Smart DAS uphole acquisition: hybrid geophysical approach for enhanced imaging and monitoring below complex near surface

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Summary

This study tackles onshore seismic monitoring challenges, focusing on near-surface noise and data repeatability. Conventional methods, such as surface seismic and multi-well 3D VSPs, face limitations, leading to the smart DAS uphole acquisition system's development. This system uses shallow vertical DAS arrays (50-500 m deep, 100-1000 m apart) linked by surface DAS cables, enhancing channel count without relying on deep wells.

The smart DAS uphole system combines surface seismic and borehole geophysics benefits for improved imaging and near-surface characterization. Field tests validate its cost-effectiveness and efficiency against traditional buried sensors. The study explores various 3D configurations for effective reservoir and gas storage monitoring, with a focus on scalability.

Design considerations involve optimizing uphole depth and array spacing, particularly beneficial in Carbon Capture and Storage projects for monitoring horizontal injectors. Successful field trials demonstrate the system's robust imaging capabilities in challenging environments.

In CCS projects, the system introduces cost-efficient acquisition geometries, improving signal-to-noise ratio and repeatability. It provides 3D coverage similar to surface seismic, but with the advantages of buried receivers. Smart DAS Uphole Acquisition System excels in onshore applications through integration of surface and borehole techniques, offering precise imaging and monitoring in complex near-surface conditions.

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Introduction

Reflection-based seismic monitoring for onshore reservoirs and gas storages faces challenges like strong near-surface noise and non-repeatability. Traditional surface seismic struggles with these, while multi-well 3D VSPs are limited by deep wells. A novel solution is the smart DAS uphole acquisition system (Bakulin et al., 2017). It uses shallow vertical arrays (50-500 m deep, 100-1000 m apart) for better data quality, avoiding reliance on deep wells. Long DAS cables connect these arrays, enabling efficient acquisition with a small number of interrogators. This hybrid approach combines surface seismic and borehole geophysics, providing improved imaging and near-surface characterization. Field tests show its effectiveness, offering a cost-effective alternative to buried point sensors. We outline potential scenarios for various 3D configurations from grid to multi-azimuth and discuss their scalability for extensive 3D monitoring of reservoirs and gas storages.

Smart DAS uphole acquisition system

The advancement from surface seismic to vertical array sensors marks a significant leap in seismic data quality and reliability for subsurface imaging and monitoring, including applications in Carbon Capture and Storage (CCS). Traditional surface seismic, while offering flexible sensor placement, struggles with near-surface noise and data repeatability, demanding complex processing and large crews. Conversely, buried receivers provide clearer reflections and less noise, reducing the surface density of the arrays. Figure 1 (left) illustrates a dense (50x50 m) system of shallowly buried point sensors effectively monitoring a CO2 Enhanced Oil Recovery (EOR) project within a carbonate reservoir in a complex desert environment (Bakulin et al., 2018; Jervis et al., 2018).

The shallow DAS uphole acquisition system (Figure 1, right) emerges as a hybrid solution, blending the advantages of buried sensors with the flexibility of surface seismic. This approach employs shallow, interconnected vertical DAS arrays to boost channel counts and decrease surface hole density, crucial for CCS projects where precision and minimally invasive methods are paramount. The system's adaptable placement is particularly useful for imaging and monitoring long horizontal injectors or producers in CCS operations.

This research examines the smart DAS uphole acquisition system, focusing on its real-world application, efficiency demonstrated in synthetic case studies and field tests, and its suitability for 4D monitoring. Additionally, the study highlights near-surface characterization capabilities of this innovative system, underscoring its role as a game-changer in seismic data acquisition for CCS and other subsurface monitoring applications.

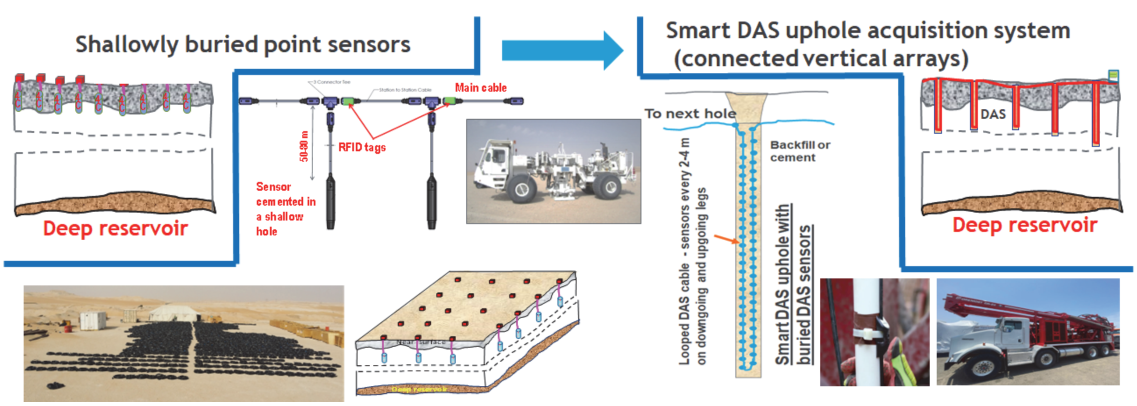

Figure 1 *Progression from a dense system with shallow buried point sensors (left) to a sparse connected vertical DAS arrays (right), dubbed Smart DAS uphole acquisition system.*

Survey design considerations

Figure 2 showcases the 2D and 3D acquisition geometry for the innovative system. Utilizing deeper smart DAS upholes, the spacing between vertical arrays can be increased, leading to a sparser system layout, as shown in Figure 2a. This approach is particularly beneficial in 3D configurations (Figure 2b), as it substantially reduces the number of upholes that need to be instrumented. However, it's important to note that, despite the wider spacing, the dense sensor arrangement in the vertical dimension enables the system to maintain a trace density comparable to that of shallowly buried point sensors (Figure 1, left) or surface seismic methods. The fiber cable, which is either backfilled or cemented in place (refer to Bakulin et al., 2022), ensures optimal coupling. The fiber's small size and low cost make it well-suited for permanent installations. Additionally, the vertical arrays have a minimal surface footprint, and if the connecting fibers are trenched, the entire system becomes fully buried and invisible from the surface. The complexity of shallow drilling also plays a significant role. For instance, if significant drilling challenges arise beyond a certain depth (e.g., 150 meters), it may be more economical to limit the holes to this depth rather than aiming for deeper holes (such as 300 meters). However, to maintain the same trace density with 150-meter holes, the spacing between the holes must be decreased by a factor of $\sqrt{2}$, which is a crucial factor to consider in survey design.

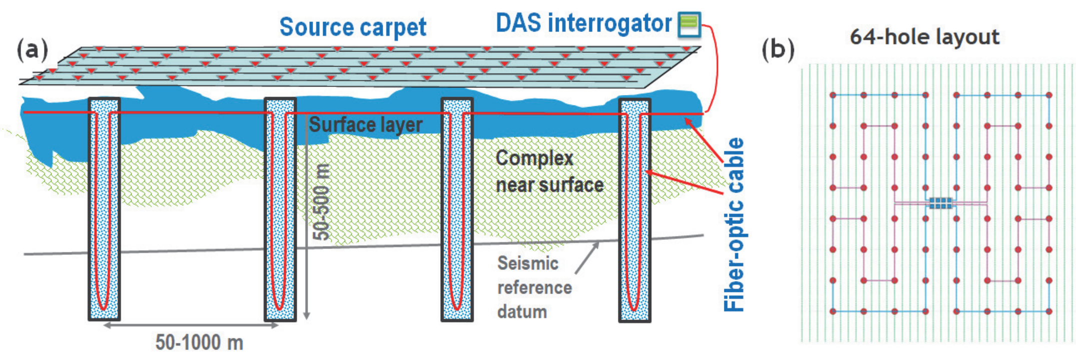

Figure 2 *Smart DAS uphole acquisition system in 2D (a) and 3D (b).*

Field evaluation

Figure 3 presents a summary of field testing results for the 2D smart DAS acquisition system, compiling findings from multiple studies including Bakulin et al. (2017) and Smith et al. (2019). The experiment involved six connected DAS upholes (shown in red in Figure 3b) with varied depths. The system utilized 1,180 channels spaced at 4 meters, with 299 channels in vertical arrays and the rest on the surface. Acquisition used several 2D lines with vibroseis sources, resulting in 2843 vibrator points. The focus was on downhole channels due to their sensitivity to near-vertical *P*-wave reflections, whereas horizontal sections recorded groundroll and refracted energy for near-surface modeling. Data comparison with modeling showed high-quality field data, with horizontal surface sections capturing refracted events and surface waves, while reflection events were absent due to horizontal directivity. Modeling suggested that increasing receiver depth would enhance signal-to-noise ratio and visibility of reflections. Field data confirmed this, showing clear subsurface reflections on vertical DAS channels but not on horizontal fiber segments (Figure 3d). For processing, a cross-line stack of three shot lines was performed to improve signal-to-noise ratio. Data was projected from downhole locations to the surface using conventional static time shifts, followed by typical seismic data processing. This resulted in robust prestack reflections suitable for deep imaging. Comparing the smart DAS uphole acquisition with 2D surface seismic revealed similar reflectors in both, although DAS data contained more linear noise (Figure 3d). After processing, both datasets showed similar amplitude spectra, confirming the broadband nature of DAS channels. Ultimately, both DAS and geophone data revealed identical targets and structures (Figure 3e), demonstrating the efficacy of the smart DAS uphole acquisition system in challenging environments like deserts. This experiment showcased the potential of this system for robust, detailed subsurface imaging and monitoring.

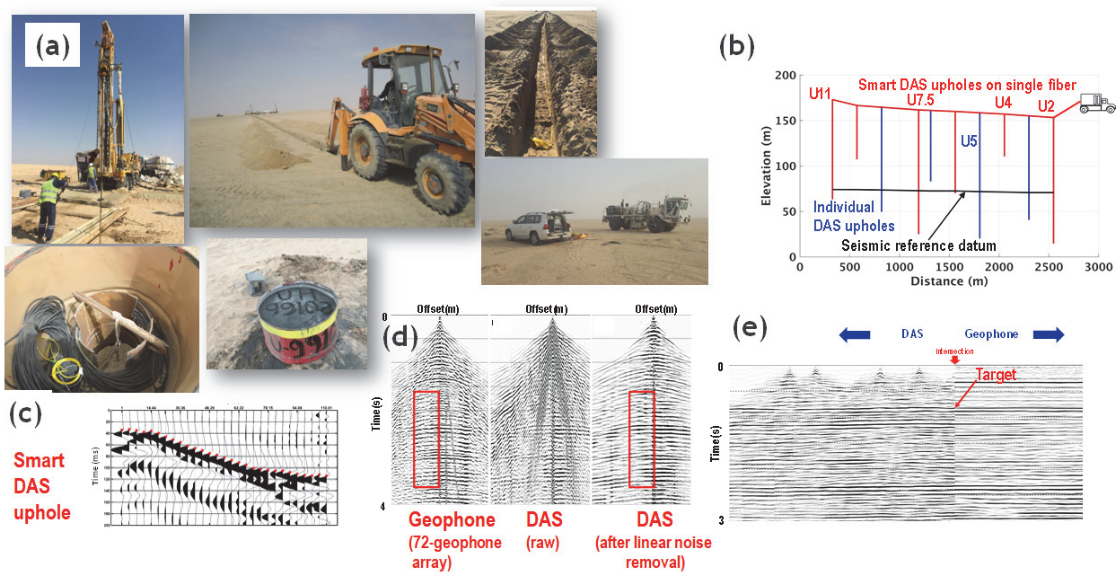

Figure 3 *Field trial of the 2D smart DAS uphole acquisition system: (a) photographs taken during the acquisition phase; (b) the actual DAS acquisition layout; (c) example data from an uphole at zero offset; (d) pre-stack reflection data displayed in common-receiver gathers using both DAS (vertical cable, 15 m depth) and surface geophone arrays; (e) the ultimate stacked images derived from both traditional surface seismic and the smart DAS acquisition method, as documented by Bakulin et al. (2017).*

Monitoring project design

Following the successful field testing and refinement of acquisition procedures, from drilling to fiber deployment (Bakulin et al., 2022), the system is now slated for use in seismic monitoring projects in challenging onshore desert environments. The need for highly repeatable, durable, and cost-effective receivers is crucial for monitoring over the whole projects' lifespan, especially considering that sand movement along could alter the surface topography by several meters over a few years (Jervis et al., 2018) having drastic impact on repeatability.

Figure 4a presents potential acquisition geometries centered around fiber technology for cost efficiency. The DAS VSP monitoring is estimated to map areas up to a 400-meter radius around the well, making suitable for early near-well monitoring (Figure 4b). In contrast, the smart DAS uphole acquisition system offers 3D coverage akin to surface seismic but with enhanced Signal-to-Noise Ratio (SNR) and repeatability due to buried receivers. If the time-lapse signal proves significant, a simpler multi-azimuth design using only a few select uphole lines might suffice (Figure 4a, red lines). This approach is similar to the multi-azimuth 2D walkaway DAS VSP as reported by Harvey et al. (2022), but it boasts the advantage of not being confined to deep wells and offers uniform coverage that can be tailored by the placement of smart DAS upholes. In comparison, walkaway VSP's fold/illumination tends to decay with depth and faces limitations due to the fixed position of borehole DAS arrays (Figure 4b).

Conclusions

The Smart DAS uphole acquisition system, initially designed for desert environments, has proven effective for various onshore applications. Utilizing interconnected shallow upholes with DAS fiber, it achieves precise seismic imaging and monitoring under complex near-surface conditions. Field tests confirm its robust imaging capabilities, comparable to traditional surface seismic, thanks to its high signal-to-noise ratio and dense channel sampling. This system excels in detailed near-surface

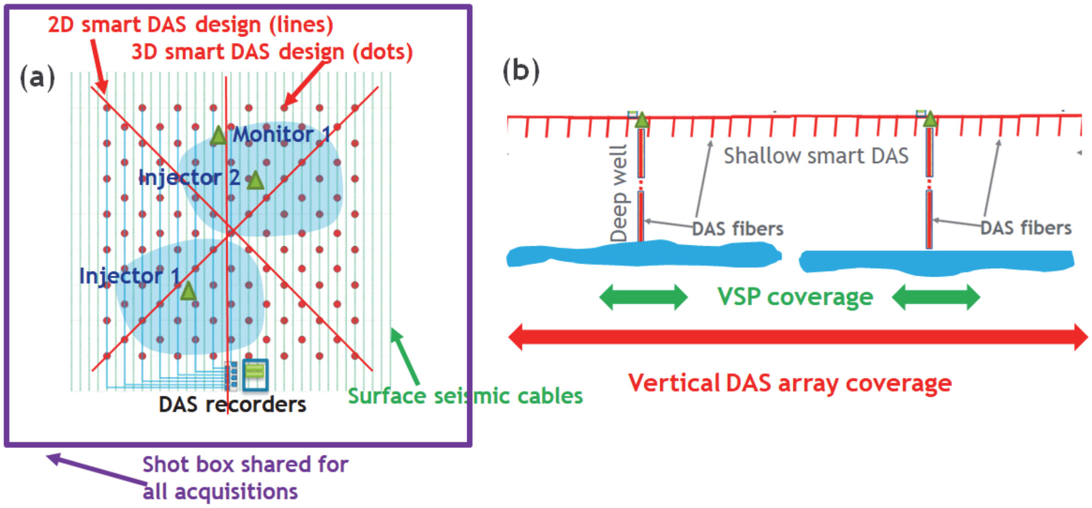

Figure 4 *(a) Illustrates a potential design for seismic monitoring, showcasing a combination of 4D geometries that include surface seismic, DAS Vertical Seismic Profiling (VSP), and smart DAS uphole acquisition arranged in an orthogonal grid and multi-azimuth configurations. (b) Presents a cross-sectional view detailing the fiber layout for DAS systems. This highlights the limited coverage offered by VSP due to the constraints of the borehole array. In contrast, the smart DAS acquisition system features an expandable design that mirrors the broader coverage typically associated with surface seismic methods.*

challenges posed by shallow overburden, offering enhanced data quality from its buried receivers. Furthermore, its scalable design for buried-receiver seismic monitoring makes it a cost-effective solution, mitigating limitations associated with traditional buried geophone arrays. With the increasing demand for efficient monitoring of subsurface CO2 and H2 storage, as well as oil and gas reservoirs, the Smart DAS uphole acquisition system stands out as a viable option for onshore reservoir monitoring. Its integration of surface seismic and borehole geophysics techniques makes it a comprehensive and versatile tool in cost-effective exploration and monitoring.

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