Waveform inversion of surface seismic data without the need for low frequencies

*Nikhil K. Shah *, Michael R. Warner, Lluis Guasch, Ivan Stekl, and Adrian P. Umpleby, Imperial College London*

Summary

Waveform inversion is a technique with capability of generating velocity models with unprecedented resolution and clarity from seismic data. However it often requires unrealistically low frequencies in the data to achieve this. We propose a scheme designed to mitigate this need – a necessary key step for realising the potential of the technique in a far wider range of datasets and targets than currently possible. The scheme operates by preceding the inversion of the field data by inversion of intermediate datasets – synthesised by extracting the irrotational component of the phase mismatch at the lowest useable frequency. We demonstrate its effectiveness over the corresponding conventional approach by inverting data from the Marmousi model with a minimum frequency of 5Hz.

Introduction

The ultimate goal in full waveform inversion is to extract the best-fit, high-resolution velocity model for a given seismic dataset – making use of only a realistically obtainable starting model and minimum frequency.

It is formulated as a iterative localized minimization of the misfit between recorded and modeled waveforms, and whilst various advantageous minimization criteria and regularization strategies have been devised to help mitigate the inherent non-linearity (Virieux and Operto 2009), the fundamental problem of convergence to one of the numerous local minimum points which invariably surround the true model often remains.

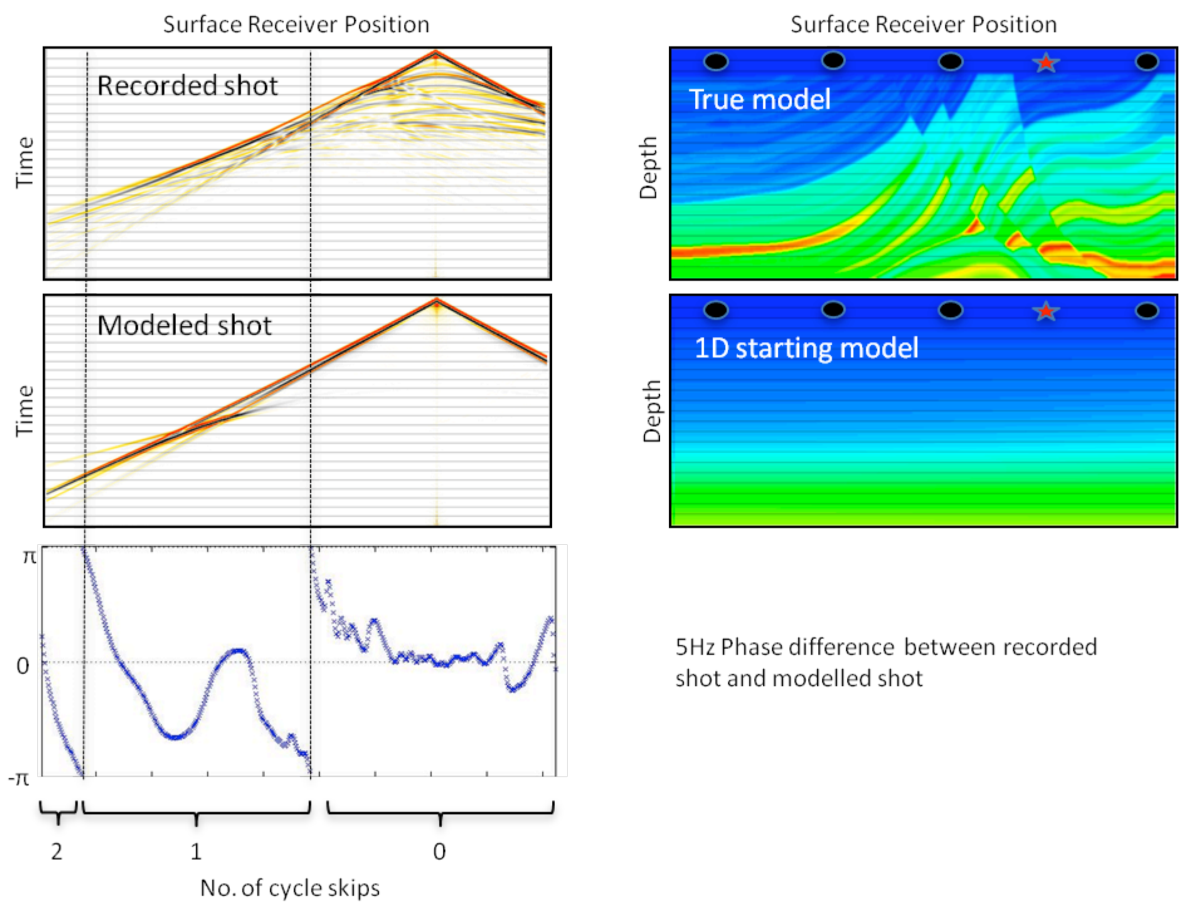

Figure 1 – The 1-D starting model generates data that is cycle-skipped relative to the true data at longer offsets.

The underlying issue with localised inversion is that the modelled waveform gets shifted only to the nearest cycle of the recorded waveform, which may be several cycles away from the global minimum at longer offsets (Figure 1). The residual drip-feed scheme overcomes this by releasing only a fraction of the total residual into the inversion at each iteration. This is carried out by inverting intermediate target datasets – constructed from the irrotational component of the phase mismatch – designed to steer the modeled waveform to the correct cycle of the recorded waveform. This opens the possibility of reaching the global minimum even when cycle-skipped local minima stand in the way, thereby enabling waveform inversion to proceed without relying on low frequencies.

Drip-feed inversion methodology

Working in the Fourier (or Laplace-Fourier) domain, the intermediate datasets are inverted at the lowest useable frequency, phase-only. These are constructed by first extracting the irrotational component of the phase mismatch i.e. the part with zero-curl gradient (Figure 2). This eliminates the non-2π discontinuities, thereby enabling the 2π discontinuities which map the cycle-skip boundaries to uniquely identify the number of cycle-skips, n, between the modeled and recorded data at each point. We can construct an intermediate target dataset that is not cycle-skipped with which to begin inversion by adding $2n\pi$ to the mismatch and finally scaling the result back into the $\pm\pi$ range once more.

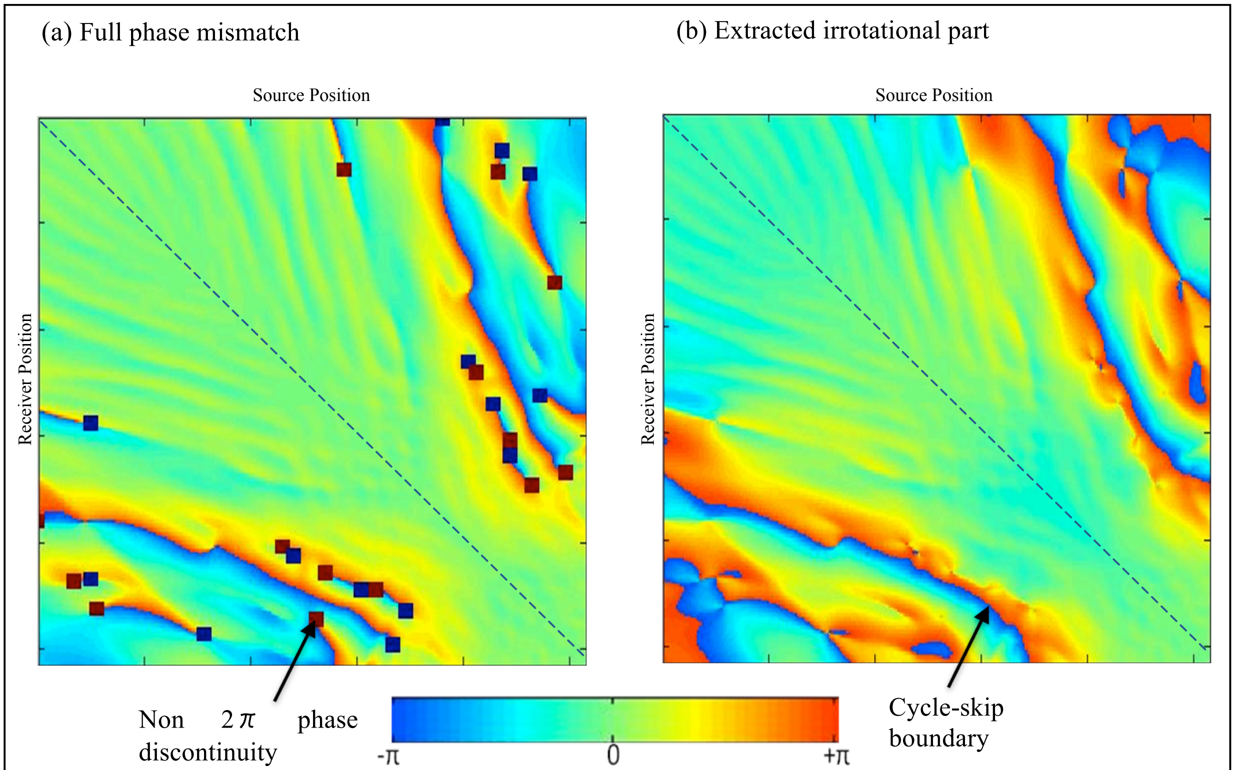

Figure 2 – 5Hz phase mismatch between true and 1-D starting models. Extracting the irrotational part (b) eliminates the non-2π phase discontinuities (marked with squares) allowing the cycle-skip boundaries to be established.

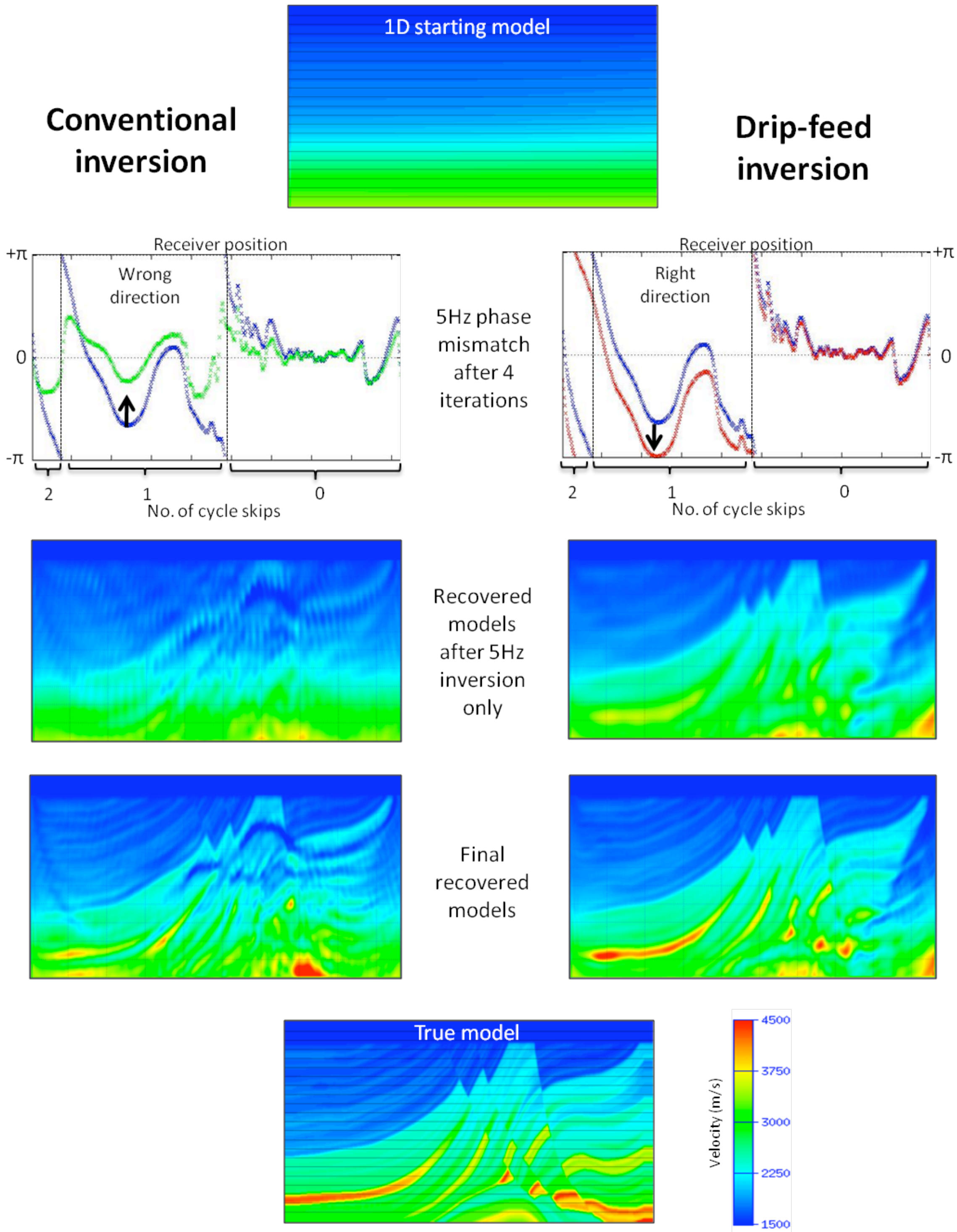

Figure 3 – Inversion results comparing the new inversion scheme (right) with the conventional approach (left) using a 1-D starting model and a minimum frequency of 5Hz.

Initially forming the misfit gradient and model update with this intermediate target dataset rather than the true data steers the model towards global minimum rather than the nearest local minimum from which it cannot subsequently recover. When the model is no longer cycle-skipped, the inversion switches to the true data.

It is the absence of low frequencies in the data (where the phase-residuals are at their lowest and global minimum broadest) which gives rise to the need for a local minimum avoidance strategy. The strategy for handling cycle-skipped data need only be utilised at the lowest useable frequency, since the updated model is then able to invert successive higher frequencies directly (Sirgue and Pratt 2004).

Drip-feed inversion results

As a test-case, we invert the synthetic Marmousi dataset from a 1-D starting model with frequencies no lower than 5Hz. A section of the 5Hz phase-residuals for this starting model is displayed in Figure 2.

Under conventional inversion the cycle-skipped phase mismatches all move to 0, i.e. the modeled data shifts to the nearest cycle of the recorded data. At cycle-skipped longer-offset points this implies converging to the nearest local minimum. This is shown for a given shot in Figure 3.

In contrast, initially inverting 5Hz intermediate datasets, the longer-offset mismatches shift in the right direction – towards the global minimum – leading to the accurate reconstruction of the background velocity from the 1-D starting model. Subsequent 5Hz and above true data iterations are then able to a large extent recover the heterogeneous structure which is completely absent from the starting model.

Conclusions

The residual drip-feed strategy appears to provide a robust and straightforward-to-implement methodology for inverting seismic data in the absence of an unusually accurate starting model or of unusually low frequencies in the field data. As we have implemented it in the frequency domain, it is the irrotational component of the phase mismatch at the lowest useable frequency that gets inverted first. The full phase mismatch can then be inverted from the updated model. As such, the method will invert any dataset that can be spatially interpolated at the lowest frequencies – the vast majority of which get acquired in such a manner.

The method is now being implemented on field data as well as synthetic data using a range of poor starting models. If these further applications continue to prove successful, the scheme will have lifted a serious fundamental limitation holding back the mainstream utility of the technique in exploration.

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EDITED REFERENCES

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