Unmeasurable aspects of seismic data and implications for QI

Patrick Connolly

In 1997 IBM's Deep Blue famously defeated Garry Kasparov and so became the first computer to beat a world chess champion. Rightly regarded as a landmark event in the history of computing it was however mostly an achievement arising from hardware improvements rather than algorithm development; the hardware became fast enough to look further ahead that any human could match in the allotted time [slide 2].

In many ways what happened next was more interesting. By the mid-nineties most chess grandmasters were already working with computers to aid their preparation for conventional tournaments. It soon became apparent that the combination of human and machine was more powerful than any individual human or machine. This created a lot of interest as a way of exploring higher levels of chess and tournaments were organised for teams of humans aided by computers in what became known as Advanced Chess.

A significant Advanced Chess tournament, promoted by Garry Kasparov, was held in 2005. A number of 'dream teams' entered comprising grand masters combined with computer scientists using the latest algorithms and with access to lots of compute power. It was widely anticipated that one of the dream teams would win.

But they didn't. The tournament was won by Steven Cramton and Zackary Stephen, two amateur chess players from New Hampshire who were running software on laptops. How did this happen? Steven and Zachary offered an explanation; 'We had really good methodology for when to use the computer and when to use our human judgement'. Kasparov observed 'A clever process beat superior knowledge and superior technology'.

The result demonstrated the importance of the interaction between human and computer. With the correct process the combination could be greater than the sum of the parts. This is an example of Moravec's paradox; computers and humans have complementary skills.

The seismic data processing industry was an early adopter of large scale computing but has always required this to be combined with human interaction. After graduating in the late seventies I joined a seismic processing contractor and on my first day they set me to work picking velocities, a task a computer couldn't do. Technology has moved on somewhat but data processing still requires human intervention, in particular to select optimum parameters [slide 3].

Why is this necessary? Why can't be devise algorithms that allow the computer to read a set of field records and after a few weeks or months obtain an optimally processed dataset? The main reason is that there are aspects of the seismic data that cannot be measured, or cannot be measured accurately enough [slide 4].

Algorithms cannot reliably measure levels of coherent noise. Signal-to-noise estimation is usually based on a model that the noise is incoherent. But incoherent noise is easy to remove, or at least the incoherent part is! What is left are spurious correlations [slide 5]. It is often difficult, for example, to clearly distinguish between primaries and multiples (one of the reasons that humans are usually involved with velocity analysis). Scaling errors are also a form of coherent noise; if data is mis-scaled than amplitudes will be incorrect. It is very difficult to determine if data is correctly scaled. All through the processing sequence there are decisions to be made requiring human judgement.

Seismic data processing is a mature, large scale industry. Seismic data processors have been fine-tuning the interaction between humans and machines over many decades. Many of the same issues also apply to quantitative interpretation but, as a less mature discipline usually operating at a much smaller scale often locally, the human-machine interaction has not been so optimised.

Coloured inversion converts seismic to band-limited impedance and optimises resolution by broadening the spectrum. The extent to which the spectrum can be broadened depends on the signal-to-noise but noise levels, and even more so noise spectra, cannot be reliably measured [slide 6]. The only way to determine how far the high and low frequencies can be extended is by human judgement; test a range of frequency limits and select the best by the eye [slide 7].

More difficulties arise with any form of AVO analysis [slide 8]. This requires the measurement of not just amplitudes but the rate of change of amplitude with incidence angle. And incidence angles depend on interval velocities which are estimated from rates of change of stacking velocities [slide 9]. We therefore are trying to analyse a derivative as a function of another derivative; an inherently noise prone situation.

There is simple theory to relate combinations of AVO intercept and gradient, parameterised as rotation angle chi, to a number of elastic properties [slides 13 & 14]. However in practice the AVO gradient measurements will always be significantly in error due to many of the factors mentioned above; the impossibility of knowing of the pre-stack offset scaling is correct [slide 10], the inaccuracy and limited resolution of interval velocity and hence incidence angle estimates. Add to this anisotropy for which we rarely have good estimates but can be assumed to be present and which will also change gradient values [slides 11 & 12].

Gradient measurement errors will result in actual chi values being different from apparent chi. You may combine intercept and gradient with a -45° coordinate rotation to estimate $\mu\rho$ but the angle you actually get could be quite different [slide 15].

The 19th century Prussian field marshal Helmuth von Moltke is famous for, amongst other things, his maxim “No battle plan survives contact with the enemy”. An adaption of this is applicable for the situation outlined above; “No theory survives contact with the data”. Just as Von Moltke wasn’t suggesting that generals shouldn’t have battle plans I’m not suggesting that theory is worthless. The field marshal was merely emphasising that any plan won’t take you through to the end of the battle; it must be adjusted depending on events. Similarly our theories are important but we can’t apply them blindly; they must be adjusted to account for unmeasurable aspects of our data [slide 16].

We cannot rely on theoretical chi values: we must assume the actual chi values will be different. We have to scan through a range of chi angles, producing sections and maps and look for patterns such as fluid contacts or geological features, to indicate the correct chi value [slide 17].

Another factor to consider is random noise which has the effect of shifting the chi angle of the maximum signal-to-noise away from the chi angle of the maximum signal [slide 18]. But again, as we can’t reliably measure noise we must use a chi scan to accommodate this effect.

Probabilistic inversions applications are becoming more widely available [slide 19]. They require data uncertainties to be quantified [slide 20]. But uncertainties are inevitable subjective. Some obviously so, for example, our prior expectation of the proportions of the various lithofacies [slide 21]. But even when measuring the variance between two variables for which we have data such as porosity and acoustic impedance we can’t avoid a degree of subjectivity. We must choose a model for the relationship, make allowance for noise and decide whether out data sample is representative of the total reservoir; all subjective choices [slide 22].

A Bayesian method requires quantification of the likelihood of the data; the seismic uncertainty. We've already discussed the difficulty of conventional signal-to-noise estimation. But if we're utilising AVO information in the inversion, as we typically are, then the gradient measurement errors are likely to dominate inaccuracies in the amplitudes. Perhaps a better model for seismic uncertainty is therefore to describe it as an uncertainty in the chi angle. We're still left with a subjective estimate of the component uncertainties but it is perhaps a better model to describe the resultant amplitude errors [slides 23-25].

Well calibration is unlikely to rescue us. Calibration uncertainties arising from the relative positional uncertainty of the well to the seismic can be large particularly if the lateral geological variability is large – as it's likely to be in areas where we apply QI methods [slide 26].

The most-likely Bayesian solution, the maximum a posteriori or MAP, depends on the *relative* uncertainties of the component data. But, as these uncertainties are subjective, we are in effect choosing the answer. The posterior probabilities depend on the *absolute* uncertainty values we assign to the prior and the data and therefore are highly subjective [slide 27]. Even the supposedly most rigorous Bayesian inversion is essentially still an interpretation.

Humans are prone to a cognitive bias known as the overconfidence effect which results in us routinely underestimating uncertainties. However we can probably perform better at assessing relative uncertainties. The structured, quantitative nature of the process forces us to consider all uncertainties so a probabilistic inversion is highly likely to provide a better most-likely solution than a deterministic inversion that fails to account for uncertainties or a direct interpretation of the seismic.

In summary we need to design QI workflows that allow us to intervene at multiple points. Inputting gathers or angle stacks into an inversion application, calculating a set of theoretical parameters and pressing the button is highly unlikely to produce good results. We need to test and iterate and optimise at each step [slide 28]. The process is just as described; quantitative interpretation.

patrick.connolly.451@gmail.com