Seismic acquisition in Western Siberia: a comparison between conventional cabled receiver arrays and lightweight autonomous nodes

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Introduction

A trend in the recent history of resource exploration is the increased demand placed on the execution and outcome of 3D seismic surveys. This demand is two-fold. First: a desire for ever-better image resolution, depth accuracy and pre-stack amplitude fidelity as resource development companies seek to maximize the accuracy of trap definition and reservoir characterization. This desire is especially pronounced when prospects targeted for exploration have subtle expressions (for example, weak contrast/low amplitude and lithological traps). Second: an increasing pressure on the cost, efficiency, and environmental impact of seismic surveys – especially on land.

Typically, seismic acquisition on land over the last four decades has been undertaken with vibroseis or explosive sources and arrays of geophone receivers, which transmit data in real time through a complex mesh of cables to a central recording unit (e.g., Cooper 2002). The signals from sub-elements of the array (or channel) are summed *in situ*, which enhances vertically arriving coherent reflections while attenuating horizontally arriving ground roll. Array summation improves the signal-to-noise ratio of the data, whilst at the same time reducing the amount of information that needs to be handled by the central recording system and subsequent digital processing flows.

However, when scaled to large sizes, cabled systems are cumbersome, slow to assemble and heavy to move and have many potential points of failure. The industry practice of line clearance for vibrator source arrays, or for drilling-crew access in the case of explosive sources, means that source-side productivity is also slow. The collective result is that large surveys with cabled receivers are very slow to execute, require large crews and have a large environmental footprint in terms of clearance for vehicle access. In areas with a short seismic acquisition season, such as permafrost tundra or dense boreal forests with marshy wetlands, these constraints place unwelcome limitations on the number of square kilometres that can be surveyed each year, and consequently limit the ability to explore for new resources. For example, seismic crews in Siberian winter conditions typically acquire only 300-400 km^2 of conventional 3D data per season.

There is now a consensus, gained from field data and modelling studies in a variety of settings, that spatial trace density is a major – if not the dominant – control on image quality (e.g., Ourabah et al., 2015a,b; Alexander et al., 2017; Yanchak et al., 2018; Tillotson et al., 2019; L'Heureux & Adamovich,

Figure 1 Overview of the latest, commercial, version of the Nimble Node.

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2020). A plot of acquired trace density against time reveals an exponential trend approximating a tenfold trace density increase each decade (Manning et al. 2019). Why is trace density so important? There are two main reasons. The first relates to sampling of noise. Source-generated near-surface noise, for example ground roll, is slow and high amplitude, and therefore often aliased in shot and receiver gather domains with typical acquisition geometries. Increasing trace density means that this noise is better sampled, less aliased and therefore easier to attenuate using standard signal processing methods. The same is true for other types of coherent noise such as that generated by traffic or machinery. Furthermore, the higher the trace density, the better any remaining noise can be attenuated through generic trace mixing processes such as imaging, post-imaging radial filtering and stacking (e.g., Regone et al., 2015; Ourabah et al. 2015). The second reason relates to subsurface sampling. When trace density is low, even if the reservoir target is adequately resolved, there will be significant gaps in subsurface reflection points in the overburden. This means that many drilling hazards, for example near-surface faults or gas pockets, cannot be imaged properly, and amplitudes throughout the section may be inaccurate. These effects are magnified when the near surface is complex, wavefields are highly scattered, and pre-stack attributes are sought as deliverables. Processes such as 5D regularization and least squares imaging can mitigate these effects to some extent, but none are a substitute for properly sampling the surface wavefield.

Figure 2 Nimble node deployment.

To achieve desired trace densities with sparse cabled receiver systems, extremely high source densities are required, which is impossible in all but the most source-accessible environments (e.g., Ourabah et al. 2015). Furthermore, even if desired trace densities are achieved, *in situ* summation of traces within a geophone array leads to problems including an offset-dependent smearing of both signal and noise and ambiguity around receiver trace positions which cannot easily be undone in processing (e.g., Ait Messaoud et al. 2005, Vermeer 2012, Tellier et al. 2021). For these, and the previously stated, reasons, the industry has been steadily moving towards the use of nodal receiver systems where each receiver point is a self-contained wireless recording system (e.g., Baeten et al. 2000, Quigley 2004). Early nodes were heavy, bulky, and expensive, which meant that inventories could only ever be small in number. However, in recent years the land seismic node market has experienced a period of rapid technology innovation, with a corresponding reduction in the size and weight of individual nodes and increase in the size of available inventories (Dean et al., 2018). Lightweight, low-cost nodes with large inventories have the potential to effectively address modern requirements for trace density, survey efficiency and environmental impact; they also create options for achieving high trace densities in source-constrained environments. Currently, the smallest and lightest nodes available are the so-called 'Nimble Nodes' (Manning et al. 2018; Manning et al. 2019). Nimble Nodes were initially prototyped by BP; then developed to scale through a joint venture between BP, Rosneft and WesternGeco; and are now

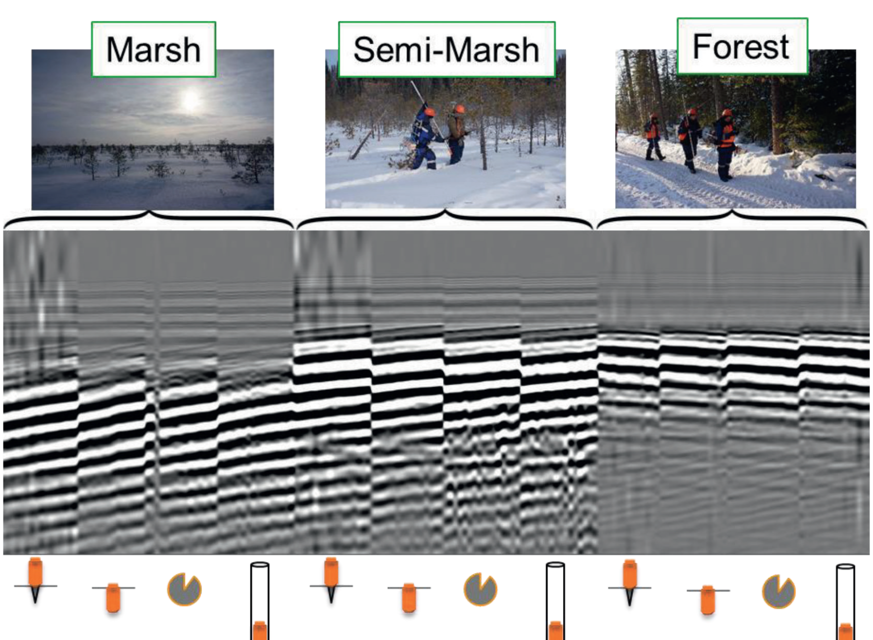

Figure 3 Shot gathers from a coupling test in snow. Order of gathers is A, B, C, D (see text). Optimal results were obtained from planting in the uncompacted snow, to ground, with a simple planting pole.

Data Acquisition parameters					
	Source XL Spacing	Source IL Spacing	Receiver XL Spacing	Receiver IL Spacing	Fold for 25x25 m bin
Conventional geometry	300 m	50 m	300 m	50 m (12 Geophone array)	44
Nimble Node geometry	300 m	50 m	300 m	5 m point receiver	440

Table 1 Cabled array and Nimble Node acquisition configurations.

manufactured and marketed by Stryde. Nimble Nodes have been deployed in surveys with trace densities of up to 184 million traces per km^2 with deployment rates as fast as 12 seconds per receiver station at 12.5 m intervals (Ourabah & Crosby 2020). Several studies have demonstrated that their minimalist design delivers data of similar or better quality than more sophisticated recording systems, with failure rates that are lower than current industry standards (e.g., Ourabah et al. 2019, Crosby et al. 2020). The inbuilt GNSS receiver corrects for clock drift and enables the node to self-survey with an accuracy of 1-2 m in all three spatial dimensions (e.g., Crosby et al. 2021). Figure 1 describes some of the key characteristics of the node.

In this article, we carefully examine the impact of nodal acquisition and increased trace density on image quality in a densely forested, snow-covered area of Western Siberia, using results from a 2018 field trial of the Nimble Node system and a co-located cabled receiver system (Brooks et al. 2018). We describe the acquisition and subsequent data processing and attempt to assess more broadly the benefits of nodal acquisition on survey efficiency and environmental footprint.

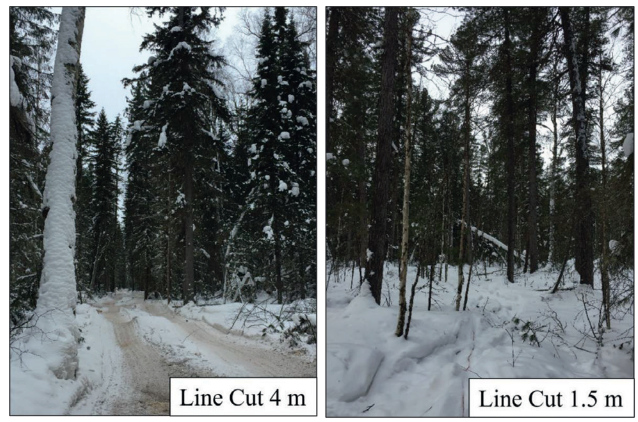

Figure 4 Photos of wide 4 m and narrower 1.5 m receiver lines. Unlike with the cabled system, there was no productivity impact deploying nodes along the narrower 1.5 m lines, which are much less environmentally damaging to cut.

Figure 5 Comparison of Nimble Node and a single geophone (each group had 12). Note reduction in equipment weight and complexity with the nodal system.

Field trial acquisition

The field trial was conducted in February-March of 2018 in temperatures ranging from -33 to -5°C in an area mostly covered by dense forest, with an average snow thickness of approximately 70 cm (Figure 2). The 36 km^2 field trial involved deploying a 3D grid of 8800 prototype Nimble Nodes along existing receiver lines of a Rosneft survey being conducted by a Russian seismic contractor using a conventional cabled recording system. Table 1 shows the acquisition geometries tested as part of this trial. The Nimble Nodes were deployed every 5 m while the 12-geophone arrays were deployed every 50 m, which means that, although the nodal receiver system provided ten times the number of processible traces for a given shot, the number of individual geophones was actually 20% higher than the number of nodes. Explosives of 1 kg in shot holes drilled to depths of several metres were used as the seismic source and were deployed on a 300x50 m grid. The crew used night shooting to ensure low levels of ambient noise.

Before undertaking the field trial, it was necessary to establish the optimal method for deployment of Nimble Nodes in thick snow, i.e., how to correctly balance sensitivity to seismic events with deployment efficiency.

Four deployment styles were tested:

A. ‘with spike on compacted snow track’ very similar to the geophone planting of the main survey.
B. ‘no spike next to compacted track’ slightly aside from the compacted track.
C. ‘planting pole with compacting plate’ a few metres outside of the track, deep in uncompacted snow.
D. ‘simple pole, pushing the node as deep as possible’ a few metres outside of the track deep in uncompacted snow.

Results of this test showed that planting in the uncompacted snow, to ground, with a simple planting pole was the preferred method. Inspection of the node plants with the simple planting pole 24 hours after deployment demonstrated a thermal 'frosting' effect around the node. In other words, the loose snow hardens around the node. We also found that the track was itself a major source of noise, guiding energy from different sources across the line (Figure 3). These results were encouraging and preserved the possibility of planting the new Nimble Node system while walking on unprepared lines. We also found that, in this operational environment, attaching the nodes to a thin string was the best way to locate and retrieve nodes, especially when buried in deep snow.

Current seismic deployment practice in West Siberia typically consists of cutting either 4m-wide receiver lines for mechanized deployment or narrower 1.5m-wide receiver lines, which require all equipment to be hand carried down the line. Intermediate access is achieved from wider crosslines cut for source equipment deployment in the orthogonal geometry layout (Figure 4).

Deployment of the cable system on the 4m-wide lines used an All-Terrain Vehicle (ATV) personnel carrier with tracks, with multiple journeys down the receiver line, spooling out the cable and dropping off equipment. A following team on foot then connected the equipment and planted the spiked geophone arrays at the edge of the ATV track. For this survey, a 12-geophone element linear array was deployed every 50 m by a crew of five people excluding ATV driver.

In contrast, a smaller two-person crew on foot was able to deploy the Nimble Nodes every 5 m in just a single pass down the receiver line (no pre-survey required). Additionally, no ATV is required on the line to accompany the 2-person Nimble Node crew in deployment or recovery of nodes. Instead, an ATV and driver would traverse down the source lines and support multiple nodal teams dropping off/loading seismic equipment where source and receiver lines intersect. Approximately half the receiver lines on this field trial were the narrower 1.5m-wide lines.

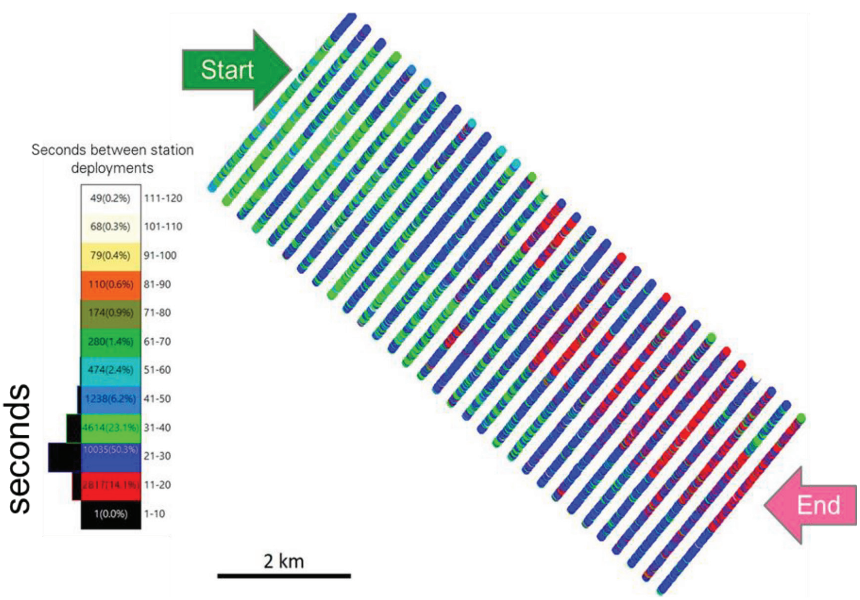

Figure 6 Map of deployment times by receiver location coloured by deployment speed.

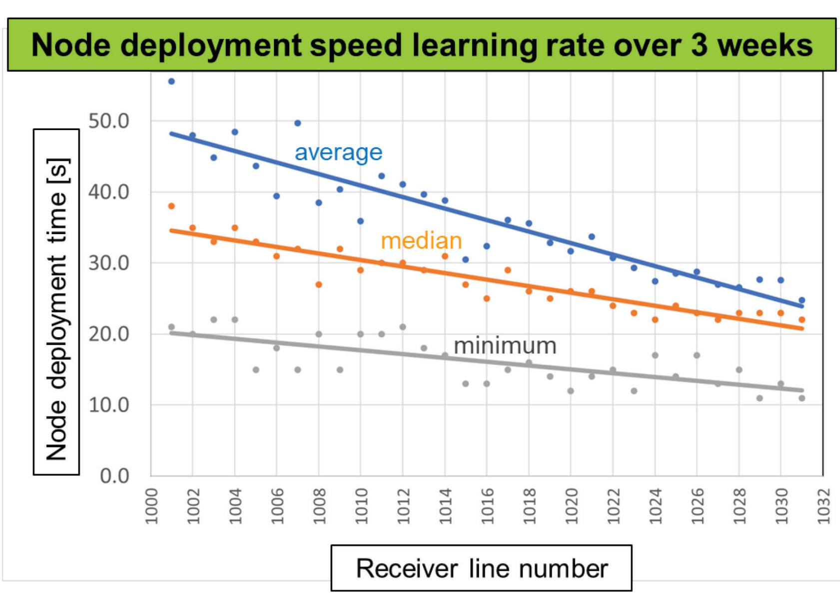

Figure 7 Deployment speed improvement as the acquisition progressed.

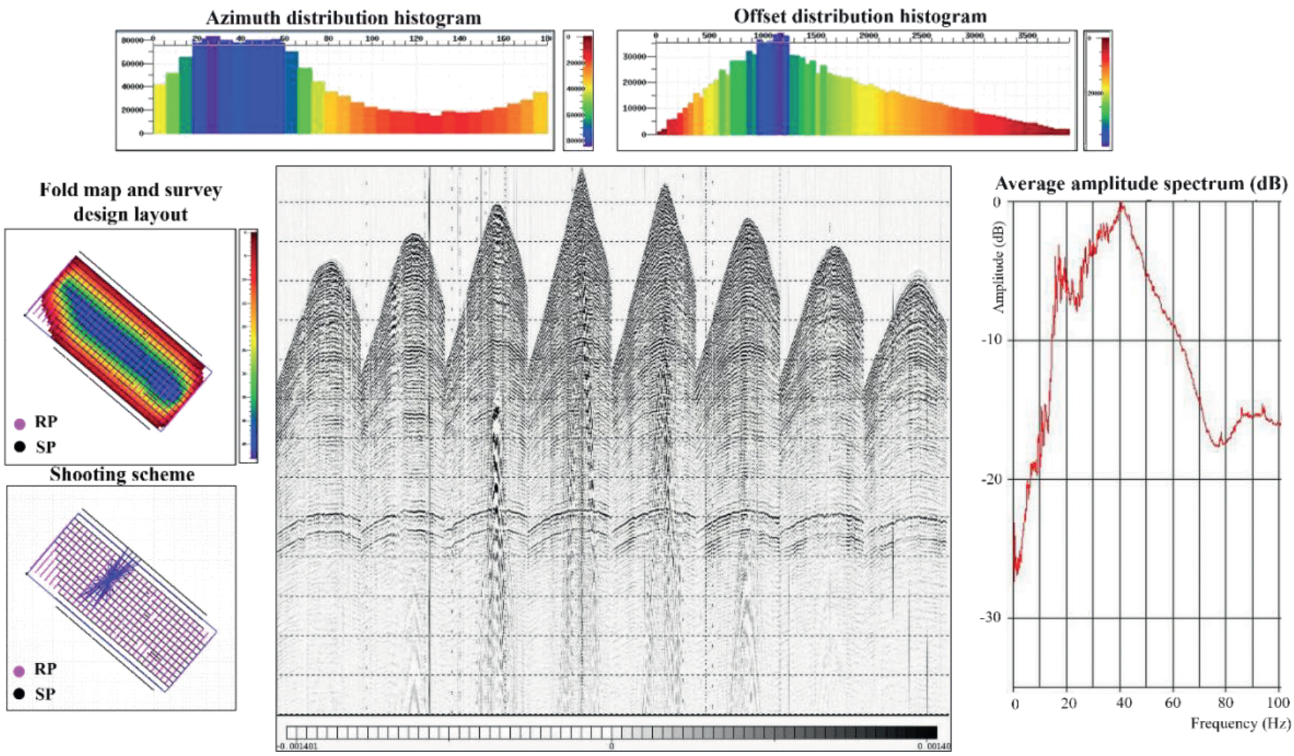

Figure 8 Acquisition statistics and raw data example from processing of Tverdokhlebov et al. (2019). Note low levels of noise in the data, which was collected at night and with a thick cover of snow.

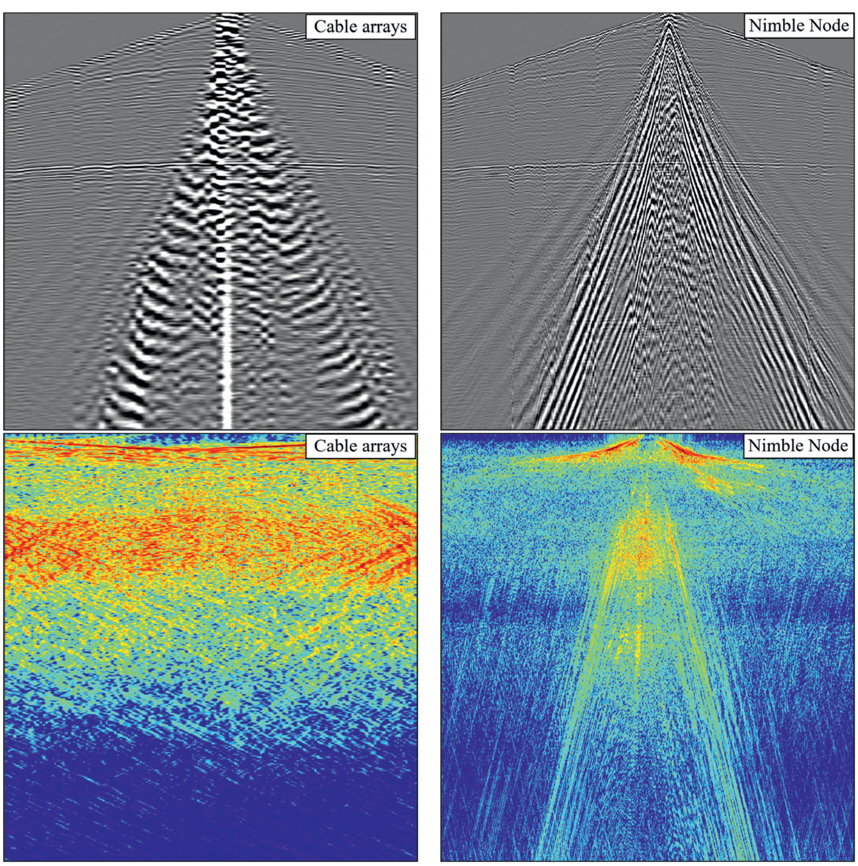

Figure 9 Shot gathers from cabled array and Nimble Node datasets in t-x and f-k domains. Note extensive aliasing of the ground roll in the cabled array data that reduces efficacy of noise attenuation.

Over 22 days, 31 cabled receiver lines were rolled, giving a rate of 0.55 km per person per day. The Nimble Node roll rate was 1.5 km per person per day. The Nimble Node can therefore be rolled twice as fast over the ground as the cable system (cable receiver station spacing 50 m, and nodes every 5 m). A two-person node crew averaged a rate of 3 km per day, while the five-person cable crew averaged 2.75 km per day. In summary: you can deploy the same line length as the cable system with less

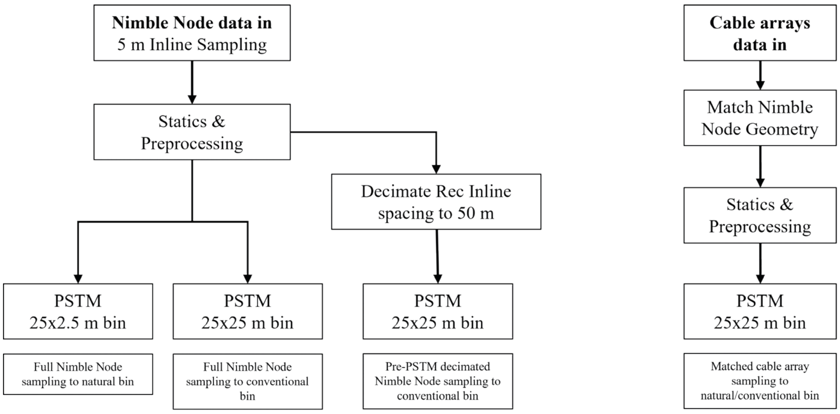

Figure 10 Four branches of PSTM processing sequence.

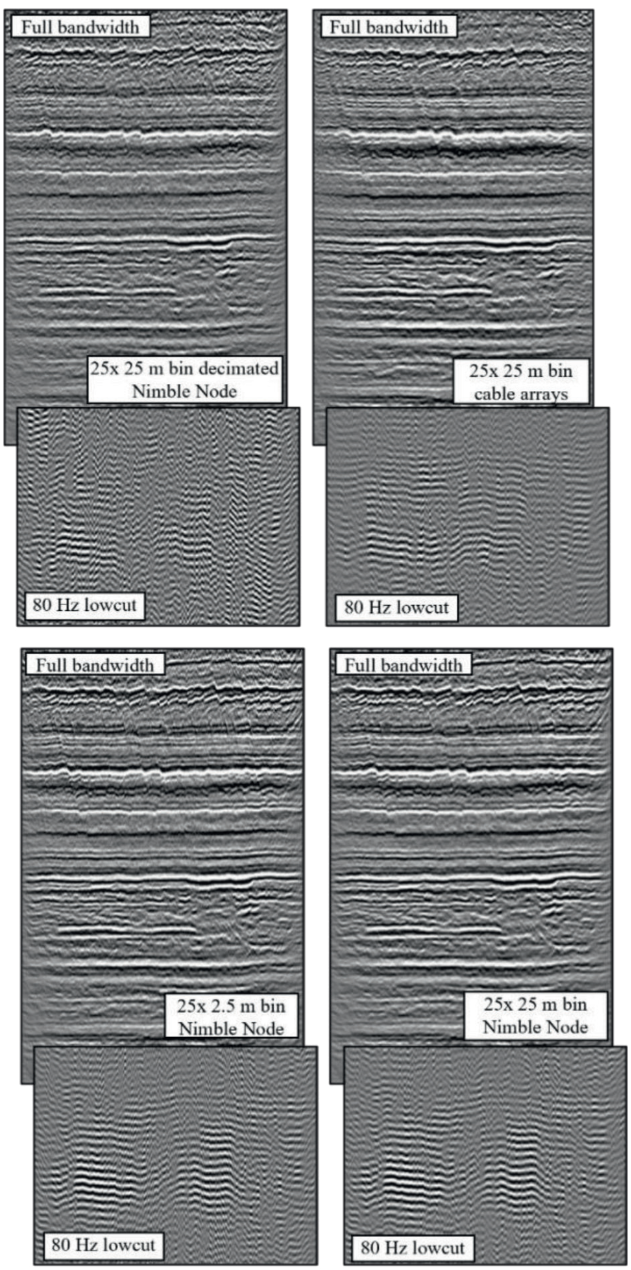

Figure 11 Vertical sections of PSTM images. Best resolution is obtained from migrating full Nimble Node dataset at natural bin size. Full Nimble Node data and cabled array data migrated at common 25x25 m bin size have similar vertical resolution. However, decimation of Nimble Node data leads to significant loss of resolution at high frequencies.

than half the people. In addition, the cable system would require additional staff for troubleshooting before the spread is ready for acquisition. As with other equipment types, recovery efforts move quicker than deployment. It was twice as quick to recover than it was to deploy.

In the basecamp on average, more than 1300 Nimble Nodes were cleaned of external debris, charged, downloaded, checked, and readied for redeployment in approximately six hours. The system is designed to turnover 20,000 nodes per day in a single 20 ft container. However, for this field trial we only needed to roll two receiver lines per day since we were waiting on cable roll and associated source patch roll.

The primary reason why these new Nimble Nodes provide the increased efficiency is their size and weight compared to existing systems currently used in this area (Figure 5). The field trial deployment tests demonstrated that wherever an individual on foot was able to walk or ski, then it was possible to quickly deploy the new Nimble Nodes. Deployment teams carried 60-120 nodes on a backpack, and, while more nodes could be comfortably carried, resupply points at the intersections with the source lines every 300 m made such a step unnecessary. For areas where walking was impeded by many obstructions (buried fallen trees, tight-knit branches), then a reduced width 1.5m-wide cut line was more than sufficient to enable quick nodal deployment. There is a very significant environmental, HSE, and cost saving to be made with having a system that significantly reduces the extent of preparation.

The seismic crew were quick to learn how to use the new equipment. We had excellent deployment rates from the first day, and as the crews gained more experience these deployment rates improved even further as shown by the station-to-station deployment times captured from the nodal initialization times (Figure 6). Most nodes took between 20-30 s to deploy, with an average of 24 s between deployments, and the fastest crews taking just over 10 s between deployments. Although these rates are generally less than can be achieved in an open desert environment (Ourabah and Crosby 2020), they are impressive given the depth of snow and frequent obstructions along the path. It is interesting to note the convergence of the average and median linear best fit lines (Figure 7), which shows how the crews continually learnt how to minimize the occurrence of delays and other outlier deployments.

Processing considerations

Figure 8 illustrates the acquisition geometry in more detail and shows some examples of the raw data from the work of Tverdokhlebov et al. (2019). Peak fold for the cabled geophone array survey is approximately 50 in a narrow strip down the centre of the rectangular survey rectangle. The data contains all source-receiver azimuths, with a peak between 20-60 degrees. Offset range is 100-3500 m, with a peak between 1000-1200 m. Bandwidth is approximately 8-80 Hz.

Figure 9 shows example shot gathers from both datasets, with their associated F-K spectra. Visual inspection shows comparable signal-to-noise levels – a surprising observation given the 12-geophone array used by the cable geometry. However, this can be explained by the exceptionally quiet environment as well as the deeper deployment of nodes into snow with improved receiver-to-ground coupling and better protection from the wind and other ambient noise.

On the other hand, the ground roll in the cabled array gathers shows a large amount of aliasing, whereas it is mostly well-sampled in the Nimble Node gathers. Clearly the 12-element cabled geophone array, which is designed to attenuate ground roll, has in this case done so only incompletely – a common observation (e.g., Vermeer 2012). We therefore found simple F-K based attenuation of ground roll to be much more effective with the Nimble Node data than it was with the cabled system, thanks to the denser receiver trace sampling and lack of aliasing.

As expected, conventional cable data produced stronger and easier to pick first breaks compared to the single sensor data, a difference attributed to the stacking power of the array. Nevertheless, due to a relatively flat surface, small near surface velocity variations and good signal to noise, both sets of data produced good picks and similar refraction statics results.

Processing results

Objectives when processing this data were to (1) compare images from the cabled geophone array and Nimble Node receivers and (2) study the impact of full and decimated Nimble Node sampling on image quality. Results and analysis are described in more detail in Tverdokhlebov et al. (2019) and Adamovich et al. (2020, BP internal report); here we summarize results from the second study, which built upon learnings from the initial fast track work. Figure 10 summarises the processing flow applied to both datasets, which was designed to be consistent despite the differences in acquisition systems.

The lack of permafrost in the near surface made the target relatively easy to image and enabled a straightforward pre-stack time

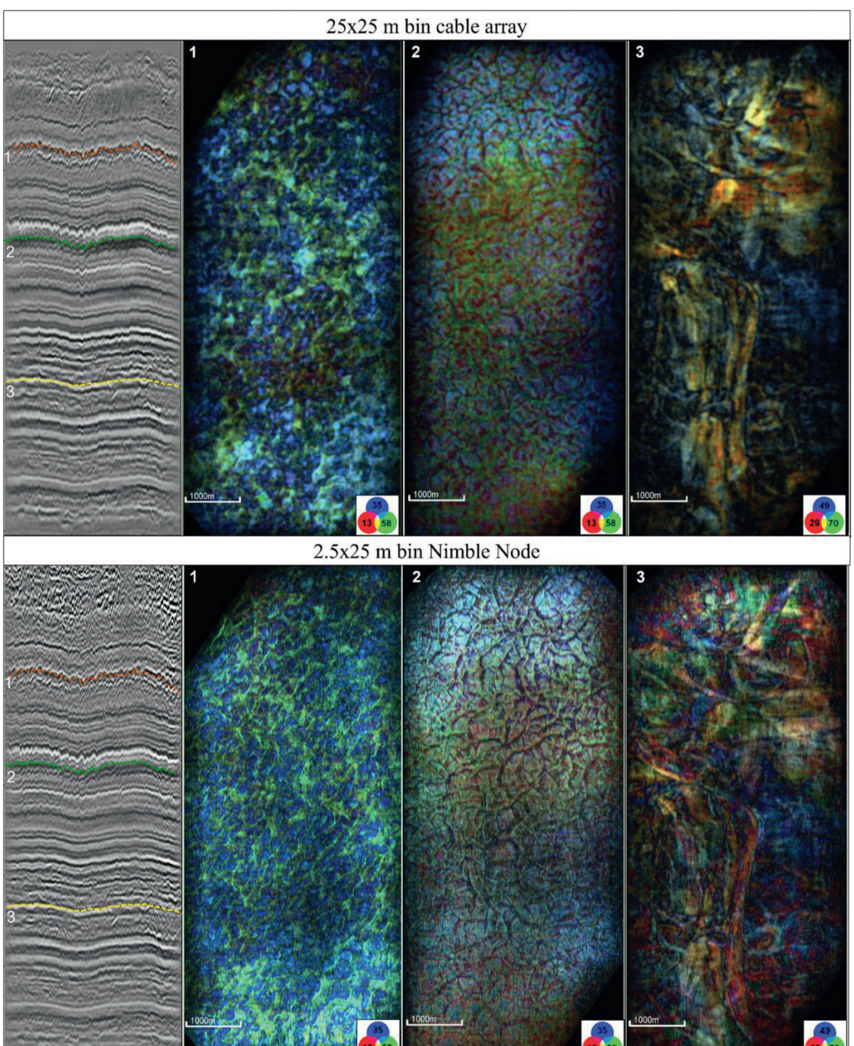

Figure 12 Spectral decomposition slices through best Nimble Node and cabled array PSTM volumes. Analysis horizons are shown on the left panels. Spatial resolution is significantly better at all depths using the nodal data.

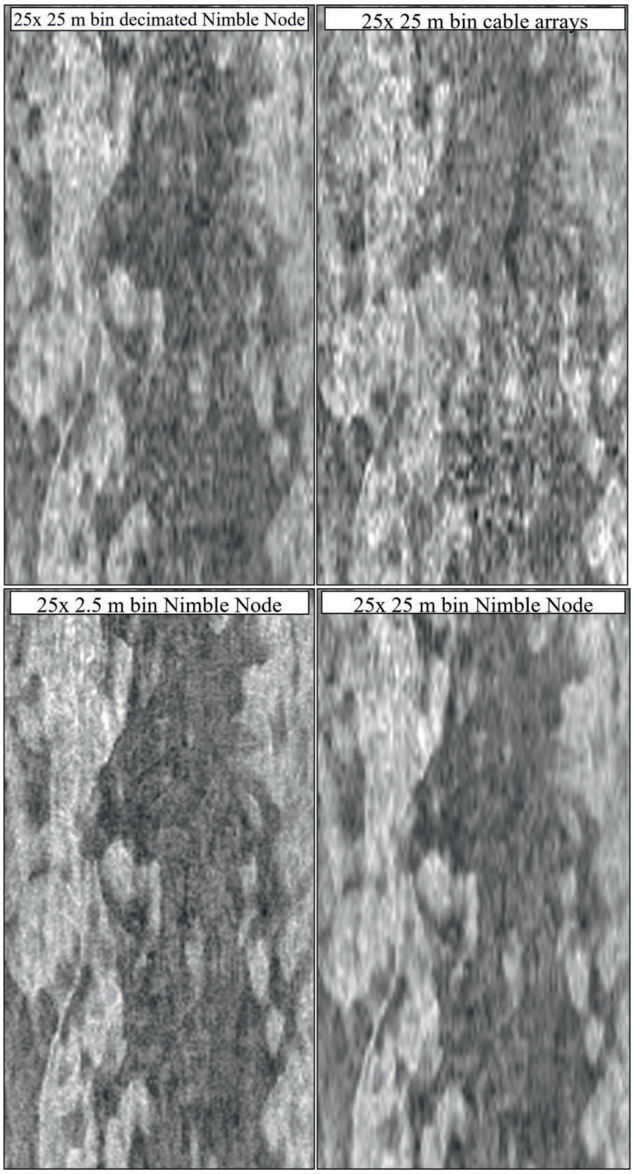

Figure 13 Shallow amplitude extractions through all four PSTM images. Best resolution is obtained from Nimble Node data migrated at natural bin size. Image from cable array data has noticeably worse spatial resolution than images from all three Nimble Node tests.

migration (PSTM) sequence to deliver a high-quality result. The near-surface geology is characterized by young clastic sediments of clay and sandstone with low shear velocities, resulting in ground roll noise attenuation being the main challenge in processing. Statics, amplitude corrections and deconvolution can be efficiently solved using traditional surface-consistent approaches. Pre-processing involved refraction and residual statics, spiking surface consistent deconvolution, and 2D FK and median FX thresholding in common shot point and common receiver point domains to attenuate coherent and incoherent noise. Noise attenuation was conservative and designed for maximum signal preservation. The anisotropic Kirchhoff PSTM operator was designed to optimize imaging of dipping events and small-scale details by including dips up to 90 degrees and using a non-aggressive anti-aliasing filter.

As Figure 10 shows, fully sampled Nimble Node data was migrated to both 25x2.5 m and to 25x25 m bin sizes to assess the relative impact of bin size on image quality. In the final flow, Nimble Node data was decimated in the inline direction to 50 m and migrated to 25x25 m bin size to match the natural bin size of the cabled array geometry. The four final PSTM stacks and gathers described in Figure 10 were then compared to estimate the impact of acquisition parameters on vertical resolution, spatial resolution, and pre-stack attributes.

Figure 11 shows vertical sections of PSTM volumes for the four different geometries. Whilst all four images are adequate for horizon tracking, differences are apparent at high frequencies. Inset lower images show the same sections at 80 Hz and above. The best high frequency image is obtained by migrating the full Nimble Node data at its natural 25x2.5 m bin size. Images of the cabled array data and the Nimble Node data migrated at a common 25x25 m bin size show similar character despite a factor of ten increase in processible traces. In other words, it appears that analogue summation of geophone recordings in the field and digital summation of Nimble Node traces in processing have a similar impact on vertical resolution. However, high-frequency detail in the 50 m-decimated Nimble Node data migrated at the same 25x25 m bin size is worse. This result is expected because this dataset represents the output of ten times fewer sensors than the undecimated Nimble Node data, and 12 times fewer sensors than the cabled geophone array data. It is a reminder that geophone arrays should not be replaced by a single node for similar results.

Horizontal slices of the final images help to identify spatial discontinuities and small-scale details and are a useful indicator of spatial resolution. Figure 12 shows spectral decomposition slices through three horizons for the fully sampled Nimble Node and cable geometries, passing through a set of complex features including channels and intricate polygonal faults or ‘mud cracks’. Figure 13 shows a slice through a further shallow set of features for all four geometries in Figure 10.

As with Figure 11, the highest resolution image is obtained by migrating the full Nimble Node data at the natural (25x2.5 m) bin size. Figure 13 also shows that increasing the migration bin size reduces the resolution. The impact of digital trace density is clear in Figure 13 when comparing full Nimble Node, decimated Nimble Node and cabled array data migrated at equivalent 25x25 m bin size: images from the full Nimble Node data, with ten times the number of processible traces input, show improved spatial resolution and signal-to-noise level than either the decimated Nimble Node or the cabled array data images. The cabled array data image furthermore shows a loss of spatial resolution with respect to all three Nimble Node images which is consistent with the array filtering effect. In other words, despite the cabled array system having had 20% more sensors in the field than the Nimble Node system, the spatial resolution of the best processed images from the cabled system is noticeably worse than the spatial resolution of images from the nodal system. This is because analogue summation of geophone signals is less effective at preserving signal and attenuating noise than careful digital processing of the raw data traces of each individual sensor.

As no well information was available, analysis was restricted to qualitative inspection of gathers and AVO attributes. Figure 14 shows a gather and attributes from one inline from Nimble Node and cabled array data migrated to a common 25x25 m bin size.

There is a significant uplift in AVO quality using Nimble Node data, which can be linked to improved signal-to-noise arising from higher processible trace density (e.g., Ourabah et al. 2015) and dimming of far offsets on cable gathers due to offset-dependent array filtering effects (e.g., Vermeer 2012).

Discussion

In this field trial, we found that dense, single-sensor acquisition using Nimble Nodes provides numerous advantages over a conventional cabled array receiver system. Nimble Nodes do not require heavy cables and the associated power and communications infrastructure. They are easily carried on a backpack, so vehicle access is not required along each receiver line. Planting in the uncompacted snow, to ground, with a simple planting pole provides optimal coupling, and threading each node in a receiver line with string prior to planting enables rapid retrieval. Mobilization of Nimble Node surveys is therefore much leaner than it is for cabled array surveys and has a much lower environmental footprint. Productivity for a given crew size is also higher (you can deploy the same number of line kilometres as the cable system with fewer than half the people), enabling a larger area to be covered each acquisition season – all of which ultimately leads to a reduction in exploration cycle time. Finally, the densification of single point receivers, and the absence of analogue summation of cabled array elements, leads to an improvement in spatial resolution, especially in the shallower parts of the subsurface, and reduces the source effort required to achieve a given processible trace density.

Processing results are in line with our understanding from other areas that processible trace density is a major control on image quality, and clearly show the advantages of well-sampled single point nodal acquisition migrated at a natural bin size over cabled arrays – even when the total number of cabled sensors in the field is similar to the number of independent recording nodes. It is interesting that even with exceptionally low levels of ambient noise and a relatively simple subsurface, the advantages of single sensor recording and increased processible trace density over geophone arrays are still apparent. However, we do not recommend replacing each array with a single nodal receiver: to obtain best results, the number of nodes should be similar or greater than the planned number of geophones. For this dataset, we also

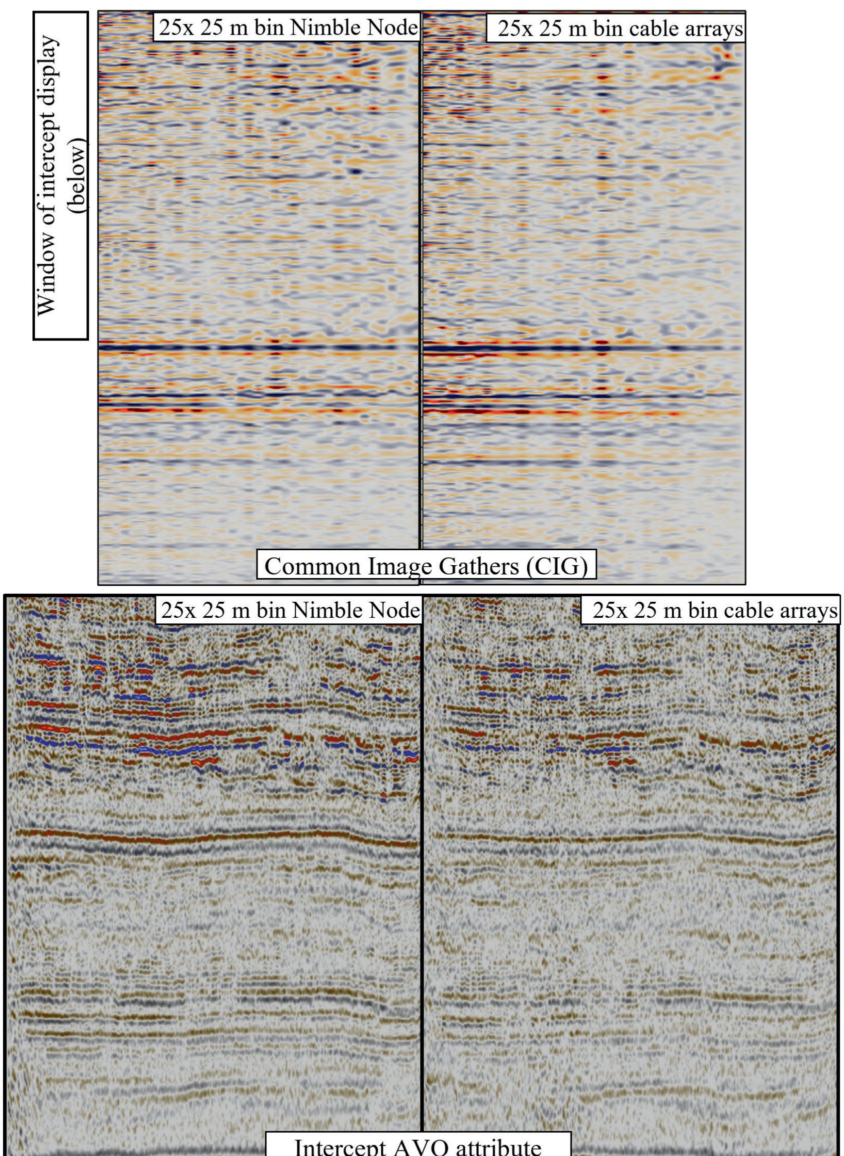

Figure 14 AVO attribute comparison, showing increase in coherency with well sampled point receiver data compared to cabled arrays.

see the benefit, in terms of improved resolution, of a conservative approach to processing that seeks to preserve signal, even at the expense of leaving some noise in the pre-processed data.

A key learning is that significant improvements in image quality can be obtained by densification in a single (inline) dimension, which is more practical than carpet geometries in highly forested areas. We also find that increased trace density leads to improved AVO sampling, and therefore has the potential to benefit reservoir characterization. In the presence of complex geology and reservoir challenges it is reasonable to advocate for an acquisition design that provides increased trace density and a finer natural bin size.

The introduction of high-density field acquisition techniques will entail a number of significant changes, namely: i) development and expansion of computing power and data storage systems due to the increasing volumes of data collected during field acquisition and processing; ii) modernization of existing and well-established approaches to in-field quality control of seismic data (e.g., Crosby et al., 2020); and iii) high-quality and timely planning and development of seismic survey concepts at the preparatory stage to minimize implementation risks. With a highly mobile and versatile receiver system, survey planning can become dynamic and tailored to the particular noise challenges and imaging requirements of the area. For example, deployment density could be increased near infrastructure in order to optimize the attenuation of the most challenging types of noise.

At the extreme, the feasibility of cost-effectively owning and operating an inventory of one million nodes was discussed and illustrated with a cross spread land geometry by Manning et al., 2019b. They found that a crew of only 260 people (a very small crew size for such an enormous channel count) could execute a survey using the entire million-node inventory, enabling the giga-scale (10^9 traces per km^2) trace density expected in the coming decade.

The advent of the Nimble Node to the Siberian acquisition market brings a new perspective to survey design in complex environments. After completion of this field trial, an extensive survey design study was carried out for a much more geologically complex part of Eastern Siberia (Naranjo et al. 2020). They found that deployment of Nimble Node receivers in dense ‘carpet’ grids (e.g., Naranjo et al. 2019) is a viable proposition, even in a heavily forested area, in a way that simply would not be feasible with cabled systems. They also found that the increased movement efficiency of receiver points also has an impact on improving the movement efficiency of source points. High-efficiency surface-based sources (vibroseis and electromagnetic impulse) continue to be tested and optimized in this region to meet data quality criteria while increasing the achievable rate at which dense 3D data can be acquired.

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References

Adamovich, O., and L’Heureux, E. [2020]. Building a geological model for synthetic seismic data in an area of complex surface volcanics, SEG Technical Program: 90th Annual International Meeting, Extended Abstracts: 2653-2657. https://doi.org/10.1190/segam2020-3428206.1.

Adamovich, O. [2020]. Impact of seismic acquisition design and trace density on resolution and pre-stack attributes: a 3D case study in Western Siberia, BP Internal Report.

Ait-Messaoud, M., Boulegroun, M.Z., Gribi, A., Kasmi, R., Touami, M., Anderson, B., Van Baaren, P., El-Emam, A., Rached, G., Laake, A. and Pickering, S., [2005]. New dimensions in land seismic technology. *Oilfield Review*, **17**(3), 42-53.

Alexander, G., Johnson, N., Jackson, Z., Riseman, S., Johnson, G. and Ruckel, D. [2017]. The impact of increased data density on a land processing workflow. SEG Technical Program: 87th Annual International Meeting, Extended Abstracts, 216–220, https://doi.org/10.1190/segam2017-17664341.1.

Baeten, G.J.M., Belougne, V., Combee, L., Kragh, E., Laake, A., Martin, J.E., Orban, J., Özbek, A., and Vermeer, P.L. [2000]. Acquisition and processing of point receiver measurements in land seismic. SEG Technical Program: 70th Annual International Meeting, Extended Abstracts, 41-44.

Brooks, C., Ourabah, A., Crosby, A., Manning, T., Naranjo, J., Ablyazina, D., Zhuzhel, V., Holst, E. and Husom, V. [2018]. 3D field trial using a new nimble node: West Siberia, Russia. SEG Technical Program: 88th Annual International Meeting, Extended Abstracts, 6–10, https://doi.org/10.1190/segam2018-2995441.1.

Crosby, A., Manning, T., Ourabah, A., Brooks, C., Dieulangard, D., Quigley, J., Vasile, C. and Ablyazina, D. [2020]. In-field quality control of very high channel count autonomous nodal systems. SEG Technical Program: 90th Annual International Meeting, Extended Abstracts, https://doi.org/10.1190/segam2020-3425467.1.

Crosby, A., Dieulangard, D., Ourabah, A., Brooks, C., Manning, T., Quigley, J., O’Connell, Vasile, C. and Ablyazina, D. [2021]. Efficient Clock Drift Corrections and Self-Surveys for Nimble Nodes. 82nd EAGE Conference and Exhibition, Extended Abstracts, 1-5, https://doi.org/10.3997/2214-4609.202010882.

Cooper, N. [2002]. Seismic instruments — What’s new? … And what’s true? *CSEG Recorder*, **27**(10).

Dean, T., Tulett, J. and Barnwell, R. [2018]. Nodal land seismic acquisition: The next generation. *First Break*, **36**, 47–5.

Manning, T., Brooks, C., Ourabah, A., Crosby, A., Popham, M., Ablyazina, D., Zhuzhel, V., Holst, E. and Goujon, N. [2018]. The case for a nimble node, towards a new land seismic receiver system with unlimited channels. SEG Technical Program: 88th Annual International Meeting, Extended Abstracts, 21–25.

Manning, T., Ablyazina, D. and Quigley, J. [2019]. The nimble node — Million-channel land recording systems have arrived. *The Leading Edge*, September, 706-714, https://doi.org/10.1190/tle38090706.1.

Manning, T., Stone, J., Ourabah, A., Ablyazina, D. and Quigley, J. [2019]. Could You Use One Million Nimble Node Channels? 81st EAGE Conference and Exhibition, Extended Abstracts, 1-5. DOI: https://doi.org/10.3997/2214-4609.201901137.

Naranjo, J., Dieulangard, D. and Pfister, M. [2019]. Using Carpet Geometries in Simultaneous Source Acquisition. 81st EAGE Conference & Exhibition, Extended Abstracts, 1-5. https://doi.org/10.3997/2214-4609.201901405.

Naranjo, J., Gurentsov, N., Tverdokhlebov, D., Adamovich, O. and Melnikov, R. [2020]. Designing High Density Land Acquisition Surveys in Complex Environments; A Case Study from East Siberia, Russia. 82nd EAGE Annual Conference & Exhibition, Extended Abstracts, 1-5. https://doi.org/10.3997/2214-4609.202010677.

Ourabah, A., Bradley, J., Hance, T., Kowalczyk-Kedzierska, M., Grimshaw, M. and Murray, E. [2015a]. Impact of acquisition geometry on AVO/AVOA attributes quality — A decimation study onshore Jordan: 77th EAGE Conference and Exhibition, Extended Abstracts, 1-5, https://doi.org/10.3997/2214-4609.201413301.

Ourabah, A., Keggin, J., Brooks, C., Ellis, D. and Etgen, J. [2015b]. Seismic acquisition, what really matters?, SEG Technical Program: 85th Annual International Meeting, Extended abstracts, 6-11, https://doi.org/10.1190/segam2015-5844787.1.

Ourabah, A., Crosby, A., Brooks, C., Manning, E., Lythgoe, K., Ablyazina, D., Zhuzhel, V., Holst, E. and Knutsen, T. [2019]. A Comparative Field Trial of a New Nimble Node and Cabled Systems in a Desert Environment, 81st EAGE Conference & Exhibition, Extended Abstracts, 1-5, https://doi.org/10.3997/2214-4609.201901136.

Ourabah, A. and Crosby, A. [2020]. A 184 million traces per km^2 seismic survey with nodes - acquisition and processing, SEG Technical Program: 90th Annual International Meeting, Extended Abstracts, 41-45, https://doi.org/10.1190/segam2020-3426358.1.

Quigley, J. [2004]. An integrated 3D acquisition and processing technique using point sources and point receivers. SEG Technical Program: 74th Annual International Meeting, Extended Abstracts, 17-20. https://doi.org/10.1190/1.1839677.

Regone, C., Fry, M. and Etgen, J. [2015]. Dense Sources vs. Dense Receivers in the Presence of Coherent Noise: A Land Modeling Study, SEG Technical Program: 85th Annual International Meeting, Extended Abstracts, 12-16, https://doi.org/10.1190/segam2015-5833924.1.

Tellier, N., Laroche, S., Wang, H. and Herrmann, P. [2021]. Single-sensor acquisition without data jitter: a comparative sensor study. *First Break*, **39**(1), 91-99. https://doi.org/10.3997/1365-2397.fb2021007.

Tillotson, P., Davies, D., Ball, M. and Smith, L. [2019]. Clair ridge: Learnings from processing the densest OBN survey in the UKCS. 81st EAGE Conference and Exhibition, Extended Abstracts, https://doi.org/10.3997/2214-4609.201901182.

Tverdokhlebov, D., Arutyuniants, I., Danko, E., Gayduk, A., Ablyazina, D., Melnikov, R., Adamovich, O., Naranjo, J. and Ourabah, A. [2019]. Processing and analysis results of the first 3D nimble node survey; West Siberia, Russia. 81st EAGE Conference & Exhibition, Extended Abstracts, 1-5. https://doi. org/10.3997/2214-4609.201901179.

Vermeer, G.J. [2012]. *3D Seismic Survey Design*, Second Edition. Society of Exploration Geophysicists.

Yanchak, D., Monk, D. and Versfelt, J. [2018]. Egypt West Kalabsha 3D broadband ultrahigh density seismic survey. *SEG Technical Program: 88th Annual International Meeting*, Extended Abstracts, 4080–4084, https://doi.org/10.1190/segam2018-2997973.1.