Broadband solutions for ultra-deep imaging: theory and experience in China and in the world

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Summary

Extending the seismic signal frequency towards the low frequencies has become almost standard on seismic projects, owing to the benefits it provides in terms of vertical resolution, signal penetration, inversion workflow results or ease of interpretation. When targeting ultra-deep targets, the broadband benefit mainly becomes a low-frequency one, as the high frequencies get promptly absorbed. Such deep, hard-to-image targets thus require a specific, low-frequency-compliant strategy. One that encompasses not only sources and receivers further described herein, but also processing. Such targets are commonly met in different areas of the world, including Western China.

Introduction

On the receiver side, MEMS (Micro Electro-Mechanical Systems) sensors are progressively replacing geophones as the broadband enabling technology of choice. Geophones have a 12 dB per octave analog lowcut. The ability of data processing to correct for this~~it~~ by instrument designature is limited by the associated boost of low-frequency instrument noise, and also by signature variations from one geophone to another owing to manufacturing tolerances. These limitations manifest as phase and amplitude jitter on time slices (Tellier, 2021). Variation in response due to temperature changes and mechanical aging also play a part. The ability to reduce the instrument noise by overall gain is limited by the full scale overdrive saturation of the near offset shots. In addition, geophones exhibit spurious instrument noise which is shot generated noise at a certain high frequency above which the geophone sensor output is no more representative of the input ground motion. Geophones have typically around 62 dB harmonic distortion. Other sensing technologies with an appealingly low price have recently available for land seismic acquisition. However their harmonic distortion is not specified. In contrast, MEMS sensors are specified with an ultra-low -90 dB distortion. Much more importantly for deep imaging, they sense seismic signal from 0 Hz and across the entire seismic bandwidth of interest with no phase error, and preserve amplitudes an order of magnitude better than geophones. As pure silicon assemblies, they neither are effected by aging effects and response variation from one device to another.

On the source side, Vibroseis is preferred to explosives not only for productivity, but also for the control it provides over the frequencies generated. Seismic vibrators have been optimized for low frequencies in recent years. Further optimizing these sources is however not a panacea, as any benefit in the low frequencies translates into an appreciable loss towards the other end of the spectrum, at the cost of a significant increase in vibrator complexity and cost.

Mass being inherently favourable to low frequencies, super-heavy (80,000 lbs) vibrators generate more low-frequency signal that heavy (60,000 lbs) ones. Solutions however exist to preserve their high-frequency capability (Tellier, 2015a and 2015b). Low-dwell or maximum-displacement sweeps with large vibrators provide the best low-frequency signal: they are the only ones that optimize the low-frequency output, and enable the generation of the low frequencies that sweep designers expects. Vibroseis must also smart: vibrators electronics are paramount to control the sweep in real-time, and provide users with QC that actually reflect the signal transmitted to the sub-surface. Distortion associated with low-frequency sweeps being inherently high, it needs to be addressed ideally at the acquisition stage (Ollivrin, 2019).

Field and synthetic data results

In this talk we show a few data examples comparing data acquired with different products. One example is shown in Figure 1 and another example from a Tarim oil field test is shown in Figure 2. Figure 3 is a synthetic wedge that explains Figure 2.

Conclusions

Broader band data brings added value thanks to the improved ability to image deep reflectors, mitigate the risk of cycle skips in full waveform inversion (FWI), improve resolution and ability to build blocky reservoir models. The differences between narrow- and broad- band data may look small on imaging but their significance to the value of information proves however very high.

The addition of Low frequency Octaves in Seismic Imaging allow to reveal informations that were invisible to us so far. This is the result of major equipment evolutions both on the source side, with effective emission of Very Low frequencies issued from hardware and sweep design innovations, as well as on the receiver side with last generation MEMS high fidelity sensors which record both very low and high frequencies with high Signal to Noise ratio.

The addition of the Low Frequency octave bring closer Gephysicist and Geologist. It allows to access both shallow and deep structures, to reduce the need for calibration wells, to move from interface attributes to internal bed rock properties such as Vp, Vp/Vs, Q.

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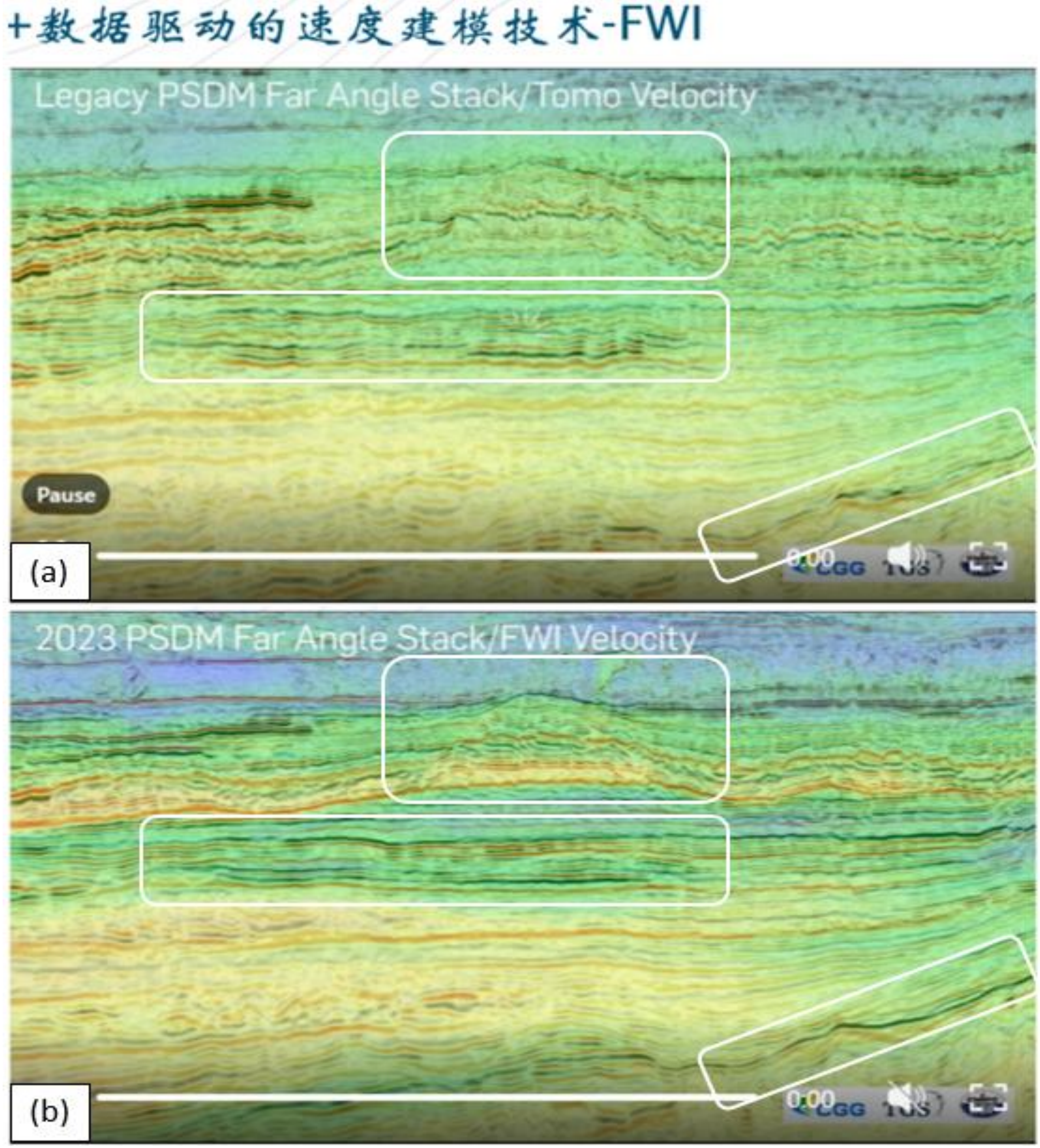

Figure 1: Images with velocity model built with (a) tomography (b) FWI. Picking errors in tomography and cycle skips in FWI are mitigated by low frequency signal. Note the improved imaging of shallow as well as deep structures.

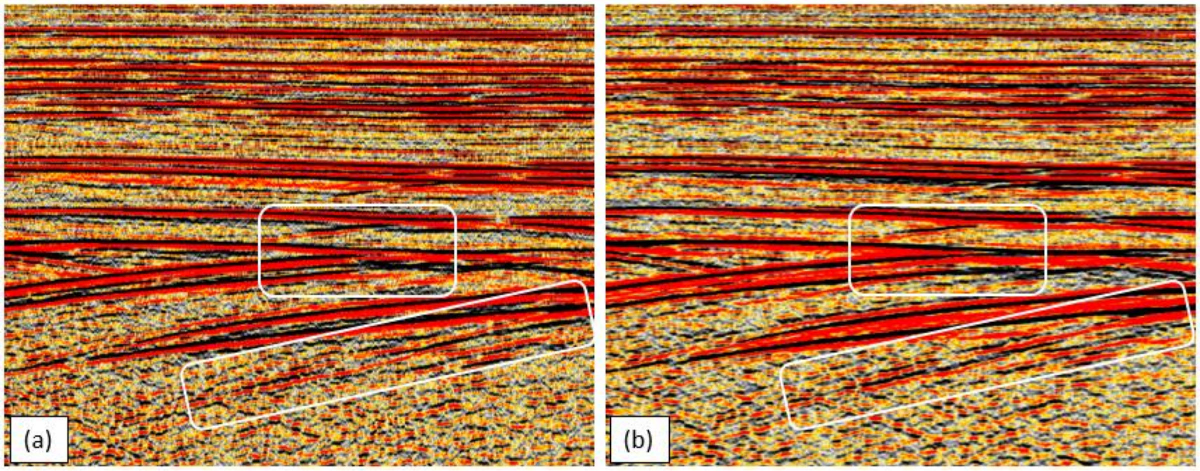

Figure 2: Images of data from Xin Jiang acquired with (a) groups of 5 Hz geophones compared to (b) MEMS. Note the small but significant improvement in imaging deep reflectors and the resolution of the unconformity wedges.

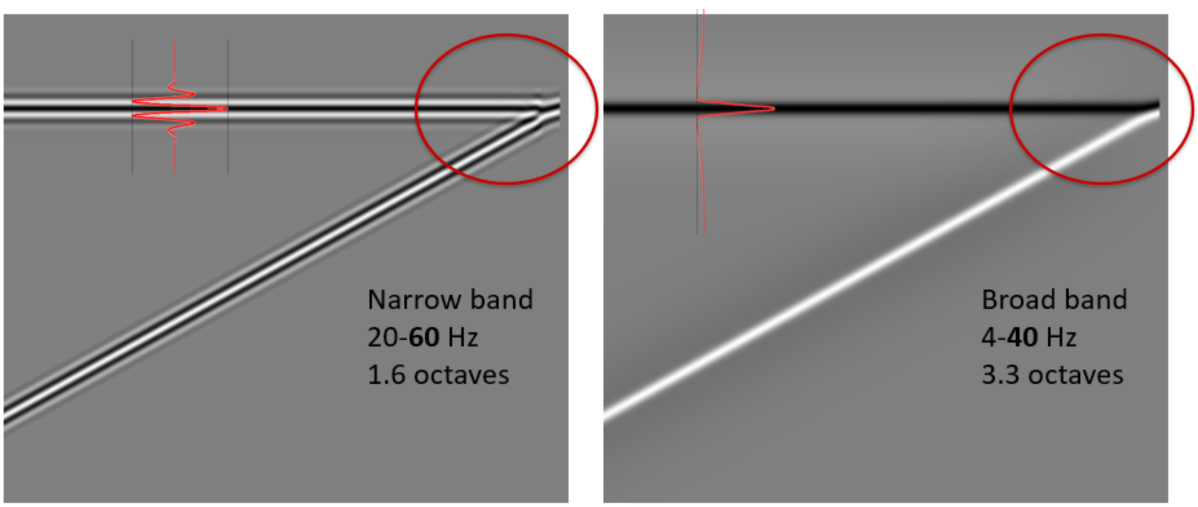

Figure 3: Sidelobes destroy resolution. The value of low frequency signal to improve resolution demonstrated with a classic wedge synthetic.

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