Monitoring with high repeatability using lightweight acquisition patterns

Monitoring subtle evolutions of geological reservoir using seismic method require a high repeatability of seismic acquisition over time. State of art solution known as 4D permanent reservoir monitorings (PRM) rely on comparison of accurate images of the reservoir at different vintages. The repeatability of images is achieved by laying permanently receivers and / or sources. Onshore, Canadian heavy oil SAGD reservoir at Peace-River (Berron et al. (2015)) has been successfully monitored for more than two years continuously, but required the drilling thousands of source and receiver 40 m deep wells, to bury 1490 hydrophones, and cement 49 piezo-eletric sources. Offshore at Ekofisk, a North Sea reservoir (Bertrand et al. (2013)), nRMS values as low as 3.5% were achieved, but required the trenching of more than 200 km of Ocean Bottom Cables (OBC) 1.5 m below the sea floor and additional 40km of connection cables. Acquisition compaigns required the mobilisation of a supply vessel for 40-50 days twice per year. Such acquisition patterns delivered unmatched 4D data quality, and allowed for the detection of very small 4D effects, but had a high environmental footprint and data heavy processing sequences.

In the context of CO_2 monitoring, where social acceptability is key and economics much more limited, we can't reproduce these heavy patterns and rather need to rely on lightweight, frequent, field monitorings. CCUS fields are always covered by seismic cubes and petro-elastic models are usually available. Building on these, instead of generating full 3D images of the field at each vintage, we can focus the monitoring on identifying changes on dedicated spots (Al Khatib et al. (2021)) using carefully taylored acquisition patterns. To efficiently monitor CO_2 injection, we use flow model simulation output to position a few spots (from 3 to less than 20), depending on the extension of the field, and expected CO_2 plume (Morgan et al. (2020), Brun and Chen (2023), Roth et al. (2023)). The number of sources and receivers are of the same order. This leads to very small footprint on the surface, which can take into account both human installation, as well as wildlife whereabouts. Operations are safer and require less time, which can be dedicated to carefully place sources and receivers to enhance the repeatability of traces from their very early acquisition. Acquisition parameters and equipement can be finetuned to reach the expected detection threshold.

In the present paper, we analyse three different lightweight acquisition patterns deployed on real focused monitoring projects, with similar reservoir depth. The repeatability of acquired data is measured before and after application of a processing sequence, and assessed against their capacity to detect expected changes in the reservoir.

Onshore gas storage usecase

On this field, four selected locations (spots) have been monitored daily over a 220 days period with a single vibrator. The acquisition pattern consisted of 6 receiver antenna and 3 vibrator positions (Morgan et al. (2020)). Receiver antennas were composed of buried hydrophones at 15, 20 and 25 m depth. On each source position, 50 sweeps have been emitted over a period of one hour, on selected locations by a small vibrator. Those 50 sweeps have then been summed together, and form a daily monitor.

Reapeatability of each daily monitor is then evaluated against nRMS (Kragh and Christie (2002)), and cross-correlation values. We compute the repeatability of each day with respect to the previous day, and average of the daily metrics. Measuring both values and not only nRMS is interesting, as nRMS is more sensitive to amplitude variations while cross-correlation reflects time-shift variations. After simple daily summation, monitors show nRMS values ranging from 5% to 20% except of one receiver level on spot 105 probably due to water table level issue (figure 1, left panel). According to Kragh and Christie (2002), these values are considered good. After a processing sequence aimed at stabilising time shifts in the overburden, nRMS values are improved below the 20% good nRMS threshold with values below 5% as shown on figure 1, right panel and most cross-correlation values exceed 0.99. This allowed for the successful detection of gas injection of the field, in accordance with results provided by the operator (Morgan et al. (2020)).

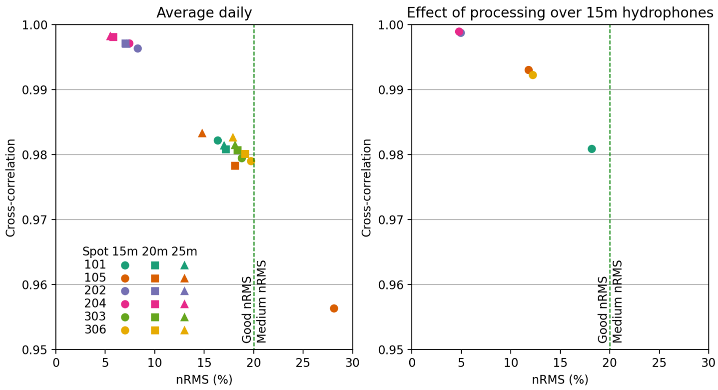

Figure 1 *Reapeatability of raw and processed data on onshore gas storage field. Left panel depicts repeatability of daily summed data for each spot, and each hydrophone level. Right panel depicts the repeatability improvement observed after processing of data, with respect to the shallowest (15 m) hydrophone level. On both panels the vertical dashed line at 20% nRMS depicts the good vs medium nRMS values, as stated by Kragh and Christie (2002).*

Onshore EOR using CO_2 injection

The field is located in Saskatchewan, Canada. Injection of CO_2 has been used for Enhanced Oil Recovery (EOR) for more than twenty years and, since 2000, 4D seismic has been the tool of choice for reservoir surveillance. On one pad of this field, between 2020 and 2022 a focused monitoring pilot has been conducted on 16 specific spots (Brun and Chen (2023)). The design was composed of 16 surface geophones, and 15 source locations. Source was a 1 kg dynamite, shot in 12 m deep cased wells.

We analyse 6 selected spots and compute repeatability indicators between base and monitor 1 (B-M1, on figure 2), monitor 1 and monitor 2 (M1-M2), and base and monitor 2 (B-M2). nRMS values of the raw data are mostly in the medium range between 20% and 50% with some values above 50%, while correlation values are pretty good and generally over 0.9 (figure 2, left panel). The difference between previous example and this project can be explained by three main elements: sensors are non permanent, located on the surface and the use of dynamite prevented temporal stack. The processing sequence was composed of a mute, spectral equalisation and several filtering operations aimed at maximizing signal-to-noise ratio of the reflected waves. It was followed by the application of a global calibration operator aimed at stabilising time shifts (Brun and Chen (2023)). It clearly improves nRMS and correlation values, as on most spots, nRMS values reach 35% with some below 20% which is considered good nRMS values. Correlation values are also improved with values above 0.95. This seismic acquisition pattern was repeatable enough to successfully detect the CO_2 plume and its subsequent replacement by water over the two years monitoring period (Brun and Chen (2023)).

Offshore CCUS project

This field is an offshore CCUS project, located in the North Sea (Roth et al. (2023)). It has been monitored over a period of 3 months, during winter 2023. A baseline was acquired before CO_2 injection, and two monitors were acquired, respectively after 2000 tons and 4000 tons of CO_2 injected. A total of 7 spots have been monitored, with 25 Ocean Bottom Nodes (OBN) spread on 17 chosen locations, and 7 source locations. To minimize environmental footprint while maximizing operations, a 600 in^3 trigun source was used onboard a standard supply vessel. The vessel was mobilized for 1-2 days for each survey. For the baseline, each source location has been shot 80 times with a location accuracy < 1 m. Following baseline QC showing good repeatability, we adjusted acquisition parameters and reduced number of shots to about 50 on each source location.

Using the same nRMS / Cross-correlation repeatability evaluation as previously, we analyse 3 selected

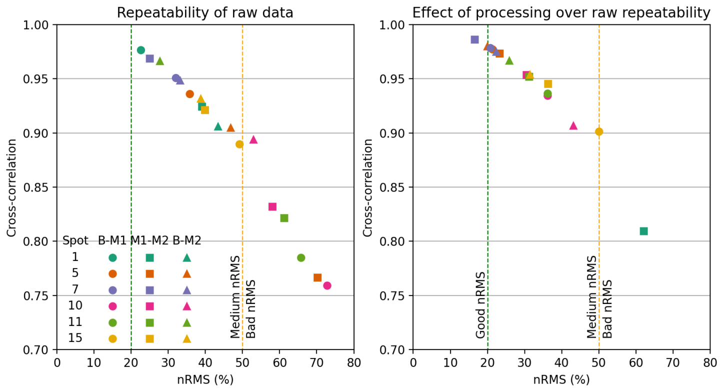

Figure 2 *Reapeatability of raw and processed data on onshore CO_2 assisted EOR field. Left panel depicts repeatability of 6 selected spots between each acquisition sequence. Right panel depicts the repeatability improvement observed after processing of data with a focus on stabilizing timeshifts. On both panels, the vertical dashed lines at 20% and 50% nRMS delimit the areas of respectively good and medium nRMS and medium and bad nRMS (Kragh and Christie (2002)).*

spots (figure 3). While spots 1 and 7 have been monitored twice in addition to the baseline, only baseline and 2^{nd} monitor were acquired for spot 6. We computed repeatability indicators from baseline to monitor 1 (B-M1 on figure 3, left panel), monitor 1 to monitor 2 (M1-M2) and baseline to monitor 2 (B-M2). When computing repeatability indicators on raw data nRMS and correlation values were not very good, with all nRMS values ranging from 30% to more than 120% which is considered bad repeatability, according to Kragh and Christie (2002). The traces were then debubbled and deghosted, and a dedicated processing sequence was applied. It consisted of amplitude recovery, mute, frequency filter, deconvolution, statics and NMO corrections (Al Khatib and Mari (2023)). The nRMS values have been improved to values globally below 10% (figure 3, right panel). Since the processing sequence is aimed at stabilizing time shifts we observe however a significant improvement of the correlation values with all values above 0.9, and some as high as 0.99.

These repeatability values were sufficient to successfully detect the very small amount of CO_2 injected over the winter 2023 campaign (Roth et al. (2023)), thus validating the sparse monitoring solution.

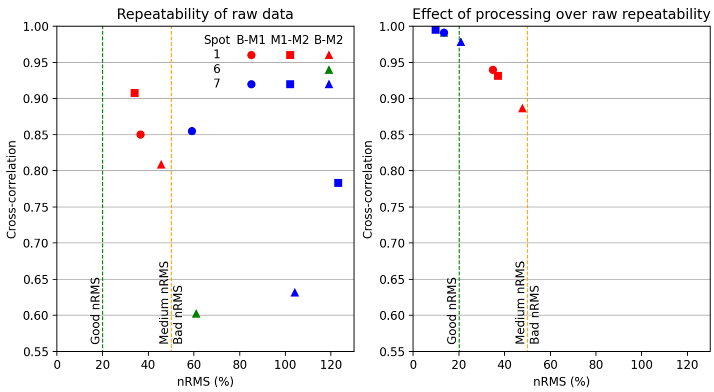

Figure 3 *Repeatability of raw and processed data on offshore CCUS field. Left panel shows nRMS vs correlation values of raw data, for each spot and acquisition sequence. Right panel shows the effect of the debubbling / deghosting followed by the processing sequence on both nRMS and correlation values. On both panels, the vertical dashed lines at 20% and 50% nRMS delimit the areas of respectively good and medium nRMS and medium and bad nRMS (Kragh and Christie (2002)).*

Conclusion

Traditional 4D PRM acquisitions require high fold to achieve good image quality, and represent a high upfront cost that seems not compatible with CO_2 economics. Using the available knowledge on most CCUS field, combining petro-elastic models, flow models and seismic, we can focus light seismic monitoring on key spots by identifying optimal source and receiver surface positions. Using this study, we have now some guidelines to finetune the selection of the most appropriate operations model: permanent or temporary source / receivers, surface or buried equipement, and temporal fold. With the growing deployment of focused monitoring projects, we are gathering more and more information which in return helps enhance these focused seismic survey designs.

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