In this issue of GEOHORIZONS we are introducing a new regular column titled ‘Expert Answers’. Under this section we pose questions of both general and technical interest to well-known geophysicists who are considered authorities in a certain area within the geophysical domain and get their ‘expert’ answers. As these answers could have an individualistic tone, we request the answers from more than one expert in any area. To begin with, we have selected the following general question and include the answers given by Al Châtenay (Explor, Houston), Malcolm Lansley (Consultant, Houston), Norm Cooper (Mustagh Resources Ltd., Calgary) and Mostafa Naghizadeh, Michael Hons, and Andrea Crook (OptiSeis, Solutions Ltd., Calgary). We thank them for encouraging us with their responses. Readers are encouraged to send us their feedback and even the questions they would like to get answered by experts.

The order in which the answers appear below is the order in which we received them.

- Satinder Chopra

Q. What are the major geophysical challenges being faced in land 3D seismic data acquisition at present, and what innovative technologies are being adopted for addressing them?

Expert answer 1 by Allan R. Châtenay*

The current state of play

The primary driver of seismic data quality is trace density (Ourabah, et al., 2014, 2015). Figure 1 shows the progression of seismic trace density over time, which follows a logarithmic trend somewhat approximating Moore’s Law (Manning et. al., 2019). Increases in seismic trace density have been driven by improvements in seismic receiver, seismic source, and navigation technology.

Recent advances in onshore seismic receiver technology have resulted in a step change reduction in the weight, size, and cost of cableless seismic receiver nodes as the industry has pursued increased trace density, more efficient operations, or both. To achieve this reduction in size and cost, many currently available seismic receiver nodes have been distilled to their bare essence and are fully ‘blind’, although some manufacturers have retained capabilities for remote telemetry and/or real-time download, albeit with larger, heavier nodes, and at a higher cost per node.

The onshore industry in North America has embraced receiver nodes, with contractors generally having made the transition to nodes in the period between 2010 to 2014. Today, North American contractors offer a wide range of options to North American customers. Hardly any cabled systems remain in North America, although a few of the contractors who have survived the challenging market conditions of recent years still have cabled systems or are saddled with large inventories of heavier earlier generation nodes that are nearly ten years old or more, as market conditions have made refreshing those inventories difficult.

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Meanwhile, the Middle East and other parts of the world have generally been slower to adopt nodal receivers. There are currently crews active in the Middle East rolling spreads of 100,000 live channels (Figure 2), with each receiver channel being an array of 12-geophones. Were it not for the abundance of cheap labour, the
Middle East would have adopted nodes long ago. There is also a persistent preference for receiver arrays, particularly in dune environments. Nonetheless, with the latest generation of very efficient nodes things are changing quickly, with over 300,000 receiver nodes having been sold into the Middle Eastern onshore seismic market in the last two years.

![Panoramic photo of 100,000 geophone strings with 12 geophones per string, tested and ready for deployment in Abu Dhabi in early December 2022.](image1)

A key capability of autonomous nodes is that the Global Navigation Satellite System (GNSS) receiver integrated in the node electronics also permits nodal self positioning. This capability enables a wide range of innovative survey designs and further reduces cost by eliminating the need for a separate survey/positioning operation (Châtenay, 2016).

The industry has also made significant progress developing efficient source acquisition methods such as Single Vibrator Single Sweep (SVSS), Distance Separated Simultaneous Source (DSS) (Bouska, 2009) and Independent Simultaneous Source (ISS™) (Howe et. al., 2008).

The advent of autonomous nodes with embedded GNSS receivers further unlocked the potential for efficient autonomous acquisition methods that eliminate the need for the traditional seismic recorder. The efficiency of autonomous source acquisition is another game-changing method, particularly when combined with the Independent Simultaneous Source with Nodes (or ISSN™) methodology (Figure 3; Ourabah et al., 2014, 2015).

![Four vibrators acquiring blended data using the unconstrained ISSN™ methodology on an Explor high density 3D project in Canada in 2018. Here blending mini and heavy vibrators in very close proximity was tested.](image2)

These blended acquisition methodologies have proven themselves capable of delivering one or two orders of magnitude greater daily productivity, enabling cost-efficient high density 3D seismic data acquisition and thus, significant improvements to seismic data quality (Ourabah et al., 2015) (Yanchak et. al., 2018), (Thacker and Châtenay, 2019). These methods have been embraced by major proponents in the Middle East, where various methods of single vibrator, single sweep blended acquisition...
are now standard operating procedure. Proponents on the North Slope of Alaska have also followed suit, and there have been a few projects acquired with various high efficiency source acquisition methods in Canada and the US. However, in the realm of source acquisition, other parts of the world have generally lagged the Middle East by a decade or more. We still see customers paying for flip-flop Vibroseis with multiple-vibrator source arrays in North America – a terribly inefficient and obsolete methodology that condemns the end user to the expensive and sparse seismic datasets of yesteryear.

This resistance to blended acquisition (and a lingering preference for dynamite acquisition in certain geographic areas) has generally kept seismic trace densities low in North America, with many surveys still being acquired in Canada and the US with the same acquisition parameters used in the late 1990’s. Again, this is changing as the North American industry begins to recover from the profound downturn of the past eight or nine years.

To drive the efficiency of high-density acquisition as well as 4D monitoring, considerable work has also been done on lower energy sources and the ability of these sources to match the performance of conventional heavy Vibroseis and dynamite sources when acquired at very high density or by extensive stacking. This work extends the concepts developed with the aforementioned transition from vibrator source arrays to SVSS operations. While a long-standing industry axiom holds that deep targets require high power sources – or, said another way, that low energy sources are incapable of imaging deep targets, a growing volume of work in this field (Varsek and Lawton, 1985a, 1985b; Miller et. al, 1986; Meunier et. al., 2001, Châtenay and Thacker, 2017, 2018, 2019; Ourabah and Châtenay, 2022, Châtenay, 2022, Ahmad et al., 2022) is proving that long-standing axiom to be at best a half-truth. At very high densities, we have repeatedly demonstrated that sources generating as little as 4kJ of chemical energy output (about 0.06% of the energy in a 1 kg dynamite charge) are capable of imaging reflectors at over 2,400 metres depth. Additional research, engineering and field testing completed in 2022 and planned for 2023 is all but certain to prove the capability of low energy seismic sources to image much deeper targets than previously thought possible.

Perhaps the most impressive recent example is the work by Dr. Takeshi Tsuji and his colleagues at the University of Tokyo with the Portable Active Seismic Source, wherein they produced a vibrator using an eccentric mass weighing less than 10 grams and being only 4 cm across to propagate signal recorded via Distributed Acoustic Sensing (DAS) 900 metres away (Ahmad, 2022; Tsuji et. al., 2023). Dr. Tsuji’s work is exciting as it further extends the lower limits of usable active seismic source energy and reinforces previous work to deliver higher trace densities cost efficiently with low energy seismic sources.

Acquisition using low energy sources is yet another disruptive innovation faced by geophysicists.

**Geophysical challenges**

A defining attribute of disruptive innovations is that they have the attribute of initially being lower quality, and then gradually supplanting the previous technology as the quality improves and is accepted by progressively more demanding customers. (Christenson, 1997). Disruptive innovation also has the effect of destroying competencies as the skillsets required to deliver the new technology are different than the skillsets of the technology it replaces (Christenson, 1997). Consider the disruptive technologies listed herein and a summary of their outcomes:

- “Blind” Receiver Nodes:
Cables eliminated.
New survey design concepts possible. No longer need to connect receiver points with cables.
No recording truck is required.
Live shot gathers no longer possible.
Conventional QC methods no longer possible.
Massive increase in spread size possible.
All live spreads possible for small to medium size 3Ds, extending far offset coverage.
Very high trace densities possible, with digital array forming an option.
Million-channel crew is possible.
Traditional compromise on spatial sampling and far offset sampling altered.
Receiver gathers are the natural data sorting order.

Nodal Self Positioning
Fully stakeless operations possible.
Surveying as a separate activity is eliminated.
Node self-describes its position, supplemented by deployment and retrieval positioning.
Positioning solution may require integration with a robust digital elevation model (DEM)
Requires new methods.

Autonomous Acquisition
No observer is required.
QC, navigation and recording of time breaks embedded into source-side systems.
In the near future, solutions will include networking for live remote monitoring and QC.

Single Vibrator, Single Sweep (SVSS)
Lower signal-noise on individual shot and receiver gathers.
Many more source points, each with a lower S/N ratio.
Requires high density acquisition design to overcome lower S/N ratio.
Every vibrator operator is the lead operator, needs to navigate.
Navigation and QC capabilities reside in the vibrator.

Blended Acquisition
Radical change to field operations, especially when combined with autonomous acquisition.
Field management and coordination significantly different, requiring real-time navigation and tracking.
Shot gathers appear noisy and chaotic, especially when combined with SVSS
Total amount of ambient noise per acquired shot is reduced (Monk, 2022).

Low Energy Sources
New acquisition technologies and vendors.
New, ultra high-density survey designs.
Elimination of line clearing in boreal forests disrupts status quo, causing a defensive reaction from incumbents.
Lower Signal-to-Noise ratio requires changes to processing workflows.

No wonder adoption of this complex set of changes has challenged many geophysicists. Very clearly, many of these changes will destroy competencies of acquisition contractors, operations geophysicists, and processors. What used to work won’t work anymore, and new skillsets and techniques must be mastered. While many have embraced the ability of this new suite of capabilities to deliver higher quality images and to reduce risk, environmental impact and cost, we have also seen a strong defensive reaction from incumbents in some areas, particularly where this disruptive technology upends strong relationships in densely knit homogenous networks (Powell and Grodal, 1995).

Geophysicists resistant to change may conclude that it is simpler to continue doing things the same way, pursuing the existing practice of acquiring sparse data with strong seismic sources and using various interpolation methods to fill in the gaps. In pursuing the direction of sparsity and interpolation, potential improvements to seismic data quality are sacrificed, risk, cost and environmental impact will remain unnecessarily high, and geophysicists’ ability to deliver value across a number of industry verticals will be held back.

**Implications for processing**

In a memorable and erudite presentation given at the New Advances in Land Geophysical Acquisition Technologies Workshop in Muscat, Oman, in 2019, the Petroleum Development Oman (PDO) Head of Geophysical Data Processing Abdullah Al-Maamari described the implications for processing driven by these disruptive innovations in land seismic data acquisition. He gave his perspective of a processor dealing with the explosion in seismic data volumes, the transition from vibrator arrays to single vibrator acquisition, and the advent of blended data with very high blend fold. This presentation preceded PDO’s use of nodes – it would be great to hear an updated perspective from Mr. Al-Maamari now that PDO has experience with high density nodal acquisition.

Processors faced with processing blended high density 3D seismic datasets acquired with SVSS (or other lower energy-per-source-point sources) will have both the advantage of well sampled datasets in the source, receiver, cross-spread, offset and azimuthal domains together with the challenges posed by a much larger number of traces, each of which is noisier than the traces on a sparser dataset that uses a more powerful source, and with the added challenge of energy from interfering blended source points (Al-Maamari, 2019).
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Conventional Flip Flop

81 VP's/km²
250,000 traces/km²

Same vertical scale

HD3D Slip Sweep

380 VP's/km²
2,400,000 traces/km²

HD3D ISSN™

826 VP's/km²
4,600,000 traces/km²

Figure 4: A comparison of three sections from three different 3Ds acquired in Alberta, Canada at the same vertical scale (After Thacker and Châtenay, 2019). Each survey used the same number of vibrators. On the left, three sets of three vibrators each acquired expensive flip-flop acquisition. In the middle, the acquisition was transitioned to a single vibe, single sweep with nine vibrators using slip-sweep acquisition. On the right, nine vibrators acquired in single vibe, blended (ISSN™) acquisition. The improvement in data quality and bandwidth is obvious.

The first instinct of many processors faced with noisy data is to apply noise attenuation algorithms, but the danger with an aggressive approach to noise early in the workflow with lower S/N ratio high density dataset is that it will be difficult to properly separate signal from noise, and as such, signal can be inadvertently destroyed. As such, processors need to be prepared to nibble away at the noise by sorting the data into different domains to carefully model and remove the noise, while running repeated pre-stack time migrations to assess the efficacy of the noise-nibbling approach (Bouska, 2022).

Much has been written about de-blending seismic data (Kumar et. al., 2022). Major advancements are taking place in this field of work, with impressive outcomes. However, a processor without advanced de-blending capabilities need not be too discouraged. Our experience is that at relatively low blend folds, routine noise attenuation algorithms in different sort orders can achieve good outcomes. It is also worth noting that with blended acquisition and a robust deblending algorithm, the total ambient noise in the blended gather is spread across multiple deblended gathers, effectively reducing the ambient noise per source point (Monk, 2022).

Conclusions

Despite the challenging market conditions of the last several years, the onshore seismic industry has made several major technological advancements. These advances in both technology and methodology can deliver significant improvements in seismic data quality while reducing cost and risk, but they require a willingness to change and build new competencies.
Often, the biggest barrier to adoption of new technologies is fear of failure. Geophysicists faced with acquiring an important dataset will often fall back to doing what worked last time, thereby generating a similar outcome. While this may (or may not) protect against downside risk, the opportunity cost of not taking advantage of new techniques is very high given the incredible advances made in onshore seismic data acquisition in recent years.

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Expert answer 2 by Malcolm Lansley*

This is an interesting question because not all land 3D seismic acquisition is acquired in similar areas with the same geology, topography, environmental restrictions, climate, permitting issues and governmental restrictions. All these factors affect what are considered challenges in different locations around the world, with the result that different areas appear to have different challenges. Although some of these challenges are not necessarily “geophysical”, they do impact the geophysics directly in many cases and indirectly in others.

I will begin with a list of the major and most frequent issues that I have been encountering in recent times and then address these in more detail in later segments of this answer:

1. Evaluating the Value of Information (VOI) for projects to justify significant expenditures for higher quality 3D surveys.
2. Accurate determination of the velocity / depth model for optimal imaging.
3. Lower signal/noise ratio on surveys because of use of single sensor recording without compensating with the recommended increases of trace density.
4. Justifying an adequate migration aperture and potentially adding more longer offset data for FWI.
5. Interbed multiples, particularly in carbonate sequences (Middle East).
6. Reliably obtaining strong low and high frequencies to provide a “broadband” seismic section at an acceptable cost.
7. Accurate determination of a near-surface model and processing software that can be used to make near-surface corrections that fit the model and optimize the subsurface imaging.

1. Evaluating the value of information (VOI) for projects to justify significant expenditures for higher quality 3D surveys.

I have put this at the top of the list because usually, when a geophysicist is asked why they don’t shoot more or larger 3D surveys, the answer is frequently “because of the cost” and sometimes because “management doesn’t believe in them.” For geophysicists working in some major oil companies this is not a primary issue in many cases because their E & P teams have learned the value of having good quality 3D seismic surveys. However, for smaller companies with lower budgets, it is extremely important for the geophysicist to be able to understand and analyse the advantages and disadvantages of different options in the survey designs and to be able to justify increased costs and explain the benefits that should be achieved with a well-designed, high quality 3D survey. The VOI approach is an important tool for geophysicists.

2. Accurate determination of the velocity/depth model for optimal imaging.

This is a problem that is of great importance for all 3D surveys, not just those that are onshore. A problem with many land 3D surveys is that their areal coverage in many parts of the world is relatively small. This is frequently because of cost, but also may be a result of permitting problems or environmental concerns. The velocity determination for the shallow formations may be quite good. Both refraction and reflection
tomography are commonly used to help improve the analysis. However, it needs to be understood that short offsets are important with tomography as well. There can be a problem with large line intervals when these algorithms cannot function correctly because they don’t have the data needed. However, a more difficult issue is the accuracy of the velocity computed for the deeper formations. Errors in this can introduce long spatial wavelength errors when converting to depth.

Full Waveform Inversion (FWI) can be used to help overcome this problem, but there are two fundamental requirements that need to be satisfied before we can acquire adequate data. These are that (a) we must have sufficiently large source-to-receiver offsets to acquire energy that has penetrated to the formations of interest and (b) the source must have sufficient low frequency energy that it can generate signal that will travel over the longer distance and remain strong enough to be recorded with adequate strength. [(a) and (b) will be discussed in more detail below in Sections 4 and 6 respectively.]

![Grazing incidence raypaths computed in a gradient field with $V_o = 2151$ m/s and a gradient of 0.414. Note that for this velocity gradient, the diving waves only penetrate to ~600m with a source-to-receiver offset of 5200m.](image.png)

If we look at the grazing incidence raypath plot in Figure 1, we can see that for the particular velocity gradient used, the depth of penetration is only about 615 m with a source-to-receiver distance of 5200 m. If we require FWI-derived velocity information for greater depths, then the offsets will need to be increased accordingly. As the offsets increase the need for a stronger low frequency source also increases.

Another issue is that, if there are high velocity formations such as salt or basalt, the raypaths of the longer offset rays will go critical at the top of the high velocity layer and the diving waves will not appear at the next range of offsets. Depending on the thickness of the high velocity formation and its rugosity, the more vertical energy arriving at the layer might pass through it, then travel below it and reappear at offsets much larger than expected. These have been seen at offsets of over 20 – 25 kms.
3. Lower signal/noise (S/N) ratio on surveys because of use of single sensor recording without compensating with the recommended increases of trace density.

![Figure 2](image)

*Figure 2. An example (AGORA) of a single sensor recording (a) before noise attenuation, showing significant ground roll noise. (b) The same record in (a) shown after noise attenuation.*

As surveys are being conducted in more difficult operational areas, together with the increased pressure to reduce costs, we have seen a dramatic increase in the use of nodal acquisition. Associated with this has been
that many of these land nodes have a single sensor contained in the node that makes them very easy to transport and deploy. Unfortunately, many surveys that have been designed for single sensor nodal acquisition have been acquired with similar receiver spacings and trace densities to those typical for surveys using 6, 12, or even more geophones per receiver station. These surveys frequently show severe spatial aliasing on source-generated noise trains due to the large trace intervals. Aliased noise is more difficult to attenuate than well-sampled noise. The normal recommendation for moving to single sensor recording is that 1 single sensor can usually replace 3 geophones in a group. Therefore, to get comparable S/N ratio to a survey that was acquired with 12 geophones per group, with a single sensor survey we should acquire a trace density that is 4 times greater.

This has resulted in the acquisition of surveys with very noisy individual shot records. The noise increase is seen in the coherent source-generated noise (i.e., ground roll), scattered source-generated noise and random ambient noise. Fortunately, we have seen some excellent new processing algorithms to help attenuate some of these noises, although some of these algorithms do not work as well in 3D as they do in 2D or more regularly sampled data sets. An example of one of these coherent noise attenuation algorithms (AGORA from CGG) is shown in Figure 2. This is an adaptive filtering technique (Le Meur et al., 2008) that has several advantages over techniques such as FK filtering because it better preserves the signal and works even when the noise is aliased, dispersive and has irregular spatial sampling, as in 3D recording. Although there is still some residual coherent noise on the lower plot, the signal is now visible, and the remaining imaging should not be adversely affected. Spatial aliasing of the ground roll and air waves is also a problem because the nodes are often still using the same receiver interval as was used with arrays – this makes attenuating it considerably more difficult, almost impossible sometimes. More recently developed algorithms such as the greedy Radon transform (Wang, 2021; Wang, 2022) can deal with some aliasing and the irregular offset sampling that is inherent in land 3D data. Of course, the less aliasing there is, the better any of these algorithms work.

4. Justifying an adequate migration aperture and potentially adding more longer offset data for FWI.

When survey areas are small, the increase in total acquisition area when adding even a small migration aperture and Fresnel zone aperture can be very large when viewed as a percentage of the original area and cost. This has led to too many poorly imaged “postage stamp” surveys over the years. One very successful answer to this has been the acquisition of much larger multi-client surveys being acquired by seismic contractors. These provide efficiency in recording because the crews are working almost continuously for several months or even years in some cases, and there is not a significant impact from acquiring correctly calculated migration apertures.

In areas where large area multi-client surveys are not feasible, perhaps because of isolated prospective regions or governmental regulations, the geophysicist needs to again use his knowledge and experience to explain the need for fully migrated data to justify the additional expenditures. Inadequate migration apertures cannot be mitigated by any data processing algorithms as processors should not be creating data where no data exist. 5D interpolation algorithms work exactly as stated, they interpolate, not extrapolate. They also assume some form of smoothness or regularity that may not exist.

The small areal extent of many land 3D surveys does not lend itself to the large offsets required for FWI. Even though we do not need the same small spatial sampling for FWI as we need to the main central part of a survey,
the use of more sparsely located sources and receivers around the perimeter of a survey will still add to the cost and so is frequently cancelled. This problem is even worse when we have high velocity formations, and the diving waves go critical for the longer offsets.

Sparsely located source and receivers can be used, but this can become extremely expensive when considering the large area over which they would need to be distributed.

5. **Interbed multiples, particularly in carbonate sequences (e.g., Middle East).**

These have been recognised as problematic for all stages of exploration and production for decades. The Chief Geophysicist of Aramco in Saudi Arabia in the 1970s (John Hoke) once stated in a meeting that “he had found more oil than anyone else in the world by interpreting interbed multiples.”

Because of the repetitive cyclic layering of the high velocity carbonates, or often repetitive anhydrite/clastic sequences, there is virtually no velocity discrimination and therefore all multiple removal techniques that have been attempted have failed and the imaging itself is left to do whatever it can. In many cases, some of the highest trace density surveys ever acquired have been in the desert regions of the Middle East, the higher density of long offset traces will provide some additional attenuation of interbed multiples if there is any velocity discrimination between the primaries and the multiples.

The Internal Multiple Elimination (IME) algorithm (Jakubowicz, 1998; Wang and Wang 2013; Wang and Wang 2014) is probably the best at removing interbed (or internal) multiples and can be understood as SRME followed by a travel time correction.

6. **Reliably obtaining strong low and high frequencies to provide a “broadband” seismic section at an acceptable cost.**

The use of explosives to generate strong low frequency energy is not feasible for normal seismic surveys. Not only would the cost be incredibly high, but the safety and environmental damage would be unacceptable. In order to generate very low frequencies, the mass of explosives required would need to increase cubically as we move to lower frequencies. These charges would also need to be buried at greater depths to contain the explosions and the by-products. In addition, there is a surface ghost problem that attenuates both low and some high frequencies from buried sources, in a similar way to the ghost problem in marine acquisition, except that the air/ground surface may be more irregular than in marine and the velocity more variable. This problem is very terrain/location dependent, but it is present.

The generation of low frequency signal today is most often achieved by the use of what are called low dwell sweeps with vibrators. In these, the sweeps are designed to sweep through the low frequencies for a longer amount of time to put more energy at those frequencies into the ground. Even vibrators that are designed to have improved low frequency performance cannot vibrate at frequencies lower than ~4.5 – 5 Hz at the same level as they do for higher frequencies.

Unfortunately, more time spent sweeping means the acquisition time is longer and therefore the cost is higher. Many seismic crews in desert areas have as many 40 vibrators on the crew and operate 24 hours per day to acquire very high numbers of source points per day. Some of the larger vibrators that have been manufactured to provide greater force at low frequencies are also larger and heavier, with the result that they are not road-legal in many areas. To solve these issues, there is now a modification that can be used on smaller vibrators
that significantly improves the low frequency performance of the vibrators without affecting the high frequency performance. (Reust, 2021) Also, the addition of this modification does not add sufficient weight to affect road- legality in most circumstances.

Another option is to sweep occasional low frequency sweeps on a coarser grid using very long sweeps whilst the regular production continues with shorter sweeps from 5Hz and up, for instance. This was given the name of Symphony when introduced by Geokinetics (now SAE). Although this works very well, it does still need the extra offsets needed for FWI, if FWI is needed.

7. **Accurate determination of a near-surface model and processing software that can be used to make near-surface corrections that fit the model and optimize the subsurface imaging.**

Most geophysicists understand that the concept of a static, or single vertical, correction for all source energy emanating from a source point, or all energy arriving at a receiver point, is incorrect. Yet this is the same model that has been used, almost universally, for all seismic data processing that has ever been done. If we consider the variations in near-surface geology, it is easy to see that travel times of seismic data will vary for a given location on the surface, both by arrival angle from the vertical and the azimuthal angle.

In the past, in areas with very variable topography and near-surface geology, attempts have been made to improve the near-surface model and time corrections, by using tomographic solutions in which all azimuths and arrival angles can be comprehended. Azimuthal tomographic refraction solutions were sometimes quite successful but could not be guaranteed because of the ambiguous solutions. Also, in lower density 3D surveys, stability frequently became a problem.

The most common solution that is still being used in a majority of processing centres is still to use a single static value at each source and receiver point and then use residual “trim” statics to improve the image quality. Unfortunately, this is not a satisfactory solution because it still applies a single time shift to a complete seismic trace and does not allow for the apparent time variance of the shifts that should be applied because of the arrival angle differences between deep and shallow reflections. What is needed is a better way to define the near-surface model and a dynamic time correction algorithm that can apply the necessary corrections appropriately.

In the case of fast over slow velocity formations, e.g., surface carbonates or basalt over a clastic, the wave arriving at the receiver may be closer to the horizontal than the vertical. In such cases a 3C sensor can be used to find the arriving P wave. These do not have to be deployed throughout the survey, just in these problematic areas, and are not for converted wave processing but for P wave processing.

The use of non-seismic methods to assist in the definition of the near-surface model is definitely something that should be used more regularly. Both gravity and airborne EM are relatively inexpensive and can, and have been, used to help define the N-S model. Also, in Saudi Arabia the ground stiffness and viscosity reported by vibrator control electronics have been used to define the velocity beneath the vibrator down to an estimated 50m depth. (Al-Ali et al., 2003)

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Expert answer 3 by Norman Cooper*

The major challenges in land seismic acquisition can be summarized in two major categories. The first relates to social and political pressures. Although these factors have dramatically increased the difficulty and costs of seismic projects, they are not issues that have technological solutions.

The second major challenge is to continue to provide higher quality data with increasingly useful attributes while lowering the operational costs. The tools and techniques to best address these goals depend on the area of operations. For example, high productivity Vibroseis methods are amazing, but of little value in mountainous terrains. Nonetheless, I will attempt to summarize some of the powerful technologies available today.

Social-political environment

Certainly, the current social atmosphere that vilifies our industry is one of the biggest obstacles to modern operations. Field operations have become encumbered by landowners who are against development of resources. We see activist groups assembling to block our operations. We are experiencing more occurrences of vandalism. The cost for security forces to accompany crews in North Africa and the Middle East is a significant part of those operations.

We need to replace our retiring expertise with enthusiastic and innovative new talent, but encouraging new people to enter our industry is becoming very challenging. University enrollment in geosciences is dropping each year. Hiring and retaining dependable field staff is a major problem for seismic contractors.

All of this is partly due to popular social wisdom that places our industry as a target for contempt. Even the most experienced of us are sometimes reluctant to discuss our professional roles in social settings due to the disdain that is often displayed by some of the public. In this environment, we must all learn to be better communicators and better ambassadors for our industry. This is one place to start improving our skills and participate in the rebranding of our profession.

Regulatory compliance, licensing, permits, and socialization are now a considerable portion of the time and expense of seismic programs. The balance has shifted between front-end costs versus the actual field operational costs of recording a program. The former tends to be a fixed cost and is somewhat independent of program size. The latter is a function of program density and operational efficiency. There is little our industry can do to reduce the cost of regulatory compliance other than aggressive lobbying.

If initial fixed costs are disproportionately high, significant gains in efficiency that reduce the operational cost may have a low percentage impact on total costs. For a client who is concerned about the trade-off of data quality versus program cost, be aware that as fixed costs escalate, the relative cost for higher density diminishes.

Environmental considerations have resulted in many improvements in seismic operations. LIS (low impact seismic) operations have become commonplace in lieu of wide lines cut by bulldozers. Mulchers and small mechanized drills now wind their way through a forest, minimizing destruction of mature trees and allowing complete re-growth within one or two seasons. One-pass operations and stake-less survey methods reduce the impact of heavy traffic along seismic lines. The use of detailed LiDAR and satellite imagery has dramatically improved pre-planning and operational efficiency.
Technical considerations

Autonomous nodes

As acquisition tools have evolved, processors and interpreters have found new benefits from higher density data. Noise suppression algorithms benefit from multi-dimensional analysis. Pre-stack attribute analysis in both offset and azimuth domains provides greater insight and understanding of our targets. More data leads to new interpretive tools, which leads to demand for more data!

And the seismic acquisition industry continues to respond to these demands. The density of recorded channels continues to increase and the cost per channel continues to decrease. Methods for increased Vibroseis productivity continue to evolve, enabling higher source density with lower operating costs per source point.

Certainly, the most significant development in seismic recording has been the development of autonomous nodes. Today there is a vast selection of equipment available, all of which dispense with the use of cables and connectors. These include Fairfield Z-Land, Sigma I-Seis, Inova Hawk, Inova Quantum, Smart Solo, Sercel Unite, Geospace CGL, Sercel Wing, Nu-Seis, Stryde. The list keeps growing. Some of these are already falling into disuse, but new systems seem to appear every year. My apologies if I have omitted any new or favored systems. My intent is not to review each system individually, but rather to summarize which features seem to be attracting the warmest reception from contractors and end users. It is likely that no single system will have ideal characteristics for all job environments or all users.

- **Cost per channel** – more recent systems tend to be lower cost. There will always be a tradeoff such that systems with more features will tend to be more expensive. Simple is cheap, but we may have to compromise on some features.

- **Weight and bulk per unit** – small light units allow for ease of distribution and handling. More units can be deployed more rapidly, with fewer personnel and lower physical demands on the individual (an important HSE consideration). Shipping and mobilization costs depend on bulk and weight.

- **Cables and connectors** – one of the great advantages of nodal systems is the elimination of cables and connectors. Damaged cables or faulty connections have caused many hours of downtime on past operations. Their elimination has dramatically increased dependability of new systems and increased production rates. Problems with atmospheric static and lighting strikes are almost eliminated.

However, some systems still require external battery packs or external sensors to be plugged in. In general, it is better to avoid systems with necessary external devices. On the other hand, it may occasionally be useful to have an option to interface with alternative external sensors. Also, with no connecting cables between receiver stations, there is greater flexibility in planning receiver locations. Carpet receiver designs become practical.
• **Battery life** – newer electronic components draw less current and battery technology is evolving. Newer systems are generally capable of recording for 30 to 60 days on internal batteries. Rated battery life will be sensitive to ambient temperature, so cold weather operations may have different requirements.

• **Integrated GPS** – a node remaining at one location for several days can collect a “cloud” of measured locations. The median of the cloud will provide a sufficiently accurate location and eliminates the need for surveying. However, GPS signal may be hampered in heavily vegetated areas or underwater placements. Alternatives should be available for difficult areas.

• **Retrieval of system status** – All systems have some method to check the status of the node. Many have the ability to collect status wirelessly using a handheld device while walking or driving past the node. Many crews are using such a device mounted on drones to check the status of nodes. Some of the systems have the ability to broadcast their current GPS location so that they can be located if stolen, moved by wildlife, or carried away in a flash flood.

• **Retrieval of data** – None of the current systems allow the user to download all of the channels from a large job in real time. Some systems allow transmission of limited amounts of data (a few channels). But for now, we cannot see all of the recorded seismic data until sometime after recording when the data is “harvested” from collected nodes.

The idea of “shooting blind” was initially disturbing to many users. However, the reliability of current nodes eliminates the need to check if the node is actively collecting data. As for checking wind, rain or traffic noise on the spread, alternative methods are being employed (weather stations deployed in key areas, physical observers monitoring traffic).

A major concern is theft of the node, which usually means not only the loss of the asset, but also the loss of any data that has not been harvested from that node.

Perhaps in the near future, data transmission rates will be sufficient so that drones can be used to fly over deployed nodes and harvest all recent data. In this manner, much data could be collected on a daily basis.

***Receivers***

Another change in the last 30 years has been the type of sensor used in receivers. The conventional spring-balanced moving coil around a permanent magnet is still in use. Manufacturing changes have been implemented to increase sensitivity, reduce harmonic distortion and suppress transients. Our industry now uses mostly elements with 10 Hz or 5 Hz resonant frequencies. Typically, the amplitude output below resonance drops at 12 dB/octave. This is NOT a brick-wall filter and does not mean that the element does not respond to lower frequencies (a common misperception). The output of a 10 Hz geophone at 1.25 Hz is still available, but 36 dB lower than the output at frequencies above resonance. Several studies have shown that such low frequency signals are still recoverable after dephasing and deconvolution (Margrave et al., 2012). Some interpreters have found moderate improvements of inversion techniques when using sensors that have lower frequency responses.
Since the early 1990s, we have also had a choice to use digital MEMS sensors. They provide improved instantaneous dynamic range, reduced sensitivity to tilt, lowered harmonic distortion and direct digital output from the sensor. They also have a fairly flat amplitude response to very low frequencies.

Some of the available nodal systems use MEMS sensors internally, but many continue to use low distortion moving coil sensors. The Stryde system uses an internal piezoelectric crystal. Users should be aware that moving coil sensors that are in common use produce a signal proportional to velocity. MEMS sensors produce a signal proportional to force (which is proportional to acceleration) and piezoelectric sensors produce a signal proportional to pressure (also proportional to acceleration). Data from MEMS sensors and piezoelectric sensors are both 90° different in phase compared to moving coil sensors. This should be adjusted in processing if the data is to be integrated with projects using a variety of receivers.

**High productivity Vibroseis**

Gone are the days when we used to require 12 sweeps of 12 seconds at each source point. Chaotically-scattered source-generated noise is perhaps the most troublesome mode of noise (Cooper 2017). This noise is exactly repeatable for sources duplicated at the same source point. If signal and noise are the same in all occurrences of the same source point, then averaging multiple sweeps from the same source point does not improve signal to noise ratio. Data quality is far more enhanced when single sweeps are recorded from several unique source locations rather than several sweeps repeated at one source location. It is most common now to use only one sweep per VP but to reduce VP intervals. We sometimes use two sweeps at the same source point when coupling may be very poor throughout the first part of the first sweep.

Over the past 25 years, the size, power and efficiency of vibrators have been steadily increasing. Where 35,000 lb units were once standard it is now rare to use large vibrators less than 60,000 lb and quite common to see them as large as 90,000 lb. Even where projects require deep penetration and recording of long offsets, we now find that a single vibrator provides sufficient signal strength.

At the same time, development of small footprint vibrators has continued to evolve. Vibrators than can be moved on small vehicles with low gross vehicle weight are desirable in many situations where available trails are narrow, gates on fences are restrictive and necessary access includes bridges with limited size and capacity. For projects other than those in wide open desert and prairie, small vibrators have earned a place in reducing environmental impact. We once were restricted to 6,000 lb machines, but now can have 26,000 lb force in machines that are more eco-friendly. Although these machines are not as powerful as their large cousins, we have obtained good signal penetration to more than 4000 meters using three units in tandem.

Vibrator design has been changing to allow sweeping in lower frequencies. Base plate rigidity, pump capacity, air bag design and other components have been modified to overcome fluid flow and mass displacement and distortion limits on low frequency sweeps. Furthermore, customized sweeps have been used to extend sweep bandwidth into lower frequencies that are desired for seismic inversion. However, these custom sweeps require lower sweep rates at reduced force through the low frequencies. This extends sweep time and may increase program costs.

The freedom to reduce effort at each source point to a single sweep with a single vibrator has encouraged the development of a variety of high productivity vibroseis methods. We have evolved from simple “ping-pong” methods where two or three fleets of vibrators are used, alternately moving and sweeping. Slip Sweep allowed us to use more fleets of vibrators provided the time between the start of vibrators at one location was separated.
from the next set sufficiently so that correlation with one data set and its principal harmonics did not interfere with the ongoing correlation with the next data set.

Since 2008 several methods have been refined that allow recording where data from one vibrator point overlaps data from other vibrator points (true simultaneous recording). These methods include ISS (Howe et al., 2008), DSSS (Bouska, 2009) and more recently xDSS (Tellier et al., 2022). Tellier et al address the requirement for specific time and distance separation of multiple sources and optimize the method.

These very high productivity methods are best suited to large projects where many fleets of vibrators are available and where the movement of the vibrators is not restricted by detours. They also require very large available recording patches. The total assets on such a crew mean high depreciation and amortization costs (or high rental costs). On suitable projects the added cost of the equipment is offset by the high production rates. None the less, the equipment costs, enlarged camp and crew costs and enlarged security costs mean that cost of any lost days of production are very high.

Simultaneous source methods require a “de-blending” process that usually involves multi-domain coherency filtering. Various methods of deblending have been developed (Willacy et al., 2019), but most still have some issues with residual noise as well as phase and amplitude stability of the deblended data.

Note that simultaneous shooting and deblending is also a viable technique for programs using impulsive sources. It has been successfully applied in marine and transition zone data using multiple air-gun sources. The method allows for rapid acquisition of many source points, which requires increased numbers of impulsive energy sources or shooters in the case of explosive sources. However, in the case of explosive sources, the high costs of drilling and loading source points are not mitigated by simultaneous methods.

**Processing and design**

Processing algorithms continue to evolve. Multi-domain noise suppression and deblending algorithms allow recovery of useful signal even in data that was too noisy to be useful in the past. 5-component (Cary et al., 2012) and 6-component (Ng et al., 2017) trace reconstruction algorithms provide very important regularization of trace statistics and can supplement data that is locally deficient over small areas. Compressive sampling techniques can be used to acquire higher resolution data without increasing recorded trace density (Millis, 2018).

Some 3D designs can intentionally skip specific patterns of source or receiver points, creating localized deficiencies at the bin-to-bin scale. These deficiencies are then restored by trace reconstruction or compressive sampling algorithms. This is particularly useful in explosive source programs where shot point costs are high. For a given desired effective trace density after restoration and regularization, total field source points can be reduced by 10 to 20 percent.

Flared grids and variable density 3D grids are being used to more effectively image targets with predictable changes in depth, or where various noise sources are identifiable and localized (Stork, 2023).

**Summary**

Certainly, the current socio-political atmosphere that vilifies our industry is one of the biggest obstacles to modern operations. Equipment and techniques have been developed that minimize environmental impact.
We need to replace our retiring expertise with enthusiastic and innovative new talent. There is much room for improvement in our lobbying and communication skills. This will not be accomplished by technical innovations, but rather by personal commitment.

In seismic operations, we must continue to increase data quality and deliver information suitable for all kinds of pre-stack attribute analysis. And we must do this while reducing the costs of field operations.

We must recognize that this objective has as many different solutions as we have different operating environments. When working in some countries, we are limited in our choices of acquisition contractors. We must often work with the equipment that is available.

We must stay abreast of new tools and technologies and the best ways to implement them. But we must also stay cognizant of older technologies that are still in use and remain proficient in their application.

Wherever you are working, and whatever your current favorite technology or tools may be ... I can assure you of one thing. In five years, you will have new favorite technologies and tools.

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Mustagh has designed more than 3000 seismic programs in more than 50 countries, representing over 400 clients.

Norm has taught more than 3000 participants in his various courses in seismic acquisition topics and has supervised the startup of more than 300 field operations.

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*A single streamer for a 2D seismic survey, being deployed from the back of seismic research vessel “Eagle Explorer” in Deep Offshore Andaman. In the picture, compass birds are being attached to the streamer to monitor azimuth angle of streamer (which will monitor cable feathering). Digibirds (not in picture) are also added to the streamer to maintain the depth of the streamer, which is very crucial for any survey but more so for Broadband’s slant cable geometry. (Photo courtesy of Ritesh M. Joshi)*

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Land seismic data acquisition has advanced in recent decades to significantly higher resolution and trace density with higher channel counts and simultaneous vibratory sources. These methods remain challenged in areas where access is difficult or has environmental impact concerns. High quality surveys are expensive in these areas, and often the survey design is still compromised in favour of budget. Recently, environmental impact has become an equal or greater issue to financial cost, especially in the boreal forest. In Canada particularly it has become very challenging to recruit workers into such a volatile part of the industry, while the experienced core of trained personnel are approaching, or now enjoying, retirement. This workforce issue has resulted in part from a protracted downturn in land seismic acquisition for most of the last decade, but the search for new subsurface targets – critical minerals, carbon sequestration reservoirs & geothermal reservoirs, for example – will usher a resurgence in land seismic programs. Balancing all these competing priorities by operating safely and efficiently to acquire high quality datasets with minimal impact, the major challenge facing 3D land seismic data acquisition. We must continue to push on all fronts to ensure we offer new industries a clear value proposition for 3D seismic.

New concepts and technologies to assist with the 3D land acquisition challenge should start with survey design, which ultimately controls the survey cost and relates directly to the environmental impact (Naghizadeh et. al., 2023). Innovative designs that balance sources, sensors and sampling into a dataset that meshes with the advances in processing can reduce impact and cost simultaneously. Modern processing flows have robust regularization steps, reducing the need to ‘regularize in the field’ and allowing greater flexibility to simultaneously achieve the triple goal of improved final data quality with reduced impact and cost. Alternate views of sampling and coverage are not only coming into use but are being shown as more optimal measures for predicting final data quality from modern processing compared to traditional design analysis. Survey design is undergoing a rapid period of innovation, which is great news as no other avenue can have as large an impact on environmental impact and cost.

New miniaturized equipment is available for both sources and receivers:

- A new generation of recording nodes has recently been released by several manufacturers, with a full station (geophone, memory, battery, and GPS timing) contained in a single unit weighing around 1kg or less. Battery endurance on these stations generally remains beyond 30 days, though this is reduced in cold conditions or with 3C/24hr recording. Equipment is available to target very low frequencies below 5 Hz, although depending on sensor type, there may be compromises for higher frequencies above 130Hz. Some broadband sensors now have excellent performance across the seismic band of interest, and research is underway on distributed receiver arrays to sample both the high and low frequency ends of the spectrum with a mix of receiver technologies. With increasingly miniaturized electronics and batteries, partly enabled by reduced power requirements, weight of equipment has gone down faster than channel count has.
increased. Weight per channel is most significant when mechanical access to lines is limited or eliminated for environmental impact, and the latest equipment allows more channels to be carried by hand with reduced effort by field crews. This provides outstanding flexibility to further mitigate environmental impacts during project design & planning.

- Miniaturized sources also show promise for delivering improved data quality through increased source density (Crook et. al., 2023). The signal output of an individual source point may be lower, but if the density of shots combined with density and bandwidth of receivers increases, this can offset the signal reduction and lead to real improvement in the dataset. More of the signal can be collected with increased receiver density, but this comes at a cost of receiver field effort and often reduced quality of receiver gathers. Sources are more difficult to miniaturize than receivers because of the difficulty in producing enough signal across the frequency band of interest to be recoverable in processing – this will generally involve a drilling vehicle for buried explosives, a carrier vehicle for a vibrator or surface impulse with non-trivial mass, or a very high density of very weak sources. All source points are certainly not equal, and the final data quality resulting from a particular arrangement of source power and density needs to be proven with rigorous evaluation.

To the greatest extent possible, new methods and equipment should be user-friendly, operationally simplified and support greater cross-training and coordination of crew members. Ideally, crew members would fulfill multiple roles (e.g., line preparation, surveying/position QC, receiver deployment & retrieval, source initiation, data QC & output) allowing for more working days on each seismic field project and a reasonable expectation of a career and livelihood in the seismic industry. More cross-function work reduces mobilization and orientation costs and helps maintain a consistent collaborative and safety-focused field culture. Some roles will always require additional training and tickets, like shot hole drilling and blasting. Nonetheless, as equipment and methods become lighter, simpler, and lower impact, workers can more easily participate in multiple phases and develop the skills to lead the next generation of seismic programs. This is only true if field working conditions are safe and efficient, presenting an attractive workplace with stable work and potential for advancement.

Lastly, to ensure we are in fact moving forwards as new technologies are deployed, there is a great need to conduct robust technical evaluations from data gathered in realistic field experiments. This needs to include fair and transparent processing comparisons, and detailed evaluation of 3D seismic interpretations (cross-sections, slices, well ties, horizons, amplitude extractions, post-stack attributes), prestack comparisons (e.g. AVO crossplots), as well as inversions of both post-stack volumes and pre-stack gathers (Naghizadeh et. al., 2023). Not all datasets will be used for all these analyses, but even a post-stack well tie requires a comparable and accurate set of amplitudes across an appropriate range of offsets. Design and equipment choices that do not produce at least equal data quality in a direct comparison with existing technology cannot reasonably be called an alternative or improvement. There are important innovations ongoing in 3D land seismic, and adopting new techniques and technologies should not involve a reduction in final data quality, nor place additional demands or risks on the field personnel. With the right combination of advanced designs, equipment and methods, 3D land seismic will continue to evolve to meet society’s needs for high quality data to characterize and monitor key subsurface projects, with reduced environmental impact.
References


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Seismic research vessel, “Eagle Explorer”, standing in all its glory at the Port Blair seaport, waiting for port clearance to sail in an expedition which might result in a boon for the nation. (Photo courtesy of Ritesh M. Joshi)