Land seismic recording systems in a changing world — a 2021 review

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Introduction

Forests, sand dunes, foothills, cities and farmland are the typical environments for land seismic acquisition. Projects have become ever more challenging, with operators requiring denser surveys at a lower cost with a reduced environmental footprint and less HSE risk. In light of the latest innovations in land seismic acquisition recording systems, we discuss the imperative for efficiency, both to meet client expectations and also to enable the use of seismic acquisition in emerging renewables industries such as geothermal and carbon capture, utilization and storage (CCUS), where the economics of acquiring seismic data are pushed to their limits. We explore the need for efficiency across some of the aspects of land acquisition, from deployment to data handling, to deliver affordable, high-quality images and attributes of the subsurface.

What qualities should we value in land seismic acquisition projects and what metrics should we use when comparing seismic acquisition technologies?

Every land survey is different, from terrain and surface conditions, equipment and expertise available in the local seismic market, to the acquisition parameters. Comparing one survey to another one is often a precarious exercise – a low channel count survey for geothermal in a city is clearly very different to a super dense reservoir appraisal survey in sand dunes or dense taiga forest. Nevertheless, let's consider scenarios such as these and evaluate the benefits of the latest nodal systems against a specific set of survey parameters.

Common attributes valued by stakeholders, whether they are an operator, an acquisition service provider or a member of the public are:

- Health, Safety and Environment (HSE).
- The quality of the seismic image and the derived products.
- The cost of acquiring such a dataset.
- The speed of acquisition (especially in limited weather windows).

We assert that all of these are central to a successful seismic campaign regardless of the final industrial application or terrain. Next, it is important to address which metrics to look at to measure how different seismic acquisition recording systems perform against these criteria.

Let's start by looking at HSE. The authors felt that the following factors would be considered important by any stakeholder group:

- The number of people on the crew.
- The number of heavy and light vehicles and the associated number of kilometres driven.
- Amount of line preparation (clearing vegetation or forest, compacting snow, bulldozing lines in deserts for safe passage etc).
- The CO_2 footprint of the seismic campaign.

Ourabah et al. (2015) demonstrated that trace density (i.e. number of seismic traces per km^2) is a very good proxy to estimate final data quality (i.e. seismic products for the geophysical interpretation). We, therefore, opted for fixed survey geometries where the trace density is the same, regardless of the seismic recording system used. We are also assuming single-point sources and receivers.

Costs vary significantly across the world with different survey geometries. As a metric to highlight the impact of different systems on cost we selected the operating cost per km^2, excluding mobilization and demobilization.

In selecting these metrics, we aim to evaluate how the efficiency of the recording system technology selected for any seismic project impacts the overall cost, image quality, and HSE profile of any land seismic project.

The land seismic recording system market landscape

The seismic recording market landscape, as described by Wilcox et al. (2019) (see Figure 1), has not changed significantly today. Systems can be broadly fit into four categories, which we classify as follows:

- 'Nimble Nodes': ultra-light weight (under 200g), with no remote QC capabilities.
- 'Medium Nodes': with a weight between 650g and 1000g. These have some level of remote QC capability, whilst some also allowing real time data transmission.

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Figure 1 Selection of land nodal systems on the market. Image courtesy of Tim Dean, BHP.

- 'Large Nodes' with a weight over 1kg. These are usually older generation nodes with external batteries and/or sensors, and multiple connecting options.
- 'Cabled systems' which have a significantly higher weight per channel but offer real-time data transmission.

Some manufacturers have developed prototypes or low volume node versions that fall between a 'nimble' and 'medium' node, but these suffer from a shorter autonomy, and they have not yet been adopted at scale and hence were omitted from this paper.

In each system, specific design decisions, performance biases and trade-offs will have been made during the development phase, which have a significant impact on the land seismic operation they will be used for. For example, some equipment providers have elected to prioritise technical features and maximizing sensor specifications, in turn sacrificing unit cost and weight. Conversely, other providers will have instead focused their efforts on one or more of reliability, price, scalability and ultimately, operational efficiency.

Evaluating the performance of nodes in efficient high-density surveys in open desert terrain

We open our assessment with a specific scenario: an ultra-dense vibroseis survey, in an open desert environment, with the parameters described in Table 1.

The scenario presented could be labelled super-dense, where the trace density is well beyond 1 billion traces per km^2 (1.17B/km^2, with an absolute offset of 3 km). This is an unheard-of trace density for a production survey, but it is indicative of where large oil and gas operators in the Middle East are heading. Ourabah et al. (2021) recap the history of trace density and show that dense surveys with hundreds of millions of traces per km^2 are becoming the norm in open desert environments and that super-dense surveys will be a viable option when efficient, fast-moving source technologies are combined with nimble autonomous receivers. An example of this combination has been observed in desert environments (Nehaid et al., 2019) and more recently for CCUS applications in Canada where a 256 million tr/km^2 survey was acquired in 2021.

Let's look at the practicalities and metrics of such a survey with the different types of receiver system. From a deployment and retrieval perspective, nimble and medium nodes may pres-

	Ultra-Dense 3D	Notes
Number of nodes considered (live spread)	1,000,000	
Area considered	3000	km^2
Receiver line length	25,000	m
Environment	Open desert	
Max offset considered -m	3000	m
Shooting type	Central	
Geometry type	Orthogonal	
Receiver spacing	25x6.25	m
Source grid	25x6.25	m
Days receivers are deployed	14	~330km^2 a month
Roll-out required a day	70,000	
Working day	8	hours

Table 1 Ultra-dense survey parameters.

	Nimble nodes	Medium nodes	Large nodes	Cabled system (point receiver)
Total receiver crew	350-500	350-1000	1000-2000	2 000-5000

Table 2 Receiver crew for 70,000 receivers cycled a day.

	Nimble node	Medium node A	Medium node B
Nodes per rack	540	36	48
Recharging time (14 day deployment)	2 hr	2.1hr	1.8hr
Rack size	1958x683x830mm	2200x600x630mm	1827*600*320mm
Estimated number of racks (70 000 nodes, 14 days)	11	170	110
Estimated number of 20" containers	2	7-10	4-5
Estimated number of operators required	2	4-6	16-20

Table 3 Recharging nodes for a 1 million node survey, data taken from manufacturers website and brochures.

Figure 2 Views from inside a 20" Nimble node container.

ent similar performance in terms of speed and number of layout and pickup crew, depending on ground conditions, receiver geometry (spacing between station and whether travel between station is by foot or with vehicles) and burial requirements. Where burial is required or preferred, nimble nodes will be significantly faster than any other system, as evidenced by the average layout speed of <15s per 12.5m station and an average productivity of around 300 nodes deployed per day per person, recorded in 2019 (Nehaid et al.). Large nodes and cabled systems suffer from slower deployment and retrieval due to the connections required (e.g. geophone, battery etc), line checking, and with burial of large nodes being slow and cumbersome. There are other factors affecting layout/pick up crew productivity, such as weather conditions, contractual set up between crew and seismic contractor, but these won't alter with the selection of the recording system. As such, the numbers from Table 2 are based on the experience of the authors on multiple projects and are extrapolated to the proposed scenario. They show that ultra-dense surveys are possible with either nimble or medium nodes through the lens of the number of layout/pickup crews. However, for cabled systems and large nodes, we see extremely high numbers of people and vehicles required, leading to very complex logistics for the operations and as described later, a radically different field exposure profile which most operators would consider unacceptable.

Recharge and download perspective. Nodal systems require data download activity and battery recharging at base camp. Some nodal systems have been designed to operate at high channel counts, while other systems rely on significant container space and high numbers of operators for this operation as shown in Table 3.

Table 3 estimates the installation requirements for the battery recharging activity with the scenario considered in Table 1 for the nimble node system and two other medium node systems. The difference in the number of racks (and consequently 20" containers) between different systems is striking. The Nimble node system can have up to six racks of six nest shelves per 20" container (see Figure 2), and so a system with 2x20" containers would suffice to allow recharging of ca. 70k nodes that have been deployed for 14 days. Note, two additional containers are required for cleaning, and data management for nimble node systems. Other systems may also require additional containers for data management.

The total number of operators (for Table 1 scenario) was estimated using field data when available and published videos otherwise. Except for the nimble node system, all other types of nodes need to be manually placed into a location within a rack.

	Nimble node (in its magazine)	Medium nodes	Large node	Cabled system (point receiver)
Weight per node, including receptacles	180g	800g	2000g	2000g
Light vehicle weight payload Number of nodes	5000	1250	500	500
Individual node volume Excluding spike, connectors, battery, etc.	170 cm^3	1400 cm^3	2400cm^3	Not considered
Estimated volume for Node with accessories for transportation	255 cm^3 (stacked)	2500 cm^3	3500cm^3	Not considered
Light vehicle volume payload: Number of nodes	2430 to 4050	480 to 720	340-540	Not considered
Number of light vehicles required for 70 000 nodes a day	18-30	100 – 150 Based on volume	130-205 Based on volume	Not considered
Heavy vehicle transport capacity per day Number of channels	Not used.	Not used.	Not used	600-1 000
Number of heavy vehicles required for receiver	Not Considered	Not Considered	Not Considered	70-120
Personnel carriers transportation	12 to 17	12-33	33-67	70-170
Total Light Vehicle Km driven a day	1 500 to 2 500	8 000 to 12 000	10 000 to 17 000	0
Total Heavy Vehicle km driven a day	1 000 to 1 500	1 000 to 2 500	2 500 to 5 400	8000 - 16000
Estimated CO2e emissions a day	600 – 1 000 t	2 000 – 3 300t	3 300 – 5 300t	2 800 – 5 600t

Table 4 Vehicle requirements for a 1 million node system (70,000 nodes a day). Numbers exclude vehicles required for source operations, project management, survey, etc. and are limited to line crew and receiver equipment.

Figure 3 4x4 vehicle with 2160 nimble nodes.

This usually only takes a second but means four operators are dedicated to this task (12 hr shift). Additionally, some systems require the dismantling of a node into its battery part and its sensor and data part, at a pace of 720 nodes per hour per machine. This translates into 16 operators (12hr shift) dedicated to the task. On the nimble node system, no dismantling is required, no connections are needed, and 90 nodes are charged and downloaded simultaneously, all helped by mechanized lifting.

Vehicles. Table 4 examines the vehicle requirements to move around equipment (from base camp or staging area to deployment/retrieval line locations). Light vehicles (typically a 4x4) were considered for nodal systems, with a payload of 1000 kg and between 1.2 to 1.9 m^3 loading space. Heavy vehicles (typically a 6x6 truck) were considered for cabled systems. Transportation of line crews was considered with heavy vehicles on all systems. It becomes apparent that using Nimble node systems results in approximately five times fewer light vehicles (and km driven and emissions) than medium node systems, and similarly five times fewer heavy vehicles than cabled systems.

Cost. As indicated by Wilcox et al. (2020), node's price 'information is commercially sensitive, and difficult to accurately source'. Nevertheless, we considered the following assumption where the nimble node is $100 per channel (including all peripherals and system management), and medium nodes are $250-350. The equipment cost was operationalized as a daily cost through an amortization over three years. The operating cost includes the difference in receiver crew numbers ($100 per day per person). Table 5 provides a summary of the operation cost per km^2 of the scenario described in Table 1. The outcomes of the cost modelling are theoretical, but nevertheless provide a sense of relative performance, cost-wise, of the different receiver technologies. The nimble system is expected to be around 30% cheaper than medium nodes and 50% for large and cabled systems. For a specific project, seismic contractor expertise would be required to consider the multiple parameters (for instance more vehicles leading to more mechanics, larger crew leading to higher water and food consumption, more waste, as well as larger camp facilities) to accurately estimate the cost.

It becomes evident that a nimble system enables affordable, ultra-dense surveys in open desert, which are conceivable to execute, in terms of crew size, vehicle requirements and cost. Other systems, from medium nodes to cabled systems suffer significantly when scaling up both in terms of the cost but also on the health, environmental, and safety metrics.

Efficient high-density survey in an area with forests and mountains

The scenario presented in Table 6 is of a dense dynamite survey, where the trace density is around three million traces per km^2 (3 km offset).

Forested areas offer significant challenge for survey operations: it is often required to cut lines through the forest for both receiver and source operations, sometimes as wide as 2-6 m. This scarring of the forest is not only slow and expensive, but also a dangerous activity. The environmental damage can last for decades, with the addition of the carbon footprint of removing trees. For a nominal 1000km^2 survey in forested environment in Siberia, Russia, several observations can be made around line access cutting:

- Permitting can take up to six months.
- Cost: ca 30% of the total project cost can be connected to line access cutting, from permitting fees to reforestation fees, and line preparation crew cost.
- Environmental: up to 20km^2 of forest could be cut for each source and receiver operation (200 m line spacing at 4 m wide), if the entire area requires line access, equivalent to losing the sequestration of 10,000t CO^2e per year (using a nominal 0.5Kg per m^2 of forest per year).
- Safety: 30-80 people are dealing with line preparation (tree clearing, line compacting etc).

With Nimble nodes, it was demonstrated in 2018 (Brooks et al.) that land seismic surveys could be conducted in forests without receiver line preparation. People can comfortably carry sufficient equipment (90 nodes) to lay out nodes every 5 m between source lines, before resupplying with nodes at the intersection.

With medium nodes, individuals can only carry between 10 and 20 nodes at once. Considering no receiver line preparation, and with 40 receivers to deploy between each source line, line crews would need to cover the same ground multiple times to resupply with nodes. The deployment and retrieval performance would be severely affected or crew size increased to accommodate this bulkier equipment. Table 7 summarizes the potential metrics for different node categories.

The authors note that, similar to the evolution towards lighter, lower footprint receiver equipment, several hand portable source technologies are emerging, making the ideal scenario of zero or near zero line clearing a possibility (Gray et al. 2021).

Nimble nodes can also change the dynamics of a survey in other settings, such as mountainous areas. Levell et al. (2018) considered drones for deploying seismic nodes in difficult places and demonstrated a system capable of deploying seven nodes payload at 1 km range with 10min turnaround; the payload with the nimble node would increase to 35-40.

Impact of quality control (QC) of acquisition or efficiency

The findings thus far make it apparent that smaller, lower cost nodes have significant advantages in all areas that end clients value. However, while nimble products are rapidly becoming the default category of node used in the market, some operators or acquisition providers do still elect for bulkier options. The primary reason given is a requirement for real time, remote data QC. The authors felt this requirement should be explored.

	Nimble node	Medium nodes	Large node	Cabled system (point receiver)
$ Cost per km^2	40,000	60,000	80,000	80,000

Table 5 Operating cost for a million-node system, for an ultra-dense survey.

	Dense 3D	Notes
Number of nodes considered (live spread)	160,000	
Area considered	1000	km^2, metrics are normalized
Receiver line length	25,000	m
Environment	Forested	Line cutting consideration
Max offset considered	3000	m Impact number of receiver line
Shooting type	Central	
Geometry type	Orthogonal	
Receiver grid	200x5	m
Source grid	200x50	m
Days receivers are deployed	14	Corresponding to ~350 km^2 production a month
Roll-out required a day	12,000	Number of nodes to be cycled
Working day	8	hours

Table 6 Survey parameters for a 200,000-channel system in a forested environment.

	Nimble node	Medium nodes	Large node	Cabled system (point receiver)
Total line crew required - No line preparation - With line preparation	70	 130 70	 190 80	210
Line cutting km^2	0	0 20	0 20	20
Operating cost % - No line preparation - With Line preparation	100%	 130% 140%	 150% 140%	170%

Table 7 Performance metrics dense forested survey, 12,000 nodes a day at 5m receiver interval.

	Design A	Design B
Common parameters	300km^2 per month, 3000m crossline offset	
	25km Receiver line, 2 zippers on source, central shooting	
Receiver grid	200x25m	100x12.5m
Source grid	25x25m	50x50m
Cabled acquisition cost	100%	120-130%
Nimble node acquisition cost	100%	70-80%

Table 8 Impact of receiver operations efficiency on survey design.

Many nodal systems offer a certain level of QC ranging from sensor test (leakage, tilt, etc…) to navigation status to noise level. Some products offer this at the node location itself (nearby communication) while some offer a remote version, allowing observers in camp to have a view of current operations. Such functionalities are often marketed as ensuring that the right data is being acquired, with noise levels meeting client specifications. However, adding such self-tests or functionalities can introduce reliability issues and an additional people burden (trouble-shooter teams, multiple pass per receiver location), without necessarily positively impacting the underlying risks. Those can often be better mitigated through different approaches (engagement with local communities (theft), use of a small subset of communicating nodes (noise monitoring). The authors also assert that real time QC is a legacy activity, resulting from unreliable equipment and 'sparse' receiver spacing, where every shot and receiver mattered to ensure good signal to noise on each trace. With modern technology (processing power and algorithms) and greater receiver (and shot) density, this is no longer the case, and contractual requirements on real time QC should reflect this.

The nimble node system was developed with focus on reliability and simplicity, making the nodes small enough, light enough and low cost enough, that more could be deployed in the field. Quantifying this, across a global fleet of 450,000 nimble nodes, observed monthly failure rates are below 0.1%. QC is still possible at the node, although as observed by Tellier (2018), as with any data checks, when people's confidence in a system grows, they rapidly stop using such checks. Crosby et al. (2020), outlined strategy required to enable rapid in-field QC of the recorded data for ultra-high channel count of blind nodal system.

Given such low observed failure rates in the latest generation of nodal technology and such a large incremental cost, both financially and in terms of HSE of adopting bulkier products, it seems unlikely that real time QC can remain a requirement for very much longer.

Impact on survey design

The seismic industry has, in open desert environments, managed to increase source productivity (simultaneous shooting) by an order of magnitude, but until recently receiver operations have continued to be slow and labour intensive. Survey designs have evolved to reflect this with source carpet grids and a more traditional line for receivers, with sometimes some sparse receiver design.

That imbalance has been broken by the nimble nodes. With the significant reduction of personnel required to deploy/retrieve nodes, reduction in equipment transportation vehicles required, and a lower price point, receiver operations productivity and efficiency have dramatically improved.

Table 8 presents two survey designs, achieving the same trace density (10M traces per km^2 at 3 km), but through a different source and receiver effort. It is interesting to note that Design B is 20 to 30% more expensive than A with a cabled system, but it is the reverse with the nimble node.

Where complicated environmental restrictions prevent source access or surface conditions prohibit carpet source techniques, Naranjo et al (2019) suggested the need for an industry transition to receiver carpet geometries given advancements in receiver technology.

In other words, the nimble node unlocks survey design options that were inconceivable in the past, in terms of cost, efficiency, field operations practicality and even data quality. Operations geophysicists should consider the impact of the nimble node when designing surveys.

Data quality and sensor performance

While technical performance (noise floor, dynamic range, distortion etc..) remains fundamental to the central purpose of seismic recording equipment (Tellier et al., 2018), a seismic recording system is only a part of the overall value chain of a seismic project. Some nodes display impressive specifications (for instance distortion at -90dB), but this brings little practical advantages and most of the added dynamic range will fall under the ambient noise of most land environments. Goujon et al. (2021) explained that the nimble node performance on distortion is already an order of magnitude better than the stated objective of -40dB for signal perturbation of a sensor (Tessman et al., 2001). Focusing on a better spatial sampling of the noise by deploying denser receivers is much more important than increasing the single sensor specifications. Therefore, the metrics considered for the overall system (efficiency, health and safety, environment) are what will truly impact the final seismic product by allowing this trace density to be acquired at a lower cost. Buriola et al. (2021) concluded that even though the legacy source-receiver array survey was acquired with a higher source and receiver effort, using source arrays and receiver arrays, the new survey using single sensor nodal [nimble] combined with simultaneous shooting (single source point) delivered superior results.

Conclusions

From an operator perspective, designing and executing efficient land seismic operations in a cost-effective way is critical to the success and overall value of a seismic project. While operators may not specify the type of equipment to be used in their contracting process, the nimbleness of the seismic equipment used has a tremendous impact on many, if not all metrics, of a seismic project. Small, light autonomous nodes that can be deployed with ease in all terrains, can free the survey design from inefficient receiver roll limitations, allowing, in some scenarios, super dense surveys when the sources are as unconstrained, and in other scenarios to compensate for the constraints or limitations imposed on sources. Once the overall system is considered (deployment and retrieval, equipment transportation, data download and battery recharge equipment and operations, camp infrastructure), the benefits of the nimble node are clear for any realistic ultra-dense surveys with mega large inventory crews (500k+), and still remain compelling for smaller projects when efficiency matters. The authors firmly believe that a combination of technical, economical, environmental and safety performance means that it is inevitable that all nodal offerings will move into the 'nimble' category in the near future.

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