SEG Workshop - Geophysical Research Towards Gigatonnes CO2 Storage

The SpotLight Proposal

PART 2: GEOPHYSICAL RECOMMENDATIONS FOR GEOLOGICAL CARBON SEQUESTRATION FOR OPERATORS AND REGULATORS

14/06/2024

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I. Introduction and method

Operators willing to develop CCS geological storage site, are required to provide evidence to the regulating authorities of the safety and security of the storage. They must provide a Monitoring, Measurement and Verification (MMV) plan describing the strategies and technologies used to control the containment and the conformance of the storage, along the CCS lifecycle and continued years after the end of the injection (Di Filippo et al., 2024). Monitoring the CO_2 plume propagation in the subsurface required geophysical methods, seismic and non-seismic (Huang, 2022). Conventional seismic technologies, widely used in the petroleum industry, includes 2D and 3D seismic imaging methods. 2D/3D seismic acquisitions are repeated at different calendar times to provide time-lapse images of the subsurface (commonly called 4D seismic). The advantage of seismic methods is the following: it provides a comprehensive characterization of the storage and overburden and a time-lapse monitoring to survey potential changes due to CO_2 injection (IEAGHGH, 2020). Although these imaging solutions are effective for reservoir monitoring (Kazemeini et al., 2010), they concurrence surface activities, impact the natural environment and are excessively expensive (Lumley, 2021).

As an alternative, SpotLight company designed a focused monitoring approach, targeted toward a "spot" within the subsurface, using an ultra-light seismic system: only one source and one or a set of receivers. It means that only a small set-up is needed for the acquisition (Al-Khatib et al., 2021). This technique aims to monitor the effect of the injected fluid in the formation and detect potential changes if present. It can be deployed with agility and survey the subsurface as often as needed. It establishes a frequent temporal density monitoring tool targeted at specific reservoir locations. The technology has been applied on various offshore and onshore cases, in the US, in Canada and in Europe (Brun et al., 2022, Ollivier et al., 2023), demonstrating the robustness of the solution and suitability for long-term CCS monitoring. The benefits of the solution are as follows:

- Enables more frequent focused monitoring.
- Significantly reduces environmental impact.
- Is cost-effective with low initial investment without compromising on result quality.
- Enhanced acceptability from regulatory & stakeholders' perspectives.

SpotLight's approach is adapted to each site's risk assessment and management plan. It is a data-centric method and adapts to any new information acquired on the field (Dean and Tucker, 2017). Especially, it leverages the reservoir model predictions (already supporting operational decisions) and selects monitoring spots location accordingly with the forecasted CO_2 plume propagation front. It aims at controlling the alignment between the predicted and the observed reservoir properties variation, and the integrity of storage containment. This approach enables to take timely preventive or corrective actions when issues are detected, in other words, it is valuable for decision making. It also can play the role of an early warning alarm that can lead to trigger other monitoring seismic technologies such as 2D, 3D or VSP seismic. The SpotLight's process is called Predictive Maintenance: a long-term monitoring procedure, to strategically determine where and when seismic measurements should be focused.

II. SpotLight focused monitoring principle

The SpotLight focused monitoring aims to use a single source-receiver pair (Figure 1). A survey design must be done to locate the best source & receiver positions. The demigration is used to link seismic events on the seismic migrated stack with its corresponding source-receiver positions in the data survey layout (Figure 2) (Al-Khatib et al., 2021). These raw traces are then extracted and sorted by offset, creating a new kind of gather specific to the focused monitoring concept called "CSG" (Common Spot Gather). A CSG shows all the traces that are contributing to the imaging of the targeted spot. The optimum selection step, consisting of selecting among the CSG, the best traces using geophysical criteria and surface conditions. The noise associated with land acquisition will be avoided so that demigrated spot is not affected by the noise affection reflections, such as surface waves and refraction.

The acquisition design is then based on the positions of those contributory raw traces. This allows the design proposed by SpotLight to be based on real field conditions and ensure an optimal acquisition.

The optimal trace from the raw data is considered as a baseline for time-lapse monitoring. The monitor acquisitions are planned based on the same source and receiver positions.

III. Predictive maintenance for an effective decision-making process

The Predictive Maintenance integrates focused seismic methods with dynamic model predictions of the CO_2 plume evolution. Its objective is to provide spot positions and optimal monitoring calendar to validate or invalidate injection scenarios and controlling containment integrity.

Dynamic reservoir models are built using geological data, well information, seismic interpretations, and legacy production parameters. The models are mathematically computed and follow physical rules of fluid dynamics, geomechanics and statistics. They are essential tools in planning and monitoring underground CO_2 injection projects (Barros et al., 2021). The dynamic model outputs (CO_2 saturation maps) are used to create differential CO_2 maps by calculating the variances between successive timestep models. These variations in CO_2 saturation across the reservoir, while informative as such, are strategically utilized for precise spot position identification both in space and time. The position of these spots would be the point where the highest variance is recorded and where the model can be validated or invalidated. An example of this procedure is highlighted in Figure 3, where these variance maps extracted from monthly dynamic models are presented, also called **intensity maps**. From month 0 to month 10, we can observe the intensity maps calculated from successive saturation maps, on which the spots will be automatically positioned at the highest variance values. The propagation of the intensity map represents the propagation of CO_2 plume versus time. Frequent confirmations and/or updates of the model increase the confidence in the injection plan and verify conformance of the storage. Other spots are added to this procedure, used as containment spots. Near the injection point a calibration spot is added, while away from the CO_2 plume, control spots are added where no saturation variance is assumed. To verify containment and prevent leakage, guardian spots are added in high-risk location such as faulting or abandoned wells, to minimize risk and ensure that injected CO_2 did not reach those points. If the models are not matching predictions, a more advanced technology such VSP, 2D, or 3D seismic can be triggered. In other word SpotLight predictive maintenance can play the role of a trigger technology, so that a technology such as 3D seismic is deployed when needed.

IV. Complementary geophysical methods

SpotLight operational model is agile and can deployed in synergy with other geophysical monitoring techniques, such as micro-seismic antennas and DAS-VSP. If a Vertical Seismic Profile (VSP) is already existing with fibre optic DAS receivers, the focused seismic is designed to target the same spot. The outcome of this synergy is to mutualize source and receiver locations, as well as the monitoring spot. Figure 4 highlights how focused monitoring and DAS-VSP should be used in parallel to monitor the same location in the subsurface.

SpotLight is currently testing and developing synergies with the micro-seismic monitoring method. If micro-seismic stations are installed in the field for a given monitoring target, a focused seismic design would be implemented to target the same location. Figure 5 shows an illustration of a micro-seismic antenna installed at few meters below the surface. The outcome of this synergy is to deploy active and passive seismic methods together, to mutualize source and receiver locations, as well as the monitoring spot.

V. Operational model and cost

SpotLight objectives are a minimal environmental impact and cost, without degrading signal to noise ratio. Thus, alternative equivalent light solutions will be considered. As an example, seismic vibrator can be replaced by is a smaller "Minivib". The number of sweeps is adapted to reach the same level of energy.

The cost of a SpotLight monitor for an **onshore** storage can be estimated by considering the parameters below:

- Equipment: a small source and few seismic sensors provided by local suppliers
- Duration: around a day
- Obstruction: limited to few meters

As a result, the overall cost for the surveillance of an **onshore** CO_2 storage site, with SpotLight, has been estimated to 5 times smaller than using conventional 2D or 3D seismic. Additionally, as mentioned above, SpotLight operational model accounts for mutualization and synergies with other technologies, thus reduce the overall costs.

The operational model described above has been used for numerous projects in Canada, to monitor different types of 4D effect. It is a proven agile, environmentally friendly and cost-effective solution: three essential factors for CCS projects.

VI. Conclusion

SpotLight technology is a **low-cost** and **high-benefit** technology. It can be used for addressing capacity, containment, contingency and public acceptance risks related to CCS. The advantage is that it provides information about the presence or absence of CO_2 in the subsurface and can detect early enough discrepancies with reservoir engineers' expectations. While the CO_2 storage behave as expected, no further actions are required. It is only when SpotLight detects early-stage deviations with the predictions, that operators would trigger more cost-intensive mitigation and remediation solutions. With an ultra-light operational model, it can be deployed frequently and at limited cost. Moreover, it accounts for mutualization and synergies with other technologies deployed on each field. It unlocks the optimization of the monitoring strategy. It this sense, SpotLight technology truly provides **an alarm for the surveillance of CCS storage.**

VII. References

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VIII. Appendices

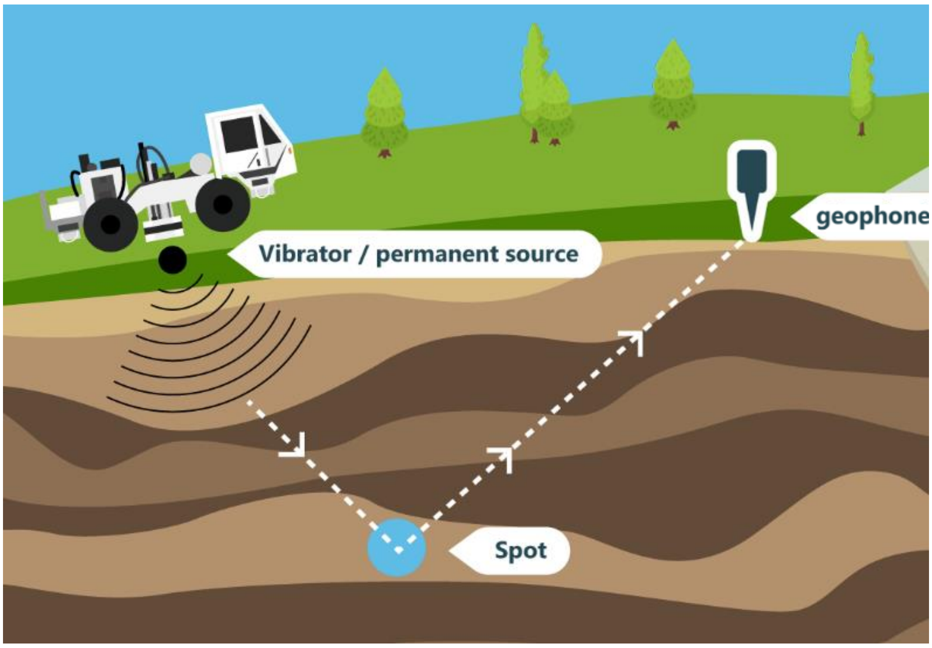

Figure 1: SpotLight single-source and receiver acquisition system deployed onshore.

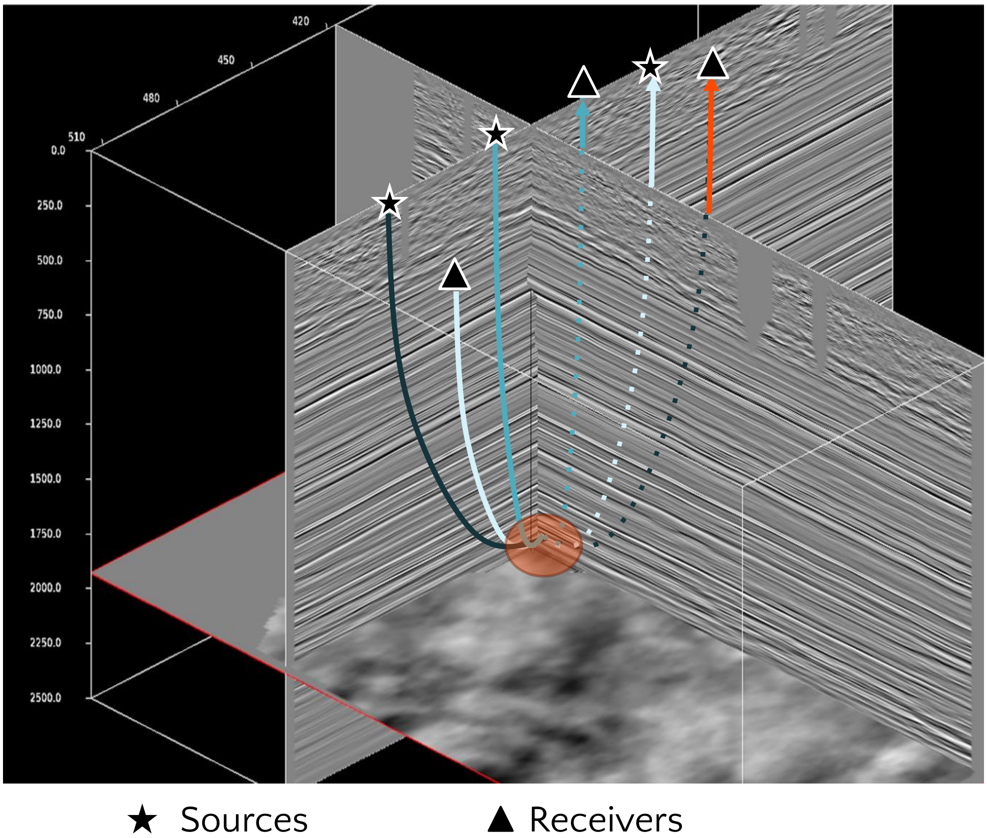

Figure 2: Diagram illustrating the process of demigration for a given spot in a 3D seismic cube, connecting the targeted spot to the source and receiver positions on the surface.

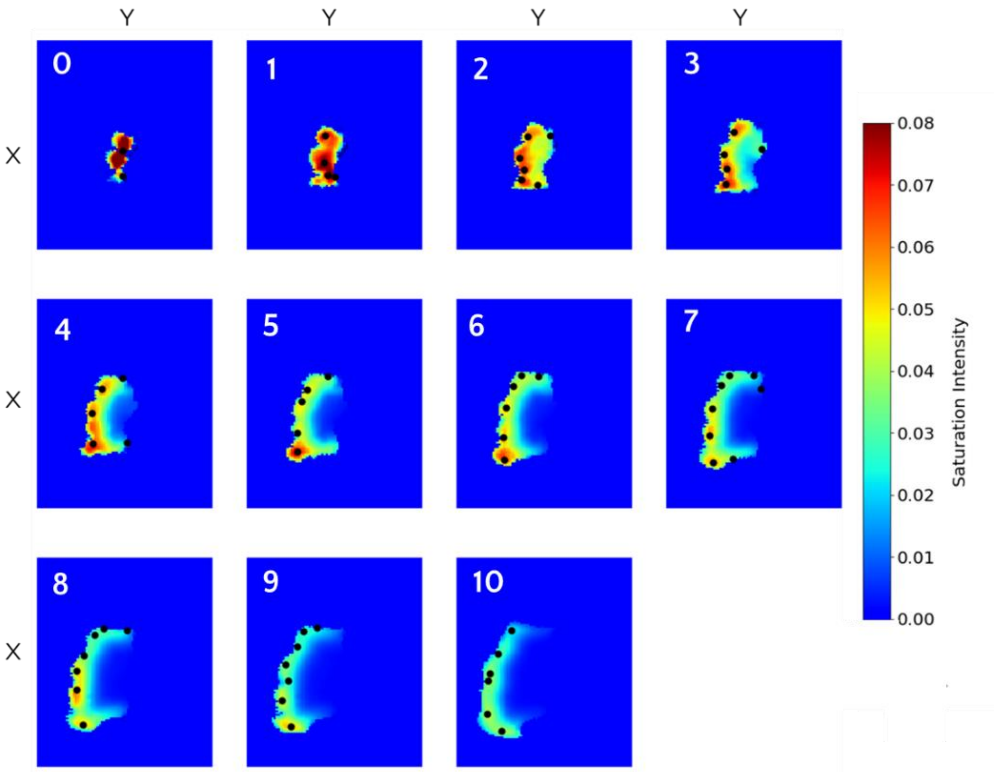

Figure 3: Saturation Intensity Map (colored background, no dimension) for every month simulated with spot positions (black dots). Number of months is written in white on the maps. Spot positions are automatically computed.

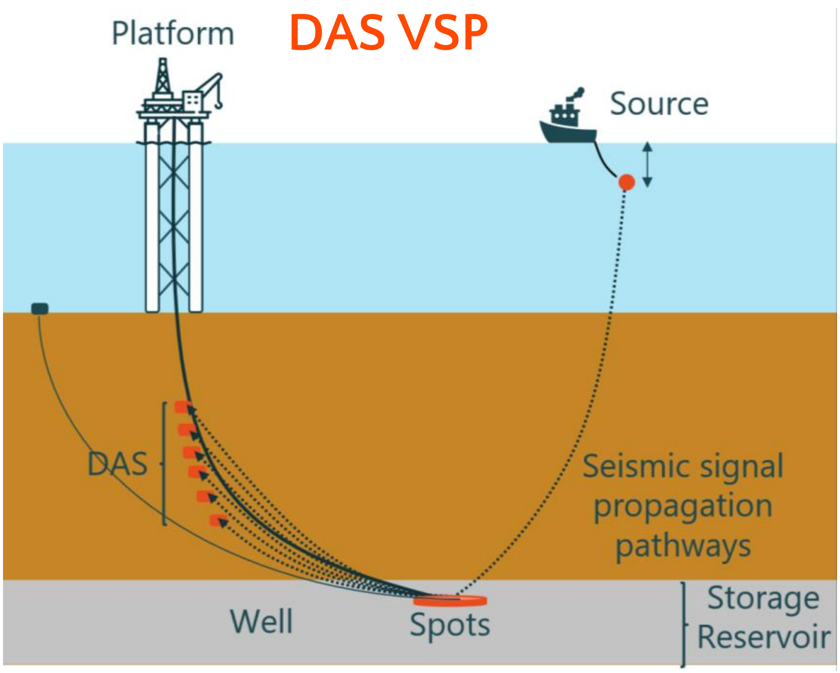

Figure 4: Representation of synergy between DAS-VSP and SpotLight focused monitoring targeting the same spot.

Figure 5: An example of a microseismic antenna that could operate in synergy with SpotLight focused seismic to target the same spot. The microseismic monitoring method is part of the CarbonWatch monitoring package for CCS, to which SpotLight focused monitoring has been added (source: www.bakerhughes.com).