: NRMS and correlation coefficients versus monitoring time after MSG processing*

To detect time variant changes in the seismic traces after MSG processing between the base and a monitor (M1 or M2), a set of attributes are computed in a 50 ms sliding window. The attributes are NRMS, correlation coefficient and Cor-NRMS. Cor-NRMS is defined as NRMS to correlation coefficient ratio. An anomalic value of Cor-NRMS indicates both a change in phase and amplitude between the base and a monitor. Figure 1b shows the variation of the attributes observed between the base and M2 for spot 7. We note that the correlation coefficient is very high and stable (average value: 0.99, standard deviation: 0.07), NRMS is low and stable ((average value: 12.7, standard deviation: 5.9), Cor-NRMS behavior is like NRMS behavior. Consequently, light monitoring at spot 7 does not detect any change between January and March 2023.

CO$_2$ detection at Spot 1

The procedure used for spot 7 is applied to spot 1. In a first step the data repeatability of the 3 surveys (base and monitors M1 and M2) is evaluated by NRMS values which show a poor result (table 3). NRMS values larger than 50 are probably due to a low signal to noise ratio and depth fluctuations of the source array.

Monitoring time	**NRMS (average value)**	**NRMS (Std)**
Base	55.6	10.74

Monitor 1	72.9	16.1
Monitor 2	73.9	16.7

Table 3 *Spot 1: NRMS versus monitoring time before MSG processing*

During the acquisition, the far field signatures of the source are recorded for all the shots of the 3 surveys giving the opportunity to compute operators for debubbling and deghosting the data at each shot. After debubbling and deghosting, NRMS values are recomputed. NRMS values indicate a medium repeatability (table 4). Consequently, the MSG processing is applied on the seismic data after debubbling and deghosting. The results are shown in figure 2.

Monitoring time	**NRMS (average value)**	**NRMS (Std)**
base	33.9	12.6
Monitor 1	47.1	9.4
Monitor 2	49.3	10.2

Table 4 *Spot 1: NRMS versus monitoring time after debubbling and deghosting before MSG processing*

As for Spot 7, correlation coefficients and NRMS coefficients are computed between the base and the monitors M1 and M2 at the first step (vertical stack after debubbling and deghosting) and at the last step of the MSG processing (fig 2a). The results in table 5 show a medium repeatability between the base and the monitors.

	MSG processing – first step		MSG processing – last step	
Monitoring time	NRMS	Cor. Coef.	NRMS	Cor. Coef.
Base – M1	36.8	0.93	41.5	0.91
Base – M2	56.3	0.84	54.1	0.95

Table 5 *Spot 1: NRMS and correlation coefficients versus monitoring time after MSG processing*

Figure 2b shows the variation of the attributes observed between the base and M2 for spot 1, using a 50 ms sliding window. We note that correlation coefficient (average value: 0.81, standard deviation: 0.2), NRMS (average value: 58.4 standard deviation: 30.1) show anomalic values in the 1.64 – 1.69-time interval, which is clearly highlighted by the Cor-NRMS coefficient. Consequently, light monitoring at spot 1 detects a significative change between January and March 2023, which is attributed to the presence of CO2 in the reservoir (figure 3). The result matches the expectations from simulation results. The same results (not shown here) are also obtained using the data without debubbling an deghosting process before the MSG processing.

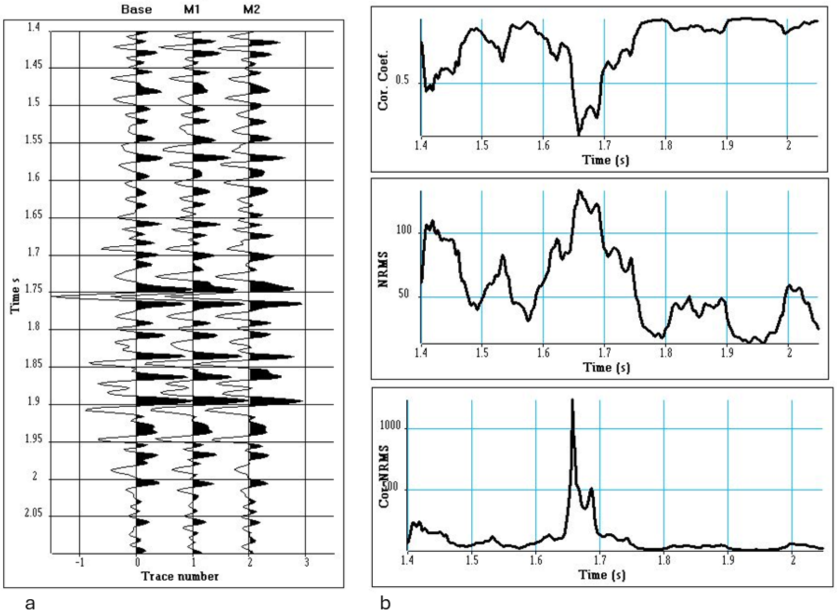


Figure 2 *Spot 1: MSG processing results after debubbling and deghosting (a), time variant attributes: Cor. Coef., NRMS, Cor-NRMS (b, from top to bottom)*

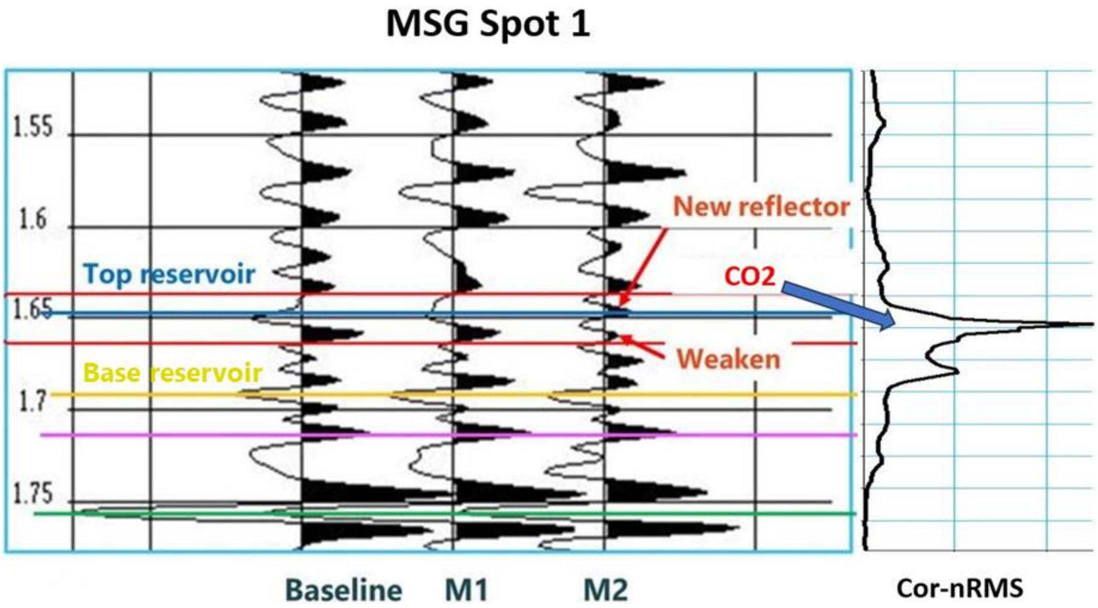


***Figure 3** CO_2 detection at Spot 1 by Cor-NRMS attribute*

Conclusions

A focused seismic monitoring method was successfully tested during the Greensand pilot study.

Seismic measurements were carried out before, during and after CO_2 injection to test the monitorability of the CO_2 plume with a single trace approach, providing information only form specific target spots. Before applying any processing flow, repeatability of the data is evaluated by NRMS at each survey independently (base and monitors) but also between the base and the different monitors. It is also shown that debubbling and deghosting can be benefitted to increase the repeatability of the data. A dedicated processing flow for such a seismic data set was developed and allowed to detect differences in the seismic traces caused by the injected CO_2. Such differences, detected by a specific attribute, named Cor-NRMS, are visible at the reservoir level at Spot 1 close to the injection location and at a structural up dip location. No effect is visible at locations down dip (spot 7) which was used as a “control Spot”. This matches the expectations from simulation results.

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