Optimal digital arrays for land seismic exploration in desert environments

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Summary

While single sensor acquisition using autonomous nodes is emerging as the preferred method for land seismic acquisition in many regions, geophone arrays are commonly used to improve field data signal-to-noise ratio (SNR), especially in areas with strong near-surface scattering noise such as karstic desert environments. Typically, arrays are formed in hardware, with a single output channel being a summation of signals from multiple geophones. Single sensor recording allows for arrays to be formed digitally – so-called digital group forming (DGF) – either on the acquisition system itself, or downstream in processing. Application of DGF directly on the acquisition system produces data deliverables to processing that are analogous to existing cabled-array outputs, greatly simplifying the transition from cabled arrays to single sensor recording with nodes. Availability of the original single sensor data assists processing of the DGF data and ultimately single sensor data can also be taken through to imaging if desired.

We performed a field test to acquire dense single-sensor land seismic data and test various DGF strategies in processing. The field test demonstrates that DGF can be performed directly on the acquisition system, and leads to a preferred DGF design that can be applied in real time during future nodal seismic production.

Introduction

Recent developments in land seismic acquisition have focused on enhancing the efficiency, scalability, and data quality of cableless recording systems. Cable-free systems offer significant advantages, including greater flexibility in survey design, the ability to access challenging terrain, and reduced environmental impact. Additionally, they minimize equipment maintenance and eliminate the risks associated with cable damage, leading to more reliable data acquisition and higher-resolution seismic imaging. Cost per channel is also significantly lower with nodes, enabling denser and larger single-sensor receiver spreads with rich offset and azimuthal sampling, bringing many benefits downstream to processing.

While nodal acquisition systems bring multiple advantages, their practical application in large-scale desert environments, and the value of the single-sensor data they produce, remains somewhat underexplored. This study aims to address the question of how nodal survey designs can be optimized to augment and/or replace conventional cabled array acquisition using strings of 6 or 9 geophone elements for various acquisition scenarios. To achieve this goal, we conducted a field trial whereby a static spread of ~16,000 single-sensor nodes was deployed alongside a 3D production survey that used a 9-geophone cabled array per channel (3x3 array with 8.33m sensor spacing inline and crossline, 25m channel spacing inline, see Figure 1).

Nodes were collocated with geophones along one receiver line to allow testing of various digital arrays during processing. The central part of this receiver line was instrumented with a total of 13 sublines of nodes with 8.33m inline and crossline spacing to allow testing of larger digital arrays with crossline dimension up to 100m. Analysis of these large arrays is outside of the scope of this study, instead we focus on data from the full receiver line with collocated nodes and geophones.

The nodes recorded continuously for ~14 days during vibroseis source acquisition for the full crossline offset range of the main production survey. Source lines were oriented orthogonally to receiver lines and spaced at 100m with 25m inline station spacing. The source geometry was designed for the production 3D survey and therefore provides relatively sparse sampling for imaging using the single receiver line for which nodal data is available. However, this geometry is adequate for the purpose of this comparative study.

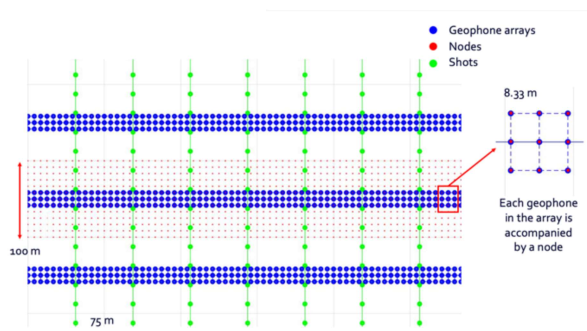

Figure 1. Schematic representation of the acquisition geometry including shot points (green dots), geophone arrays (blue dots) and nodes (red dots).

Digital Group Forming of Single Sensor Data

When forming digital arrays from single sensor data, we should consider both the spatial pattern of sensors used to form the array, and the flow used to pre-process and combine the sensor data into the DGF output. The two are interrelated as the array geometry controls the applicable set of pre-processing tools. The field test design allowed us to compare six DGF patterns (Figure 2) with end-member scenarios of 9:1 decimation (i.e., one node per station at 25m inline spacing) and the full single sensor data without DGF. Two main DGF flows were evaluated: straight summation equivalent to hardware-formed arrays wired in serial (referred to as DGF-*N* where *N* describes the number and shape of the input sensor element pattern), and pre-processed DGF including trace editing, *k*-filtering and a dune static correction (referred to as pp-DGF-*N*). For example, DGF-9 emulates the field data output by the production cabled system used in this field test.

DGF-9 was generated directly on the nodal harvesting system in the field during the test, demonstrating that it is feasible to produce a DGF output as a field deliverable in addition to, or instead of, the single sensor data. The in-field DGF software implementation is generic. Any arbitrary DGF flow, including pre-processed DGF if required, can be performed on-the-fly. For logistical reasons, the remaining DGF designs used in this study were generated in an office environment, although still using the node harvesting server and its edge-processing environment (Ourabah, 2025).

An additional advantage of digital array forming is that the position of each single sensor node is exactly known, allowing correct weighting of each trace in the DGF summation and correct computation of the array's centre of gravity. For hardware-formed arrays, individual sensor locations are unknown and the centre of gravity is assumed as the staked station location. Cabled arrays as actually deployed frequently deviate from the theoretical pattern, for example when sensors are bunched on steep dunes. These deviations introduce unknown errors into the cabled dataset that cannot be identified or addressed in processing. Similarly, quality control can be performed on the single sensor data before digital array forming, allowing bad data to be rejected without contaminating the DGF output. Common operational issues such as sensor tilt, spike noise, or reversed sensor polarity invisibly introduce errors into analog-array data that negate all noise attenuation effects of cabled arrays, even if only a single sensor element is affected (Goujon & O'Toole, 2024). Bad traces are trivial to detect and reject on single sensor data, ensuring consistent and high quality DGF output.

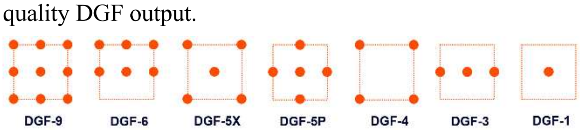

Figure 2. DGF patterns tested in the field trial.

Processing

A simple amplitude-preserving pre-stack time migration processing sequence was applied to each DGF dataset. A smooth velocity field appropriate for the relatively flat geology of the survey area was used for all migrations. Refraction tomography was performed to generate a near surface model using first breaks picked on the single sensor data. However, for practical reasons, only dune statics were applied. These statics were calculated using the dune velocity function from Hanafy et al (2020) and applied as intra-array statics to the pre-processed DGF datasets only. Random noise attenuation and linear noise attenuation were performed in 2D. 3D Kirchhoff pre-stack time migration was used for imaging and included nine source lines contributing to available DGF receivers.

Results

Comparison of the raw shot gathers shows that DGF-9 is, as expected, identical to the 9-geophone array cabled system output after correcting for the instrument response, which was required as the nodal sensor is a piezoelectric accelerometer with a flat response between 1–125 Hz whereas the cabled array uses 10 Hz velocity geophones. Small differences are seen on the raw shot gathers between DGF-9 and DGF-6 results, with a gradual degradation in quality as the number of DGF elements tends to 1 (Figure 3).

Pre-processed DGF shot gathers (i.e., including trace editing, *k*-filtering and dune statics before summation) pp-DGF-9 and 6 are less aliased and have better alignment of events when compared to straight summation DGF. However, the effect of the pre-processing is not significant in this case once the data are taken through to imaging. This may be due to the local geology of the survey area. Applying the pre-processing before DGF could be beneficial in other contexts. For example, intra-array statics applied to areas of steep dunes would eliminate the need to bunch sensors while retaining the spatial filtering effect of the digital array.

Comparison of the true amplitude migrated CDP gathers and associated stacks shows a clear equivalence between DGF-6 and DGF-9, with these results being near-indistiguishable (Figure 4). The DGF-3 results show some decrease in quality relative to DGF-6, but still provide imaging results of accetable quality for interpretation. DGF-1 (i.e., decimation to 1 node per station) shows a significant degradation of data quality both in pre-stack and post-stack imaging, clearly demonstrating it is not advisable to replace an array with one single sensor channel.

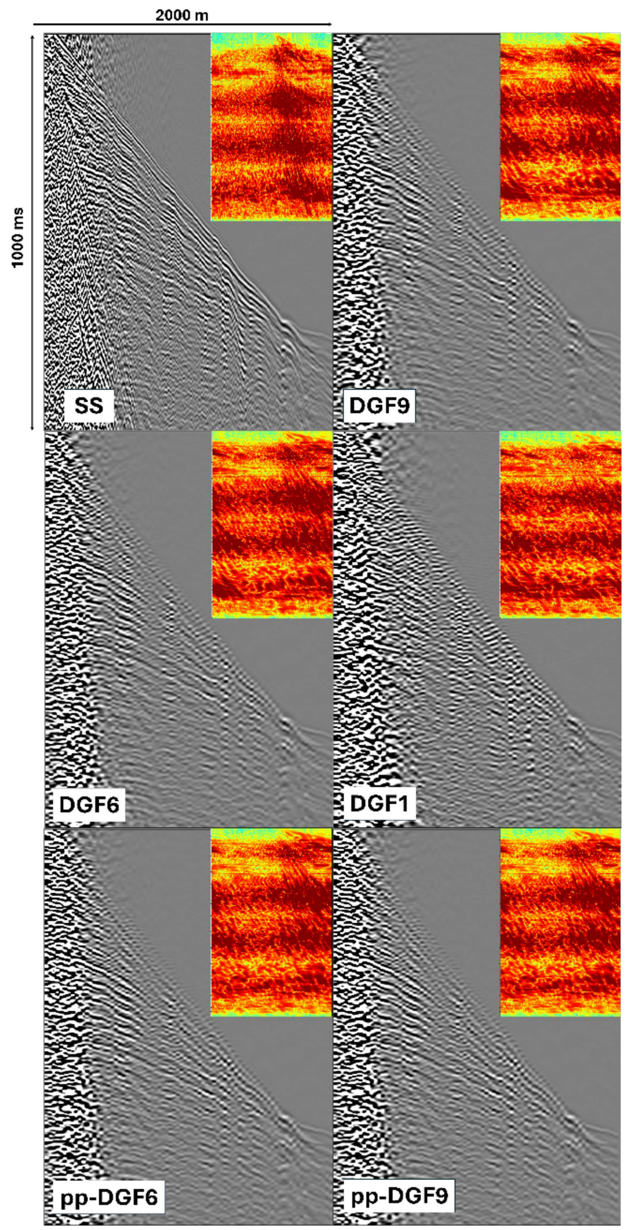

Figure 3. Raw shot gathers and associated FK spectra of the single sensor (SS) data and some of the DGF and pp-DGF designs tested in this study.

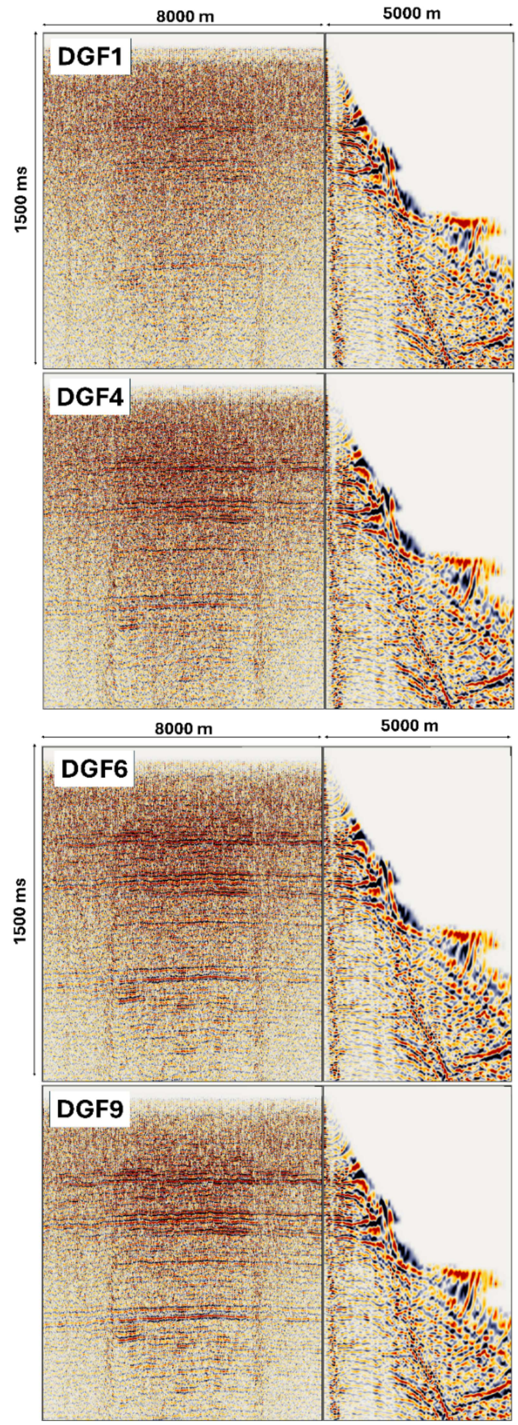

Figure 4.True amplitude migrated CDP gathers and associated stacks of a selection of DGF designs. Vertical axis is two-way time.

Conclusion

In this field trial, we have demonstrated that compact, autonomous, single-sensor nodes combined with digital group forming can be used to augment or replace cabled array systems. Comparing the different DGF designs tested in this experiment shows that, as expected, DGF-9 is identical to the 9-geophone cabled array output after impulse response correction. Nodal acquisition can therefore be mixed with conventional cabled acquisition without requiring any additional pre-processing, providing a solution for infilling cabled receiver gaps in difficult terrain, or overcoming offset limitations inherent in cabled systems. We have also demonstrated that digital group forming of single sensor nodes produces data deliverables to processing that are identical in form and volume to those currently produced by cabled-array systems, while maintaining the option to retrieve the single sensor data from the continuous recordings if required. This not only helps ease the transtion from cabled to nodal acquisition, but also provides the operator with the option to process the full single sensor data in future as computational technologies advance and costs reduce.

Simple pre-processing such as trace editing, *k*-filtering, and dune statics before summation improves raw data quality when compared to a straight sum. However, in this field test, the impact of this pre-processing on the migrated images and pre-stack data was minor. Given the large efforts put into data QC across the acquisition lifecycle, simple pre-processing before DGF such as trace rejection is a clear route to improving data quality and should be routinely applied even if the impact on imaging quality is subtle. It has been shown in other geological contexts that pre-processing such as intra-array statics and *k*-filtering yields improved high-frequency content (e.g., El-Emam, 2012).

Overall, we find that DGF-6 delivers PSTM stacks and pre-stack data of comparable quality to DGF-9 and geophone array data, especially in the lower frequency range. Further reducing the number of elements in the array (e.g., DGF-4) resulted in acceptable image quality; such designs could for example be employed in special acquisition scenarios when equipment cost and deployment speed outweigh accuracy at higher frequencies.

It is important to note that all of the digital array forming results, including pre-processed DGFs, presented in this study can be applied on-the-fly in the nodal harvesting system. This means that DGF field data deliverables to processing are identical in form and disk volume to shot gather deliverables currently produced by cabled-array systems.

While the focus of this study has been on processing of digitally group-formed single-sensor data, the single sensor data itself (still accessible via the continous recording) is a highly valuable asset, allowing targetted high-resolution processing over specific areas of interest, improved statics and noise attenuation, and high-resolution near-surface characterization (Colombo et al, 2024).

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