Repeatability issues of time-lapse marine seismic data

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Abstract

Repeatability is a key issue in seismic monitoring, as it defines the noise threshold which a time-lapse change needs to exceed. Good measures of repeatability are non-trivial to define, and while NRMS (Normalized Root Mean Square) is widely used today, more than one parameter is needed to describe various aspects of the data. The background noise level and horizontal positioning variations are basic causes of non-repeatability which need to be controlled in data acquisition. Source- and receiver positions may be controlled by towing many streamers in parallel and having overlapping swaths, by keeping the source on a pre-defined line, and by laterally steerable streamers. Timing variations, caused by water layer variations, may be corrected for by data dependent matching, provided the position variations are not too large. Optimizing the choice of sampling parameters, as streamer separation, number of streamers, amount of swath overlap, cable steering or not, may be guided by repeatability modeling. A simplified scheme taking the statistical distribution of position variations into account is suggested.

Introduction

Improving reservoir management is an ongoing challenge. 4D seismic is helping to meet this challenge in a growing number of cases. The technology has a multi-billion dollar potential value by increasing hydrocarbon recovery (e.g. Lumley 2001, Lumley 2004). However, to fulfill this potential, technical improvements are needed, as some failures have demonstrated (e.g. Eiken et al. 2003a).

The degree to which production effects in a 4D dataset are visible depends on the strength of the time-lapse signal. Preferably, the time-lapse signal-to-noise ratio should be greater than one (Waggoner 1998), as illustrated in Figure 1. Vertical position in this cross plot is determined by reservoir properties, while improved repeatability would move the data horizontally and to the left of the line. Unfortunately, some seismic monitor datasets do not achieve this, and are not very repeatable. The degree of pure time-lapse signal is a function of the reservoir and cannot be influenced. The noise portion can, however, and this is where improvements in repeatability would matter.

The industry's knowledge of the key issue of repeatability is limited, though rapidly evolving. Poor repeatability creates changes that are not related to the reservoir (i.e., artifacts) and are difficult to distinguish from true reservoir-induced changes in the seismic response. Repeatability – or lack thereof – will give a detection threshold on the minimum fluid-front movements that can be observed and on how frequent repeat surveys can be made.

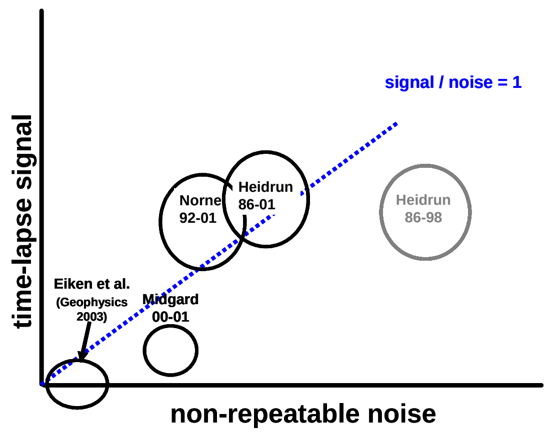

Figure 1 - The blue line represents a signal to noise ratio of one. Ideally, S/N should be above the line to see the time-lapse signal.

Repeatability measures

Quantifying repeatability is important for comparing effects and improving 4D data quality. This quantification is non-trivial. Much used is the ratio between RMS difference amplitude and input amplitudes, called normalized RMS (NRMS), in a time-window not comprising 4D anomalies. Such numbers range from a few per cent in well controlled experiments to more than 100% in legacy data with widely different acquisition and processing parameters. As pointed out by Kragh and Christie (2001), the NRMS measure is sensitive to time-shifts, while other measures, as *e.g.*predictability, will only be sensitive to amplitude changes of events. A further repeatability measure is time-shifts, either measured at discrete events or by cross-correlation in a larger time-window. Also amplitude variations of discrete reflections may be used as a repeatability measure.

In many cases these measures will depend on the strength of the reflected signals. A partition into an additive and a multiplicative (or convolution) component of non-repeatability can be a useful way of describing this property. Such a partition may also have a physical justification, as some of the causes of non-repeatability will give either an additive component (as background noise) or a multiplicative component (as source output variations). Some, but not all, of the multiplicative component may be aligned by data-dependent matching.

High frequencies and high wave numbers are less repeatable. This property can be illustrated by normalized difference amplitudes in f-k domain (Eiken et al. 2003b). Accurate repeatability measures should therefore take the temporal and spatial bandwidth into account.

Causes of non-repeatability

Causes of non-repeatability can be much different for land and marine situations, as both the shallow medium (weathering or water layer) and the acquisition systems are different. Some typical marine acquisition-related variations, such as navigation errors, source instability and varying tow depths can be better controlled now than some years ago, due to better equipment, while more basic variations of spatial sampling, water-layer variations and back-ground noise are still significant causes of non-repeatability in many cases (e.g. Strudley and Smith 2002).

Cause	typical variation
Background noise	< 40 %
Horizontal positioning	< 40 %
Water level & velocity	< 1 % or 2.5 ms in time
Vertical positioning	< 5 %
Sea state	< 5 %
Source variations	< 5 %

Table 1: Some causes of non-repeatable seismic data, listed with typical amplitude variations caused.

Some of the more important factors causing variations in the acquired data are listed in Table 1. Those marked in yellow, such as tides and varying water velocity can, to a large degree, be corrected during data processing by proper time-shifts and attenuation of multiples and diffractions. Background noise and horizontal positioning, marked in red, are more basic limitations. Background noise has to be controlled by proper acquisition specifications. As for horizontal positioning, marine data are always spatially undersampled in the crossline direction, causing alias errors, and variable cable feather and source positions from pass to pass causes both midpoint and azimuth variations in streamer data. These variations are probably the most fundamental limitations to improved repeatability in state-of-the-art multi-streamer acquisition and processing technology (Calvert and Wills 2003, Eiken et al. 2003a).

Source and receiver positions

Marine time-lapse seismic has traditionally been carried out using similar acquisition specifications as for 3D imaging surveys, and this is still the case for most 4D repeat surveys today. Processing techniques have improved over the last decade as the 4D methodology has matured, with parallel processing and more careful matching of vintages as key elements. Typical NRMS levels of 25-40% have been reported from the North Sea (e.g. Koster et al. 2000), which has been sufficient to detect changes related to moving oil-water fronts, but not always the more difficult targets of gas depletion and deeply buried reservoirs.

Even a small change in position causes a significant change in seismic response. This can be illustrated by taking a seismic section, shift it a few meters laterally and subtract it from itself, as illustrated in Fig. 2. Similarly, a small time shift will also increase NRMS amplitudes (Kragh and Christie 2001, Eiken et al. 2003b). Calvert and Wills (2003) investigated 3D VSP data, and found also high sensitivity to azimuth variations. This can be explained by propagation effects in a laterally inhomogeneous overburden.

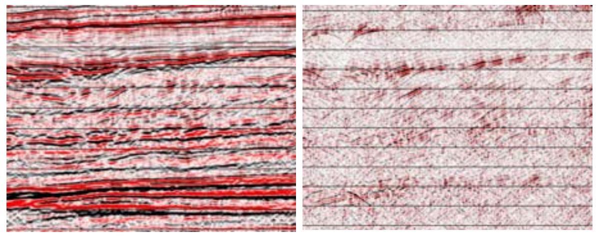

Figure 2 – Seismic section (left) and difference section after a 25 m lateral shift before subtraction with itself (right) NRMS amplitudes are about 40%.

By towing many streamers at narrow separation and reconstructing a center line (Eiken et al. 2003b), repeatability as good as 5% difference amplitudes has been obtained in zero timelag tests (the line was re-shot only days apart), when both source and receiver positions were repeated within a few meters. Lack of ability of conventional binning to compensate for position variations as small as 10m was demonstrated, as shown in Figure 3. More advanced interpolation, honoring the irregularly sampled data in the crossline direction, together with a reduction of the crossline spatial bandwidth, improved the repeatability.

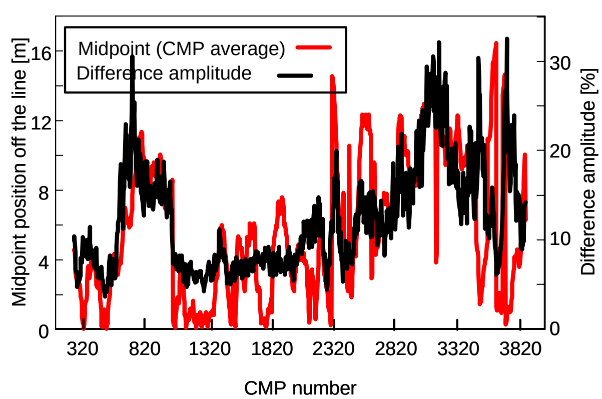

Figure 3 – NRMS difference amplitudes (black) and midpoint crossline deviations (CMP average) for a repeatability test line. From Eiken et al. (2003b).

3D marine surveys have the last decade been shot for coverage, which is time-effective when towing many streamers in parallel. In the North Sea, a typical feather distribution is as shown in Figure 4, with 70% of the data at a feather angle less than 3°. More open ocean areas, as offshore Brazil and east of Africa have significantly stronger current variations and correspondingly wider feather distributions, sometimes with as much as five times as high average feather than North Sea conditions. Much of these cross-currents are caused by meso-scale eddies rather than tides, and therefore not easy to predict. Operational implications of such strong currents are obvious, but the effect on repeatability less so.

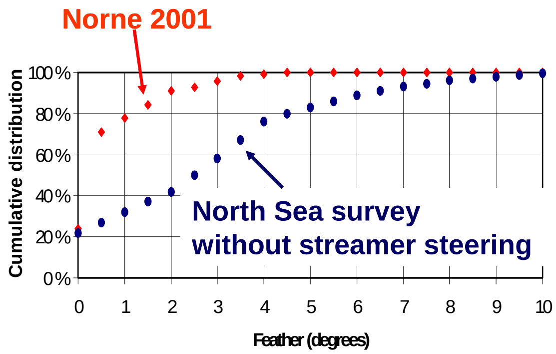

Figure 4 – Cumulative feather statistics for typical North Sea conditions (blue) and with active streamer steering (red).

There has been a growing appreciation among operators that it may be beneficial and worth the extra expense to modify towed streamer acquisition for 4D purposes. Such changes include denser cable separation and overlapping swaths (Widmaier et al. 2003), while infill-criteria based on previous vintages (baseline surveys) have been attempted. Denser spatial sampling reduces alias errors and unavoidable position errors within conventional bin-gathers. Overlapping swaths, helped by the increasing ability of seismic vessels to tow many streamers, give less variable coverage (data holes) at swath boundaries. This makes binning based on selection of minimum azimuth change possible and reduces the non-repeatability in a situation with moderate feathering. However, to completely eliminate the effect of variable cross-currents, the required close spacing between boat lines could increase the cost dramatically, depending on the current situation.

Steerable streamers, called Q marine, provide horizontal streamer steering by use of novel steering devices (Curtis et al. 2002). The ability to steer horizontally improves predictability of receiver coverage and will improve the 4D data repeatability – by a yet not quantified amount. It may also improve data coverage as well as operational safety around obstructions. The system has been used on the Heidrun and Norne fields offshore Norway, with resulting good quality 4D data (Eiken et al. 2003a, Goto et al. 2004). Cable feathering was generally reduced by 2.5^{o} – 3^{o}, and 70% of the data were now shot with zero feather. This has been a major cause of the high level of repeatability compared to “conventional” North Sea 4D surveys (Goto et al. 2004). The hole of lacking data or high-azimuth data coverage of poor repeatability around the FPSO (Floating Production and Storage and Offshore Loading) obstruction centrally over the Norne field was much reduced by being able to get as close as 40 m to the FPSO, and the date hole was almost completely removed by repeating the same undershoot pattern in subsequent Q Marine surveys.

A further improvement might be permanently installed seafloor sensors, which eliminate spatial variations on the receiver side. Such a monitoring is carried out on the Valhall field (Kommedal et al. 2004), so far with repeatability levels reported comparable to good streamer data. For such systems, coarser receiver sampling than along a towed streamer may give more aliased source-generated noise unless the shot sampling is very dense, and variable source positions will remain a cause of non-repeatability as it is for towed streamer data. Multiple attenuation could be improved by combining hydrophone and geophone data during processing, while coupling variations in time could be an additional source of non-repeatability. More experience on quality, cost and reliability of permanent seafloor receivers is needed to assess the value of such systems.

When the receiver side is better controlled, either by steerable cables, dense sampling of streamers or permanent cables, source positions becomes more important. Having a single source behind the vessel instead of a dual source makes the lead-in cables shorter and the control of source position by vessel movements easier. In some cases, it has been possible to control the source crossline position within 6-10 m. Steerable sources could improve on this performance. A way of improving source positions without re-designing the towing arrangement was described by Naess (2005), and is illustrated in figure 5. An excessive number of sub-arrays are towed, and varying subsets are fired, depending on the position of the source.

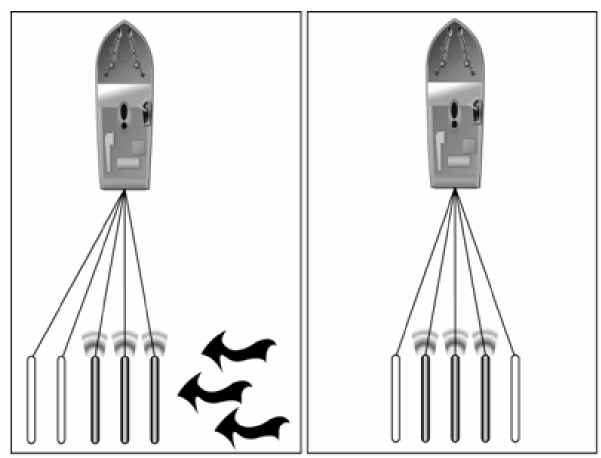

Figure 5 - Schematic illustration of the SOS (Self Overlapping Source). Left: The towed source is drifting towards backboard and the 3 rightmost sub-arrays are fired. Right: no sideways drifting and the 3 middle sub-arrays are fired. After Naess (2005).

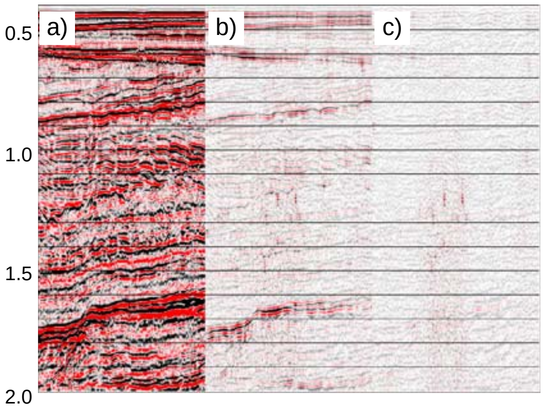

Figure 6 – Baseline image (left), difference image without tidal correction (middle) and with about 0.5 m tidal correction (right).

Timing

Marine data can have timing accuracy down to 0.1 ms when positions have been accurately repeated and necessary timing corrections have been made. Varying tidal levels can easily cause changes exceeding one ms, and must be corrected for. This is illustrated in Figure 6, using a correction derived from actual water level measurements at a nearby platform location. In most of the worlds oceans, predicted (astronomical) tides may be used, as current satellite-based models are mostly accurate to within 10 cm, which is sufficient. Multiples will not be possible to correct, and must be attenuated before differencing, unless the highly unlikely case of water layer conditions being exactly the same.

Unavoidable water velocity variations, caused by the oceanographic circulation with varying salinity and temperature, will be more severe the deeper the water is. At several hundred meters of water depth, these time shifts can amount to several ms (Bertrand and MacBeth 2003), and even in shelf areas the correction can easily exceed one ms. Such variations may be compensated for by matching the water bottom reflection (if positions are repeated), and preferably pre-stack if lateral variations are of shorter wavelengths than the streamer lengths. In a multi-streamer dataset at 300 m water depth (Tøndel and Eiken 2005), the post-stack correction improved the timing accuracy down to about 0.1-0.2 ms – which is good, but still not quite as good as a zero time lag test made at the same location. Hence, water velocity variations may be a basic limitation when other factors become more controlled than what is common today.

Source signature and tow depth changes

Changes in the acquisition system between base and monitor surveys, such as different gun arrays or different towing depths are common. These cause different source signatures and directivity pattern. These will be global changes, constant for a whole survey area, and can be compensated for by deterministic corrections, as far as the source output or tow depths are known. They may also be corrected for (or an additional residual correction) by data-derived global corrections. Our experience from making such compensations, as the example shown in Figure 7, is that they can adequately correct the data, and such acquisition changes do not need to increase the level of non-repeatability, at least not for data with final NRMS levels of 10% or more.

A non-flat sea surface will cause varying source output, varying surface ghosts and non-perfect reflection of the multiples. All this will cause non-repeatability, and most severely for the higher frequencies. However, having compared data shot in calm sea (0.5 m wave height) and at 2-4 m significant wave height, which is close to the operational limit, the influence on repeatability seems minor, at least for a 10% NRMS general repeatability level.

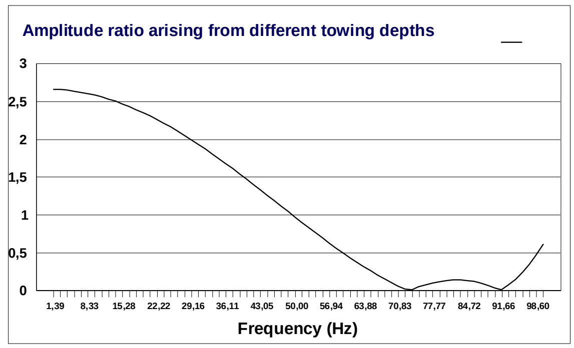

Figure 7 – Example of amplitude ratio between baseline and monitor surveys, caused by varying tow depths.

Modeling of non-repeatability

Modeling and prediction of seismic non-repeatability is a little explored subject. Traditional seismic modeling gives only one scenario at a time, and due to the computer intensive task of full 3D modeling, it is difficult to span the statistical distribution of position perturbations and wide range of possible nominal geometries. Furthermore, there is generally a lack of knowledge of heterogeneity distributions in the overburden, and thus any modeling scenario runs the risk of being an unrealistic example.

An alternative modeling approach is proposed, relating positioning variations to seismic variations by transfer functions of repeatability measures. It is suggested to split the crossline components of source (s_x, s_y) and receiver (r_x, r_y) changes into changes in crossline midpoint ($\Delta m = s_y + r_y/2$) and crossline offset ($\Delta o = s_y - r_y/2$). The average repeatability error is then expressed as a function of Δm and Δo. As there is limited knowledge of these error functions, a simple approach is suggested, with the midpoint error being dependent on the wavenumber spectrum of the emitted signal, and the offset error having amplitude and timing components, both linearly increasing with its argument. An example of this is shown in Figure 8. This makes the combined error both frequency and wavenumber dependent, as observed in real data.

For towed streamer seismic data, there will be a distribution of spatial sampling variations, mainly due to cross-currents and the chosen strategy of getting data-coverage for a survey area (“shooting for coverage” or shooting straight swaths). With statistical treatment of these variations, and by transferring the distribution functions into error functions in the seismic repeatability domain, a statistical error distribution (non-repeatability) may be predicted for a given situation.

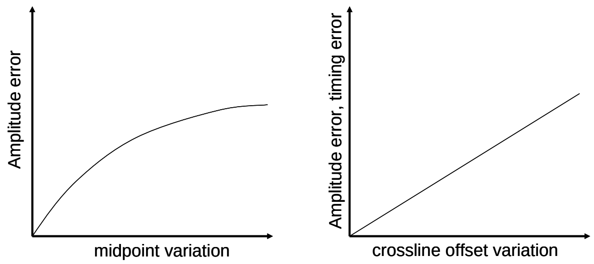

Figure 8 – An example of statistical error functions for two sampling parameters.

Key factors determining repeatability will be current variability, strategy of data coverage, number of and separation of streamers. Such modeling can help optimize the choice of overlap between swaths, separation between streamers and requirements for infill-shooting. It can also quantify the benefit of steerable streamers. Interestingly; one outcome is that such non-repeatability will increase with offset (unless the cables are steered laterally). A shorter offset range will increase the level of non-repeatable multiples, which is not a part of this modeling scheme, and the optimum choice will be a trade-off between multiple noise and positional noise.

Discussion

The proposed repeatability modeling is not taking restoration during processing into account, other than the traditional data binning. More advanced spatial interpolation techniques may help correcting the errors due to midpoint mis-positioning of primaries. However, multiples and high-wavenumber noise will be difficult to restore with the coarse crossline sampling present in seismic surveys, and correcting for azimuth variations will need a detailed knowledge of the overburden which hardly exist. Therefore, compensation for acquisition variations during processing has fundamental limitations.

Conclusions

The key factors causing non-repeatability: positioning and timing variations, need to be compensated for by a combination of acquisition and processing strategies. Denser crossline sampling and smaller azimuth variations are always desirable, but cost driving. For a given budget, optimization of the choice of streamer tow and shooting parameters may be achieved by repeatability modeling, treating the sampling variations in a statistical manner. Such modeling may also quantify any benefit of steerable streamers or permanent receiver systems.

Timing variations, due to water layer variations, are improved when they can be separated from position error effects. Data-dependent corrections may then improve accuracy down to 0.1-0.2 ms.

Improved repeatability will be important for future more challenging monitoring of tighter and deeper reservoirs, smaller saturation changes and shorter time intervals. It will also improve the possibilities of quantitative analysis and inclusion of 4D data into reservoir simulation models. Eventually it will make 4D data "harder" and more useful for the reservoir management.

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