Waveform inversion from a poor starting model – using a residual 'drip-feed' strategy

N. K. Shah (Imperial College London), M. R. Warner (Imperial College London), L. Guasch (Imperial College London), I. Stekl (Imperial College London), A. P. Umpleby (Imperial College London)
Email: nikhil.shah@imperial.ac.uk

We present a new waveform inversion scheme designed to avert the need for an accurate starting model and low frequency content in the data – a necessary key step in making the technique work on a much wider range of exploration datasets and targets than it currently can. The scheme operates by preceding the inversion of the field data by inversion of intermediate target datasets – synthesised out of the curl-free (irrotational) part 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 1-D starting model and minimum frequency of 5Hz.

Overview

The ultimate goal in full waveform inversion is to extract the best-fit, high-resolution velocity model from a given seismic dataset – making use of only a realistically obtainable starting model and minimum frequency. It is formulated as a iterative localised minimisation of the misfit between recorded and modelled datasets, and whilst various advantageous minimisation criteria and regularisation 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.

The underlying issue with localised inversion is that the modelled waveform must match the recorded waveform to within half a cycle at the lowest frequency to converge correctly. Otherwise a reduction in data mismatch will send the modelled waveform in the wrong direction, i.e. away from the recorded waveform. This is a feature of local inversion in both the time and frequency domains.

The new scheme deals with this problem by not inverting the recorded data directly. Instead we start by generating and inverting a target dataset that is not cycle-skipped relative to the starting model and will send the modelled waveform towards 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 from a poor starting model.

Method

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 curl-free component of the phase mismatch between the modelled and recorded data (Figure 1). This is done by taking the modulo-2π gradient of the phase mismatch and, by employing a Helmholtz decomposition, retaining only the curl-free part of this vector field.

With the non-2π discontinuities in the phase mismatch now eliminated, the 2π cycle-skip boundaries uniquely specify a number of cycle-skips, n, at each point. We use this to construct an intermediate target dataset which to begin inversion with by adding $2n\pi$ to the curl-free mismatch and then scaling the result back into the $\pm\pi$ range once more.

Initially inverting intermediate target datasets rather than the true data steers the model towards the global minimum – as opposed to 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 and proceeds conventionally.

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).

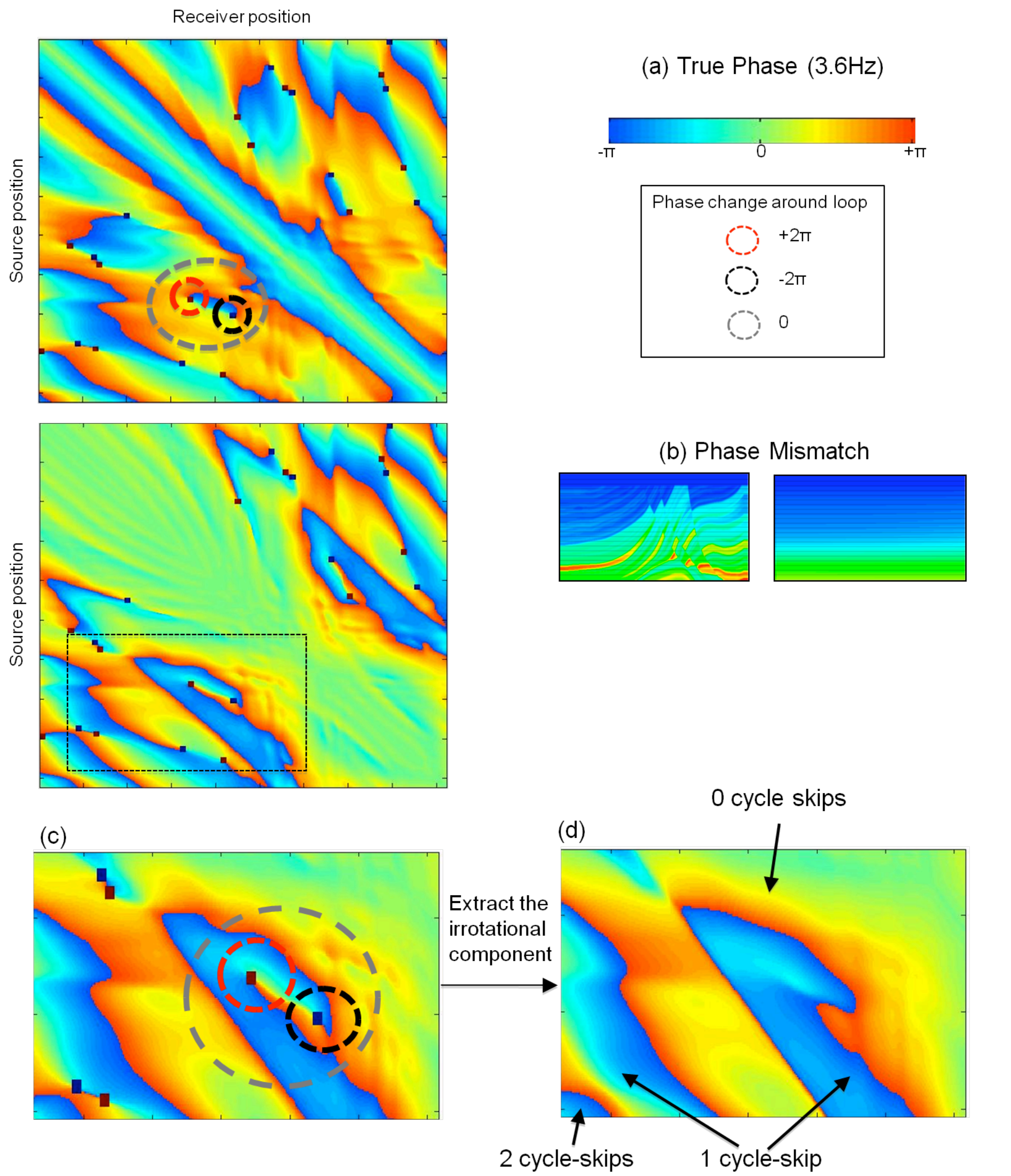

Figure 1 *Extracting the curl-free phase mismatch which gets inverted first.*

- *(a) The 3.6Hz phase of recorded data from the Marmousi model – marked points indicate non-2π discontinuities. Following a closed contour around one of these points, integrating changes in phase gives a non-zero net result.*
- *(b) Phase mismatch between the recorded and starting model data – this is less complicated than (a), but the phase discontinuities remain.*
- *(c) A close up portion of (b) showing a problematic region.*
- *(d) The same plot after the extraction of the curl-free portion of the data. Only the unequivocal 2π cycle skip boundaries now remain.*

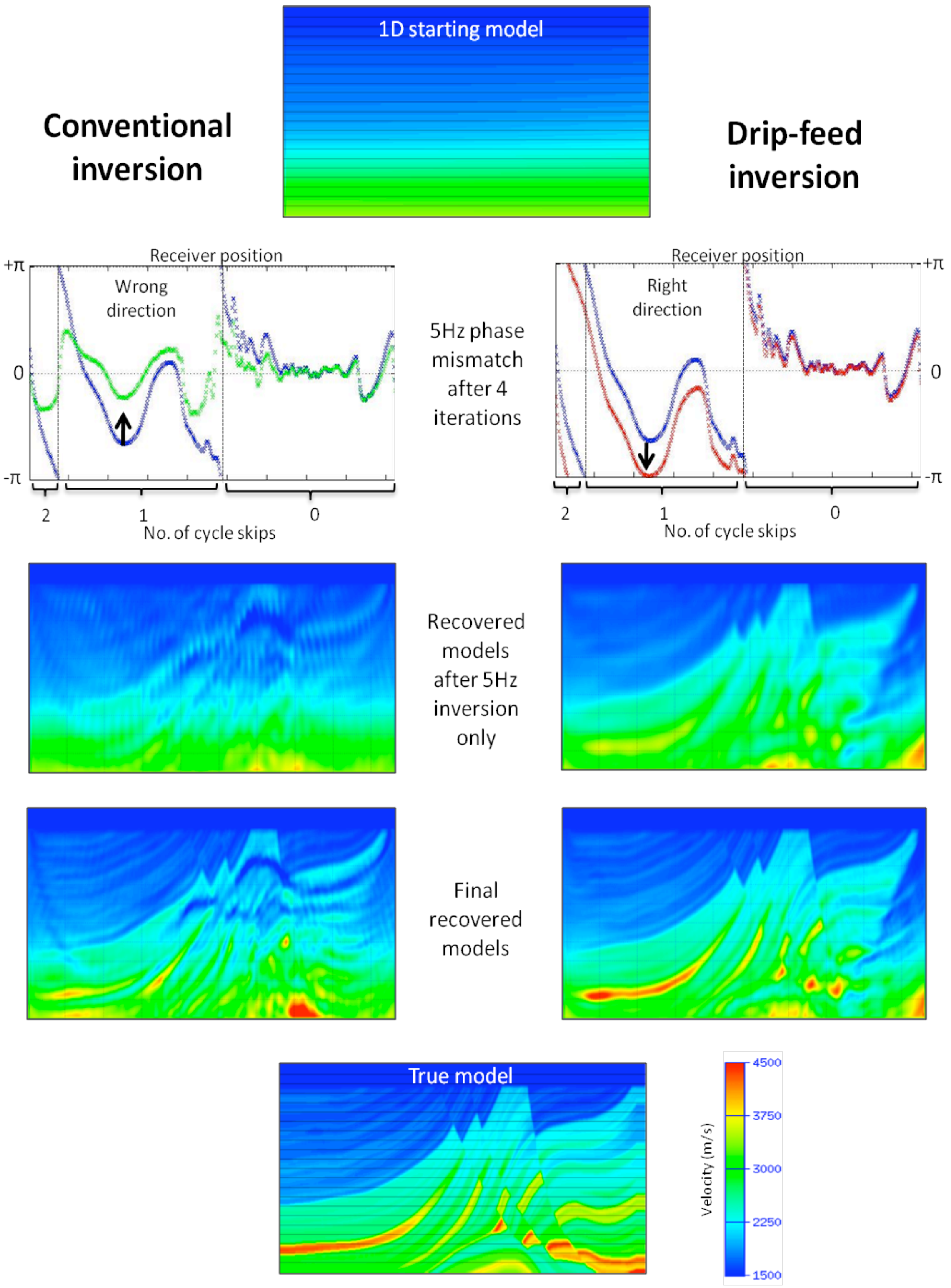

Figure 2 *Comparing drip-feed inversion (right) to the conventional approach (left). The phase difference plots show the longer-offset data mismatch moving to a cycle-skipped zero under conventional inversion (left) but through -π to the global minimum zero when initially inverting intermediate datasets (right). The result of using the new scheme is a much-improved recovered model at all stages of the inversion.*

Example

As a test-case, we invert the synthetic Marmousi dataset from a 1-D starting model (Figure 2). Residuals arising from this starting model are cycle-skipped down all the way to 1.2Hz but here we use frequencies for inversion no lower than 5Hz. When inverting conventionally, the 5Hz phase difference plot for a particular short record shows the longer-offset data mismatch moving straight to the nearest cycle-skipped zero.

In contrast, initially inverting 5Hz intermediate datasets, the longer-offset mismatches shift in the opposite direction – passing through $-\pi$ to zero. Consequently, we are now correctly matching the wide-angle transmitted arrivals - the part of the data which is most sensitive to the long wavelength component of the velocity. After switching to inverting the 5Hz true data and accurately recovering the background velocity, higher frequency iterations are then able to correctly position in depth heterogeneous structure completely absent from the starting model.

Conclusions

The drip-feed inversion scheme provides 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. Therefore it appears to lifts a fundamental constraint currently holding back the mainstream utility of the technique.

When implemented it in the frequency domain, it is the curl-free 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 field dataset that can be spatially interpolated at the lowest frequencies – the vast majority of which get acquired in such a manner.

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References

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