Demigration and image space separation of simultaneously acquired data

Chris Leader and Biondo Biondi

ABSTRACT

Separating simultaneously acquired seismic data is the link between more efficient acquisition and conventional imaging techniques. Acquiring multiple source locations concurrently, without waiting for full energy dissipation, can provide cheaper and denser acquisition. However, to integrate with current production scale imaging it is necessary to separate these data into their conventionally acquired equivalent state. Many algorithms give successful separation but all stringently require random source sampling in time and space. Herein an image-domain transformation is used to isolate and remove noise from overlapping shots for both randomly delayed and linearly delayed simultaneous data; an inverse transform is then used to recover separated, conventional data. Results show that this process is not dependent on a well constrained velocity model if the extended image space is used to preserve data kinematics.

INTRODUCTION

Migration algorithms assume a single source interacted with a stationary scattering field. Thus, when surveying it is necessary to wait between shots for energy to sufficiently dissipate. This waiting time restricts survey speeds, especially when multiple source boats are used (Verwest and Lin, 2007). If waiting time was not a restriction, denser sampling could be recorded per unit time and acquisition could be significantly more efficient (Beasley (2008); Hampson and Herkenhoff (2008); Berkhout and Blacquiere (2008)). Recording overlapping data in this manner will require more processing time than conventionally acquired data. However the economic gains from reduced acquisition far outweigh this extra cost.

These simultaneously acquired data can be used to directly invert for model properties (Dai and Schuster (2009); Tang and Biondi (2009)). However such methods require exact velocity model knowledge. Separation and subsequent imaging could be integrated into production data flows; successful existing methods rely on random sampling in the source timings and locations (Abma and Yan (2009); Moore et al. (2008)). For example, constant receiver gathers can be transformed into the f-k or tau-p domain and iteratively thresholded (Doulgeris et al., 2011), iteratively removed in the parabolic random domain (Ayeni et al., 2011), removed by using a convex projection approach (Abma and Foster, 2010), or through compressive sensing methods (Herrmann et al., 2009).

Image domain processing has been used effectively for coherent energy removal / attenutation by posing the problem in the extended image space (Zhang et al. (2012); Sava and Guitton (2005)). It is possible to untangle certain events in this domain and recreate cleaner shot gathers by virtue of higher signal-to-noise ratio and reduced dimensionality. Additionally, when using the extended image space (Sava and Vasconcelos, 2011), event kinematics are preserved. Consequently, if the velocity model is inaccurate then demigration is still possible (Chauris and Benjemaa, 2010). For the problem of simultaneous source separation the extended image space can be a powerful tool since energy from separate sources can be easily distinguished in subsurface offset, even for the case of constant time delays.

The goals of this investigation are threefold: to test the possiblity of accurate data recovery if an incorrect velocity model is used, to observe and quantify how blended data appear in the extended image space, and finally to test methods for separating data using the extended image space and incorrect velocity models.

DEMIGRATION

Demigration (Loewenthal et al., 1976) is an important concept in many seismic exploration algorithms: velocity model building (Weibull and Arntsen (2013a); Sava and Biondi (2004)), multiple removal (Weibull and Arntsen, 2013b), Hessian estimation, interpolation, and many others. If the velocity model is known the process of demigration is simple and the adjoint of the imaging procedure can be used (Jaramillo and Bleistein, 1999). When using Reverse Time Migration (RTM) our imaging algorithm can be expressed as equation 1.

$$m(\mathbf{x}) = \sum_{\mathbf{x}_s,\omega} f(\omega) G_0(\mathbf{x},\mathbf{x}_s,\omega) \sum_{\mathbf{x}_r} G_0(\mathbf{x},\mathbf{x}_r,\omega) d^*(\mathbf{x}_r,\mathbf{x}_s,\omega), \tag{1}$$

where $\mathbf{x}$ represents the spatial coordinates, $m(\mathbf{x})$ the scattering field, $\mathbf{x}_s$ the current source coordinates, $\mathbf{x}_r$ the current receiver coordinates, ω the temporal frequency, $d^*(\mathbf{x}_r,\mathbf{x}_s,\omega)$ the complex conjugate of the data and G_0 the relevant Green's function. Only the zero-offset image (Claerbout, 1971) is calculated and this will contain all necessary amplitude and kinematic information for demigration, assuming the velocity model accurately represents the data.

For demigration the adjoint of equation 1 is used; this is the first-order approximation to the Born scattering series. Here the estimate of the scattering field is used to recreate the data, using

$$d(\mathbf{x}_r,\mathbf{x}_s,\omega) = \sum_{\mathbf{x}} f(\omega) G_0(\mathbf{x},\mathbf{x}_s,\omega) m(\mathbf{x}) G_0(\mathbf{x},\mathbf{x}_r,\omega). \tag{2}$$

A single application of Born modeling recreates data kinematics correctly. However, to correctly capture data amplitudes, particularly those at short offsets, an inversion procedure must be used (Weibull and Arntsen, 2013b). Correct kinematic recreation is shown for an adapted Marmousi (Martin et al., 2006) model (figure 2, middle panel), where the image in figure 1 was used as the scattering potential. It is immediately apparent that all events have been corectly positioned but the Amplitude Versus Offset (AVO) characteristics of the input data are not accurately represented.

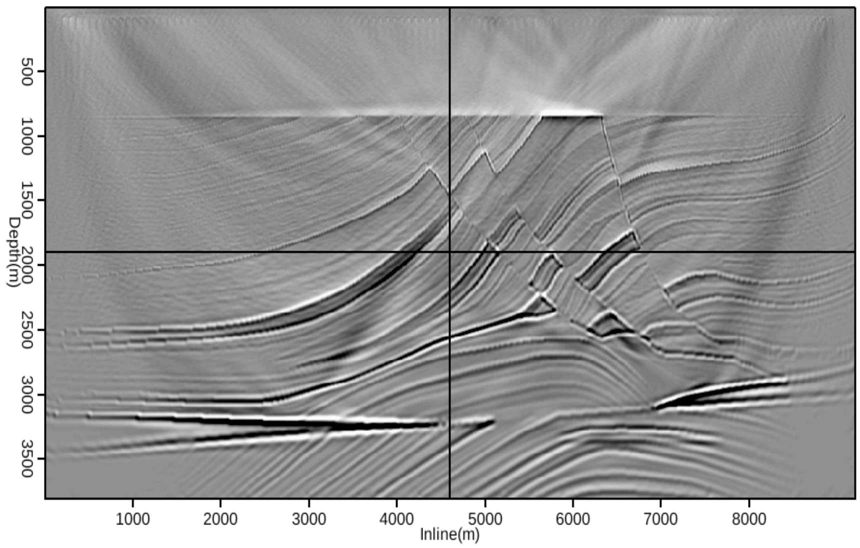

Figure 1: Zero-offset image of the Marmousi model. [**CR**]

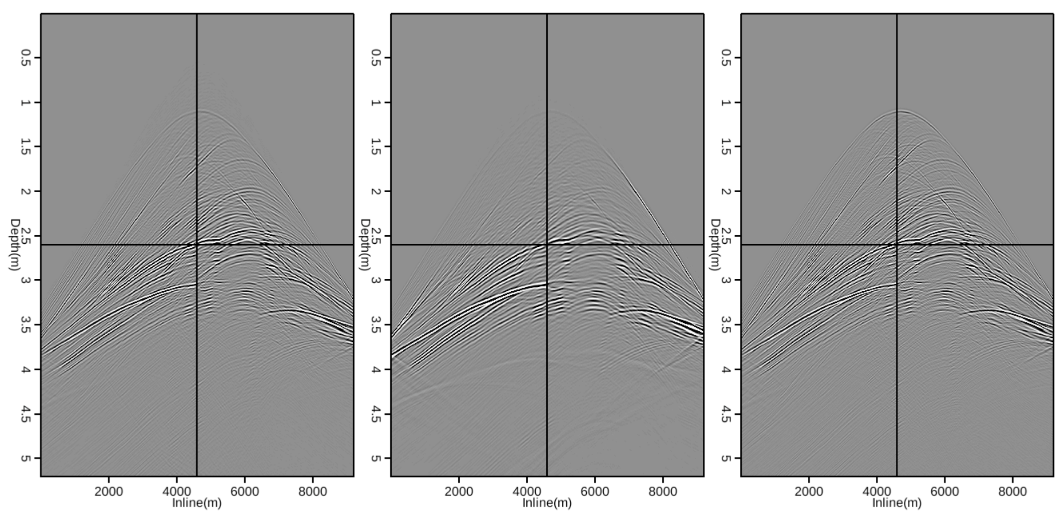

Figure 2: An example shot of the input Marmousi dataset (left), the shot reconstructed by modeling (middle) and by inversion (right.) [**CR**]

Creating an inverse process from here is straightforward. These forward (equation 1) and adjoint (equation 2) processes can be combined into a solver and a conjugate directions scheme used for updates. Each iteration is roughly twice the cost of one modeling application, but convergence is seen quickly. For a very simple two-layer model only a few iterations bring the amplitude error to less than one percent; for the Marmousi dataset fourteen iterations are needed. The inversion result for the latter model can be seen in the right panel of figure 2.

Simultaneous shot separation is not difficult if the velocity model is known; linearised inversion can be used to estimate a clean image and then Born modeling applied. In order to use the image space for exploration scale simultaneous shot separation a methodology without a strong velocity model dependence is required.

EXTENDED IMAGING

The zero-offset cross correlation imaging condition will lose important wavefield information if the velocity model has not placed the events at precisely the right location for imaging. Extending this imaging condition beyond zero-offset creates an image extended in subsurface offset. Stored in this extra dimension are the vital kinematic and amplitude attributes that would otherwise be lost. If the zero-offset imaging condition is expressed in equation 3 then the extended imaging condition can be written as equation 4.

$$I(x,y,z) = \sum_{i}^{nshots} \sum_{t} P_s(x,y,z,t;\mathbf{s}_i) P_r(x,y,z,t;\mathbf{s}_i). \tag{3}$$

$$I(x,y,z,x_h,y_h) = \sum_{i}^{nshots} \sum_{t} P_s(x+x_h,y+y_h,z,t;\mathbf{s}_i) * P_r(x-x_h,y-y_h,z,t;\mathbf{s}_i) \tag{4}$$

Here, $I(x,y,z)$ is the image in space, P_s is the source wavefield and P_r is the receiver wavefield. If lag coordinates in x and y are introduced (x_h and y_h), a 5D image can be created. It is possible to have lags in both t and z to create a 7D image, or any combination thereof. From here on this discussion will be limited to subsurface offsets in the x direction only.

SIMULTANEOUS SHOT SEPARATION

If the velocity model is known then effective data separation can be done without the need for subsurface offset extension, information is not lost with the imaging condition. A simple least-squares inverse system can be designed that aims to iteratively reduce crosstalk and output a separated dataset. With random delays between sources and a large number of shot-points, crosstalk artifacts will stack out due to their incoherence. A single application of migration and demigration can produce

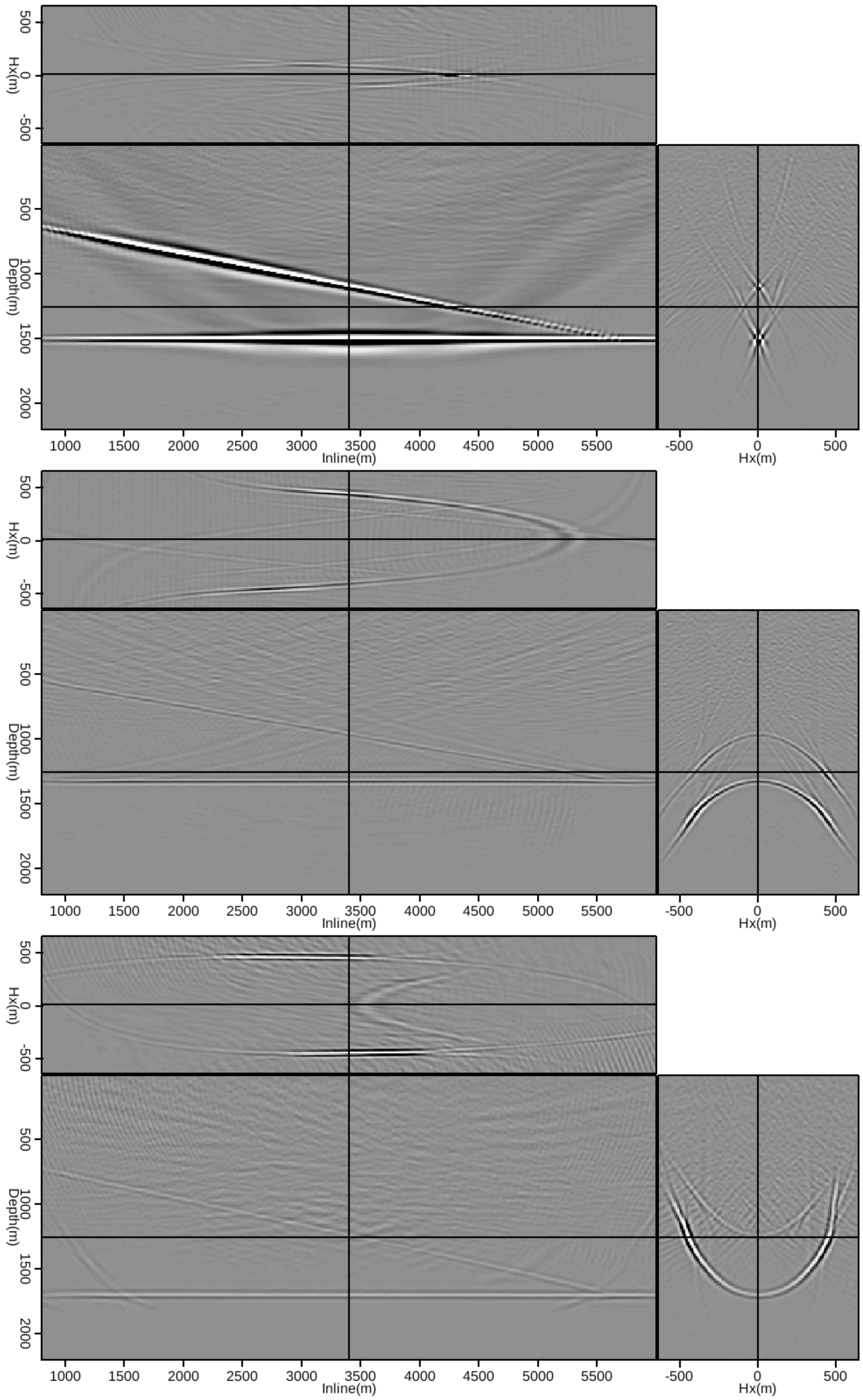

Figure 3: A simple image, with correct velocity (top), 10% too slow (middle) and 10% too fast (bottom) in the extended domain. [**CR**]

adequately separated data. A few additional iterations are then needed to reduce any remaining separation noise to the background. This can be seen in figure 5; here 100 shots were blended into overlapping groups of five and then one iteration of image space separation was performed.

Generally, the velocity model will not be known with confidence, especially if simultaneous shooting is to be done for exploration and appraisal-type surveys. Figure 3 shows examples of a two reflector model imaged in the extended image space, with correct, 10% too slow and 10% too fast velocity models, respectively. One hundred shots were used, with a fixed spread geometry. The middle and bottom panels are more loosely focused because amplitudes have been smeared across subsurface offset. However, since this behaviour has been correctly captured, demigration can be effective.

Interestingly, for the three results in figure 3, least-squares demigration converges at roughly the same rate for all models. For exact velocity, amplitudes are matched to within 1% after five iterations, the faster velocity model within seven iterations and the slower model within eight iterations.

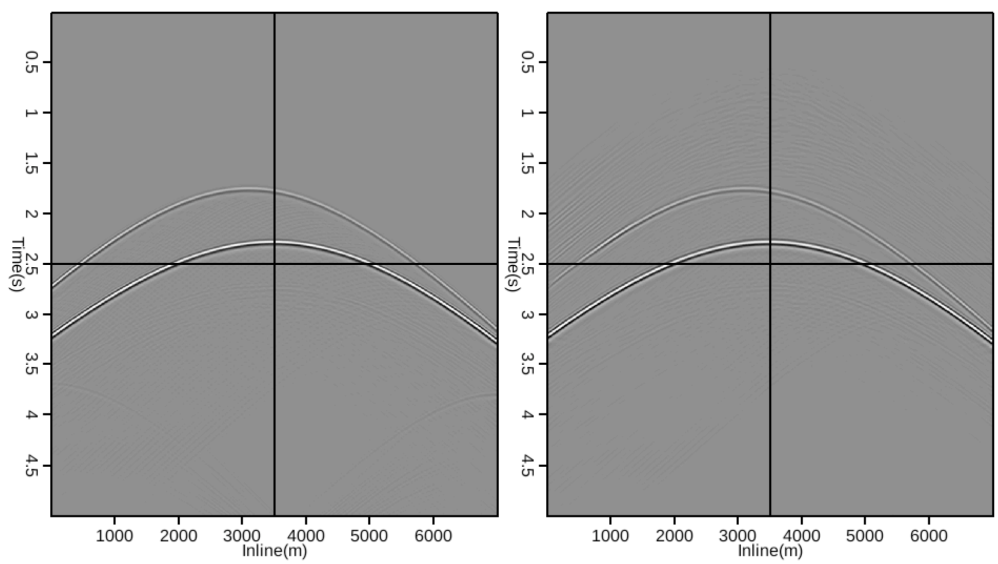

Figure 4: An original shot (left) and the raw demigration result after seven iterations using the fast velocity model (right). [**CR**]

Data blending is then performed for both the two-layer and the Marmousi datasets. Initially, analysing the two-layer images provides more insight, as each event can be easily identified. There are four different scenarios that should be investigated: random blending between neighbouring shots, random blending between distant shots, constant time delays between neighbouring shots and finally constant time delays between distant shots. To ascertain the best separation approach, observing these different blending schemes in the extended image space is essential.

Figure 3 demonstrates that extended RTM, with the correct velocity, focuses

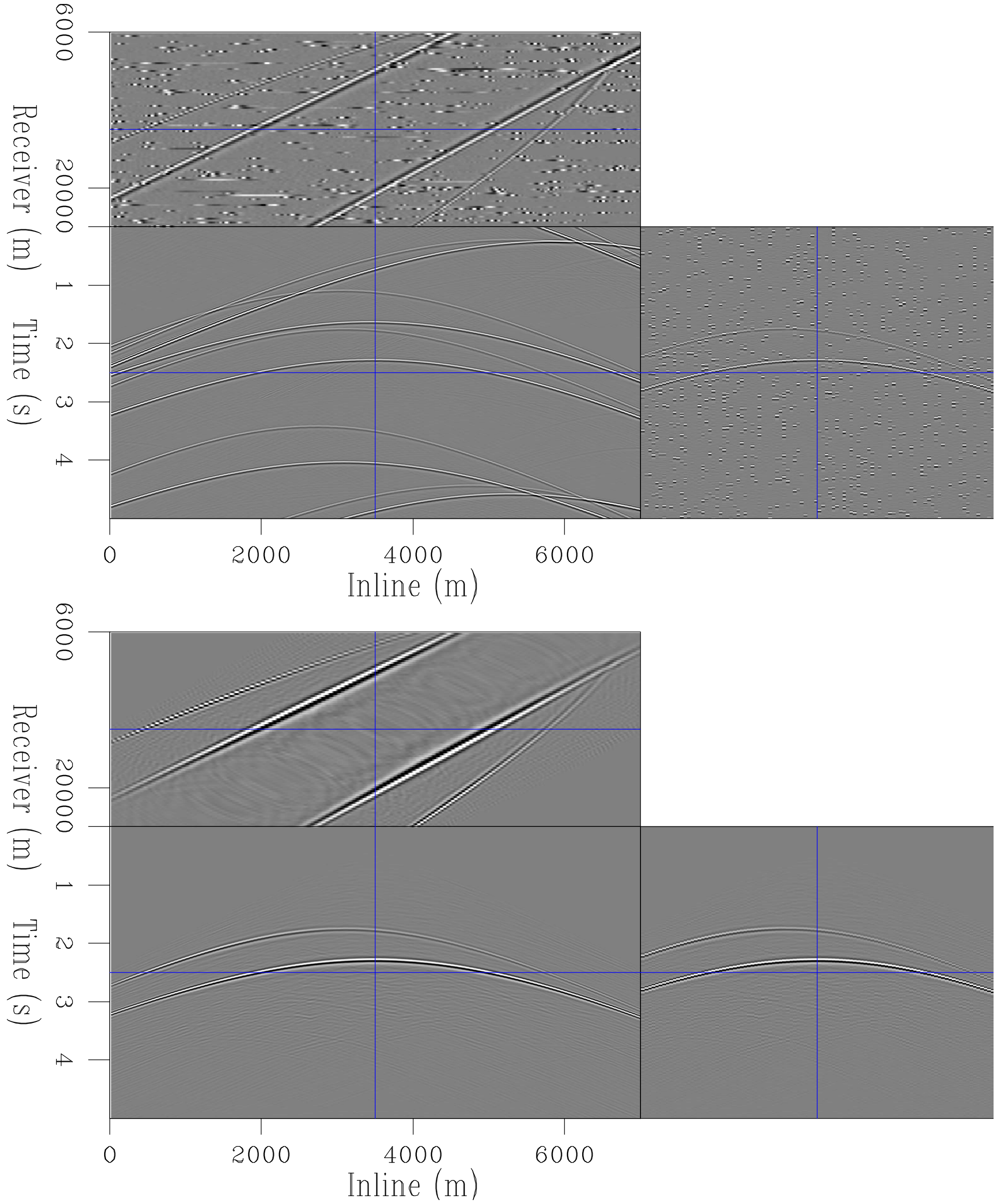

Figure 5: A randomly blended dataset (top) and the separated dataset after imaging and demigration (bottom). [**CR**]

events at zero-subsurface offset. In the case of simultaneously-acquired data, overlapping shots will be placed at non-zero subsurface offset. A trivial method to attenuate the majority of overlapping energy is to simply heavily penalise events at high subsurface offest. In the case of random shot delays this overlapping energy is spread out incoherently through all subsurface offsets. A de-noise or thresholding type removal algorithm can be applied (Abma and Foster, 2010) and the data demigrated. Reasonable separation is seen even without thresholding. In the case of constant time delays this energy is more focused and certain non-zero subsurface offsets can simply be windowed. For the case of constant delays between neighbouring shots this focusing is close to zero-subsurface offset. This approach risks losing primary information.

The less representative the velocity model, the less focused these images will be. For a very rough model many subsurface offsets are needed, and the thresholding must be done very carefully. Current work is being undergone on Fourier and Radon based thresholding methods for cleaning these offset panels prior to demigration. For the case of large shot-point differences in space and time, windowing is an effective and simple method for removing this energy and creating these unblended data.

CONCLUSIONS

Amplitude preserving demigration is possible with an incorrect velocity model. The extended image space can be used and several least-squares iterations performed. Thus, robust image space filtering and processing, with the goal of remigration, is possible. If these data are acquired with strong, coherent overlaps (simultaneous shooting) then it is possible to distinguish and filter this overlapping energy in the extended image space. Through subsequent demigration, a separated dataset is produced, resulting in the equivalently unblended data, which can then be used for conventional processing. If the velocity model is not representative, these coherent events remain identifiable in subsurface offset. However the method of removal will depend on the level of velocity inaccuracy.

FUTURE WORK

An automatic algorithm for identifying overlapping shots and removing them is currently being prepared. Preliminary results for Fourier coefficient and tau-p domain thresholding techniques appear promising, even in the case of tightly blended data. Additionally work is being undergone on designing a regularisation operator, which acts in a similar way, to make the entire process an inverse scheme that iteratively removes this energy in subsurface offset.

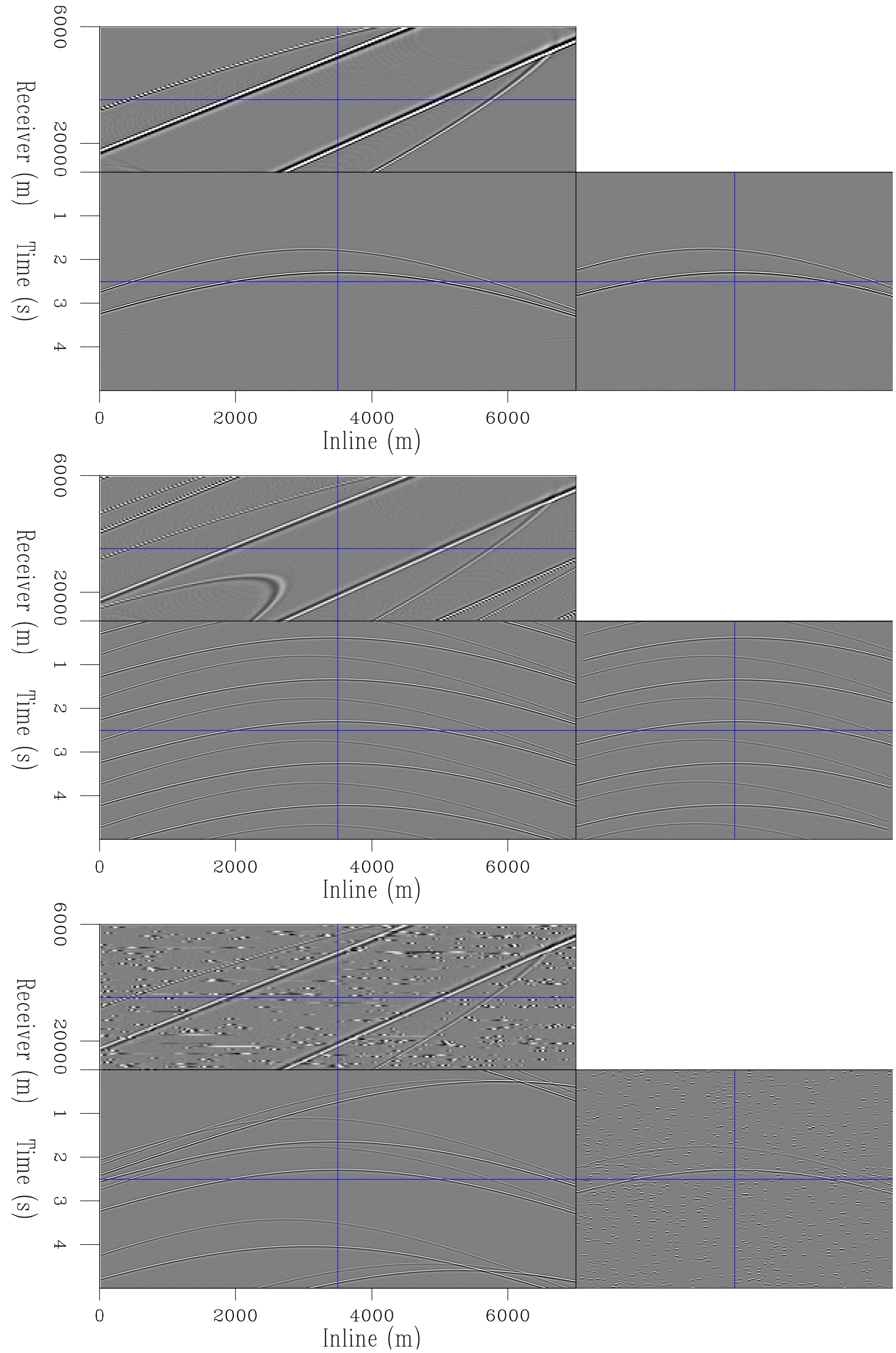

Figure 6: Three datasets - conventional (top), linearly blended (middle) and randomly blended (bottom). The sx axis acts as a constant receiver axis. [**CR**]

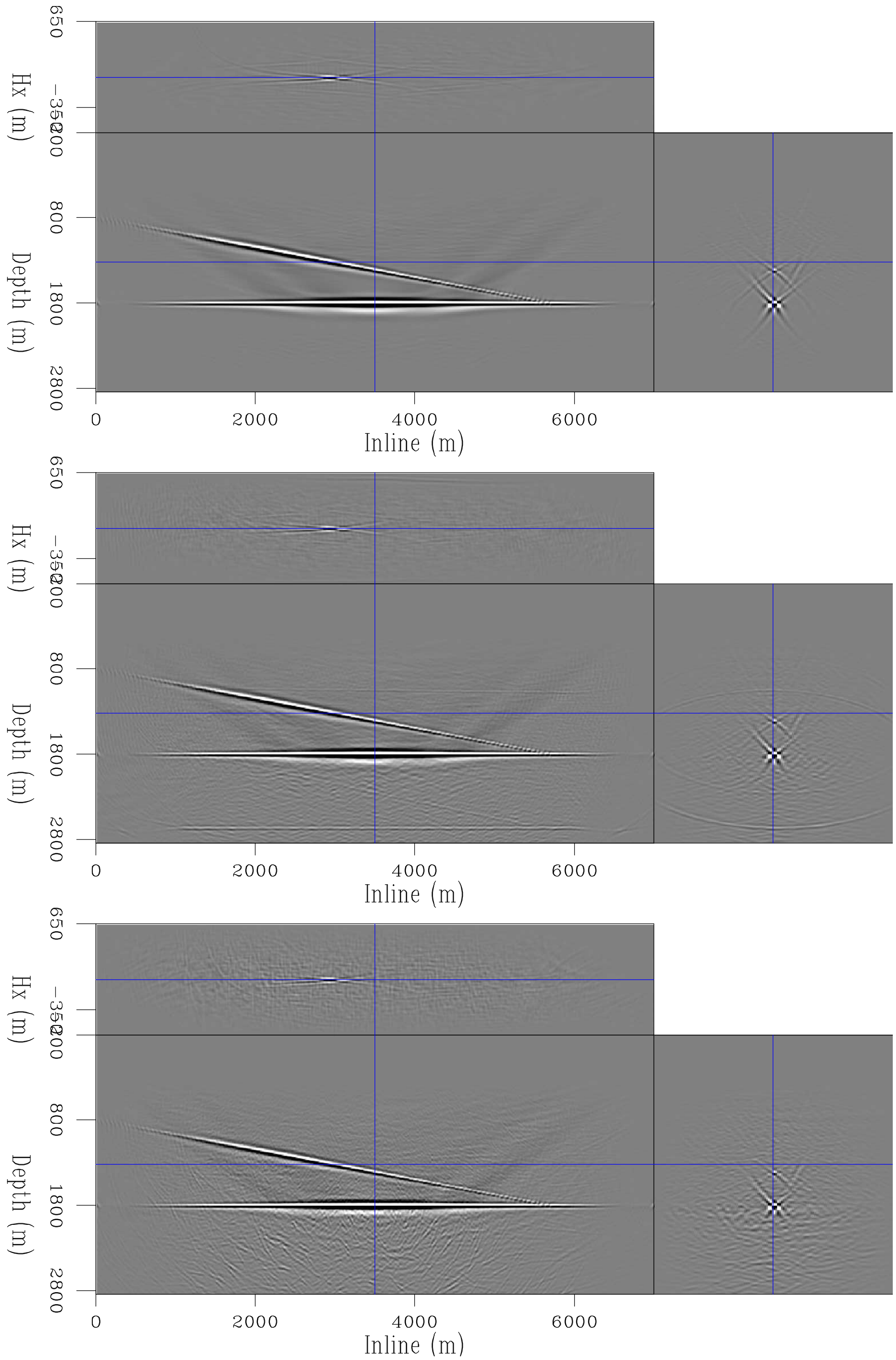

Figure 7: The three datasets in figure 6 imaged respectively in the extended domain. [**CR**]

REFERENCES

Abma, R. and J. Yan, 2009, Separating simultaneous sources by inversion: 71st EAGE Conference and Exhibition Abstracts, **71st**.

Abma, R. Manning, T. A. M. Y. J. and M. Foster, 2010, High quality separation of simultaneous sources by sparse inversion: 72nd EAGE Conference and Exhibition Abstracts, **72nd**.

Ayeni, G., A. Almomin, and D. Nichols, 2011, On the separation of simultaneous source data by inversion, 20–25.

Beasley, C. J., 2008, A new look at marine simultaneous sources: The Leading Edge, **27**.

Berkhout, A. Verschuur, D. and G. Blacquiere, 2008, Processing of blended seismic data: SEG Technical Program Expanded Abstracts, **78**.

Chauris, H. and M. Benjemaa, 2010, Seismic wave-equation demigration/migration: Geophysics, **75**, S111–S119.

Claerbout, J. F., 1971, Toward a unified theory of reflector mapping: Geophysics, **36**, 467–481.

Dai, W. and J. Schuster, 2009, Least-squares migration of simultaneous sources data with a deblurring filter: SEG Expanded Abstracts, **79th**, 2990–2993.

Doulgeris, P., A. Mahdad, and G. Blacquiere, 2011, Iterative separation of blended marine data: Discussion on the coherencepass filter, chapter 5, 26–31.

Hampson, G. Stefani, J. and F. Herkenhoff, 2008, Acquisition using simultaneous sources: SEG Technical Program Expanded Abstracts, **78th**.

Herrmann, F., Y. Erlangga, and T. Lin, 2009, Compressive simultaneous full-waveform simulation: Geophysics, **74**, A35–A40.

Jaramillo, H. H. and N. Bleistein, 1999, The link of Kirchhoff migration and demigration to Kirchhoff and Born modeling: Geophysics, **64**, 1793–1805.

Loewenthal, D., L. Lu, R. Roberson, and J. Sherwood, 1976, The wave equation applied to migration: Geophysical Prospecting, **24**, 380–399.

Martin, G. S., R. Wiley, and K. J. Marfurt, 2006, Marmousi2: An elastic upgrade for marmousi: The Leading Edge, **25**, 156–166.

Moore, I., B. Dragoset, T. Ommundsen, D. Wilson, C. Ward, and D. Eke, 2008, Simultaneous source separation using dithered sources, 2806–2810.

Sava, P. and B. Biondi, 2004, Wave-equation migration velocity analysis. I. theory: Geophysical Prospecting, **52**, 593–606.

Sava, P. and A. Guitton, 2005, Multiple attenuation in the image space: Geophysics, **70**, V10–V20.

Sava, P. and I. Vasconcelos, 2011, Extended imaging conditions for wave-equation migration: Geophysical Prospecting, **59**, 35–55.

Tang, Y. and B. Biondi, 2009, Least square migration/inversion of blended data: SEG Expanded Abstracts, **28**, 2859–2863.

Verwest, B. and D. Lin, 2007, Modelling the impact of wide-azimuth acquisition on subsalt imaging: Geophysics, **72**, 241–250.

Weibull, W. and B. Arntsen, 2013a, Automatic velocity analysis with reverse-time migration: Geophysics, **78**, S179–S192.

———, 2013b, Reverse time demigration using the extended imaging condition: SEG Technical Program Expanded Abstracts 2013.

Zhang, Y., L. Duan, et al., 2012, Predicting multiples using a reverse time demigration: Presented at the 2012 SEG Annual Meeting.