Image space separation of linearly blended data

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ABSTRACT

Separating simultaneously acquired seismic data is the link between more efficient acquisition and conventional imaging techniques. Successful methods of separating these data rely strongly on random source timings and positionings; loosening this acquisition restriction would make survey design and implementation more flexible. By performing a series of transformations it is possible to isolate and remove overlapping artifacts that are ubiquitious when imaging simultaneously acquired data with constant time delays. Initially, Extended Reverse Time Migration is applied, generating a roughly focused image in subsurface offset. The image is transformed to the angle domain and a hyperbolic radon transform is then applied, isolating certain events and allowing a separation to be performed as a function of curvature. Basic tests have shown that after a few iterations of this transform events become well separated. The reverse transforms are then applied and the data demigrated, giving the equivalently unblended dataset without requiring accurate velocity control.

INTRODUCTION

Contemporary seismic targets are increasingly often associated with steeply dipping structures and strong velocity contrasts. In order to illuminate these difficult features data with large offsets and multiple source boats are acquired (Verwest and Lin, 2007). Intuitively this leads to both more expensive acquisition and an increase in field waiting time. This latter ramification is due to the fact that it is necessary to allow the energy from the previous source to sufficiently dissipate before recording the next source point. If waiting time was not a restriction then denser sampling could be recorded per unit time and acquisition would be significantly more efficient (Beasley (2008); Hampson (2008); Berkhout and Blacquiere (2008)). Practically, it is possible to disregard this waiting time and fire the next shot when in position; this is often called continuous recording of seismic data. Recording overlapping data in this manner will require more processing time than conventionally acquired data, since separation will be necessary to mitigate imaging artifacts. However the economic gains from reduced acquisition time far outweigh this extra processing 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).

Similarly, blended data can be untangled by using extended imaging. This is done by imaging these data across a range of subsurface offsets and then applying a transformation to the angle domain. It is possible to distinguish events from separate shots in this domain, by then applying some variety of curvature dependent filtering energy from overlapping sources can be removed. These data can then be demigrated, resulting in the equivalently unblended dataset.

This discussion will investigate how these overlapping data manifest themselves in the Angle Domain Common Image Gathers (ADCIGs) and how best to isolate and remove the energy identified as noise. Subsurface offset domain image gathers will be constructed and compared for conventional data and data blended using a constant time delay, these will also be contrasted in the angle domain. By using a hyperbolic radon inversion methodology the energy from interfering shots can be focused, isolated and removed. Thus only events of interest will be left and these data can be demigrated, resulting in successful separation of blended data.

A number of existing techniques are successful in separating data acquired using a random timing approach, thus the focus of this study will be on data acquired using a constant time delay. This is referred to from hereon as linearly blended data.

ADCIG CONSTRUCTION

The imaging technique used for this study will be Reverse Time Migration (RTM.) This is an algorithm based on direct solutions of the wave equation, meaning that energy associated with multiply scattered events, steep dips and a broad range of wavenumbers will be preserved. This process can be described in equation 1.

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

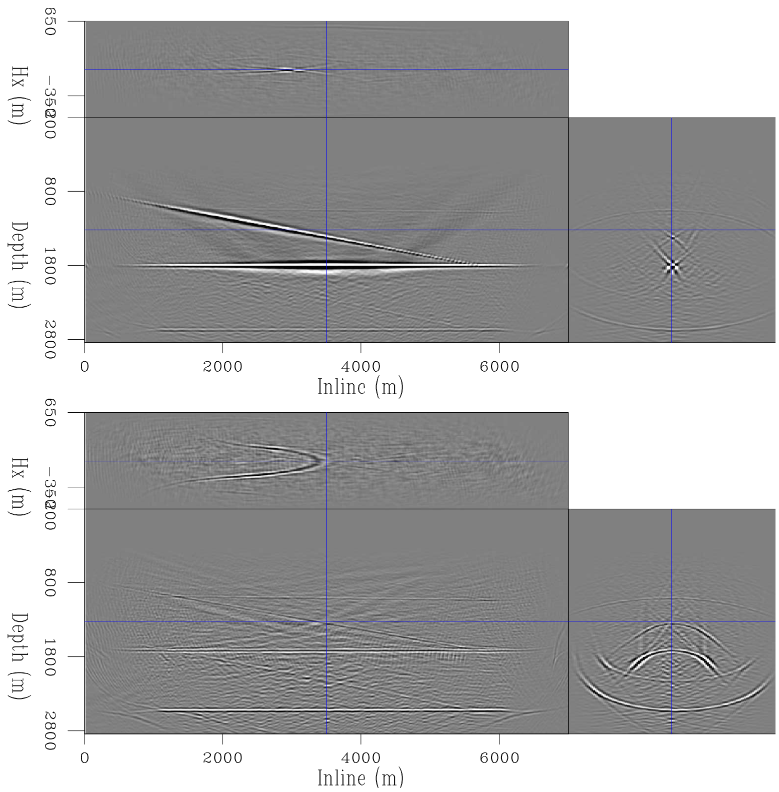

Figure 1: Linearly blended data migrated into the subsurface offset domain using the correct velocity model (top) and a model 10% too slow (bottom.) [**CR**]

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.

However, for the problem of separating continuously acquired data a stringent requirement on the velocity model is undesirable. Direct application of equation 1 with an incorrect velocity model will result in the loss of certain events, and subsequent demigration will not well represent the original dataset. To preserve all event kinematics extended imaging must be used. If zero-offset imaging can be described by equation 2, then extended imaging can be described by equation 3.

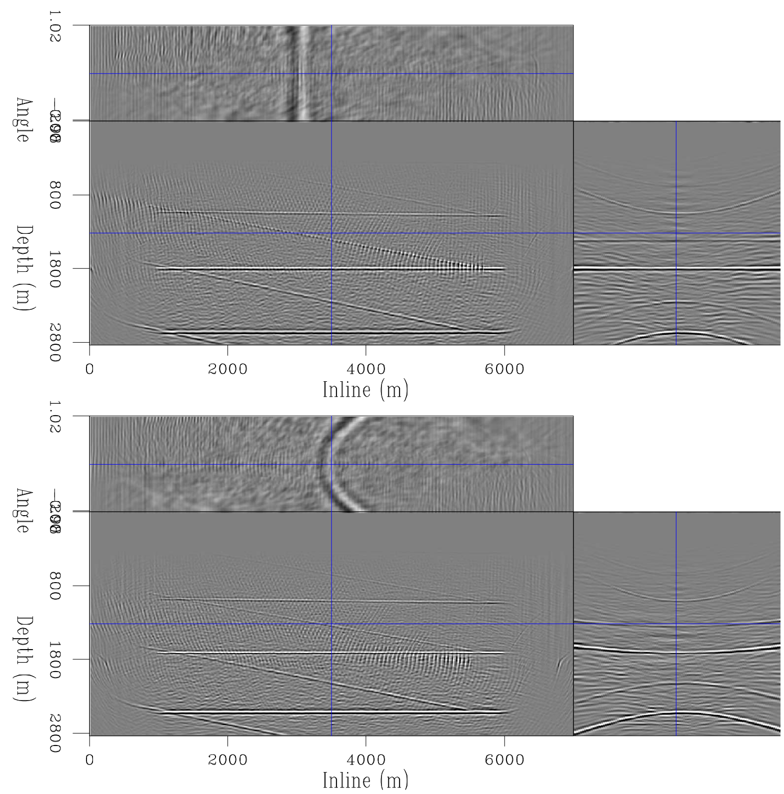

Figure 2: The same images as Figure 1 but with the third axis transformed into the subsurface angle domain, rather than subsurface offset. [**CR**]

$$I(x, y, z) = \sum_{i}^{nshots} \sum_{t} P_s(x, y, z, t; \mathbf{s}_i) P_r(x, y, z, t; \mathbf{s}_i). \tag{2}$$

$$I(x,y,z,x_h,y_h) = \sum_{i}^{nshots} \sum_{t} P_s(x+x_h, y+y_h, z, t; \mathbf{s}_i) * P_r(x-x_h, y-y_h, z, t; \mathbf{s}_i) \quad (3)$$

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.

If the correct velocity model was used for imaging then the energy will be focused to a point in subsurface offset. If an incorrect model was used then the energy will be spread out over a range of offsets. Analysing this moveout as a function of the velocity model is the core concept of Wave Equation Migration Velocity Analysis (WEMVA) (Sava and Biondi, 2003).

Figure 1 shows an image of some simple linearly blended data imaged with both the correct velocity model and with an incorrect model. In both cases the energy resulting from the overlapping data are readily identifiable. To filter this overlapping energy it is desirable to apply a second transform to these offset panels that can isolate events according to their curvature. In this paper a hyperbolic radon transform will be used.

Initial inspection shows that the subsurface offset domain is not the ideal domain for this moveout-based separation. If a radon transform is applied to a focused point, the result will be a line in the transform space. We would like our data to either be all points or all lines, not a mixture of the two. While in this case the incorrect velocity model only results in curves it is not desirable to restrict the case where the velocity may be accurate for certain events. A simple transform from the offset domain to the angle domain can be used. Figure 2 shows the same two panels as in Figure 1, but in the angle domain (ADCIGs).

It is still possible to clearly identify the events from the primary data and overlapping data. However, now all the events in this new domain are associated with a given curvature and applying a curvature based transform will not result in the spreading out of some of this energy, but rather focusing of all events.

RADON INVERSION IN THE IMAGE SPACE

Initially, a hyperbolic radon transform was applied to the ADCIGs in Figure 2, and the result can be seen in Figure 3. Two things are evident from studying these images - the transform has been successful in beginning to separate these data according to their moveout, however they are not well focused in this new domain. There is some

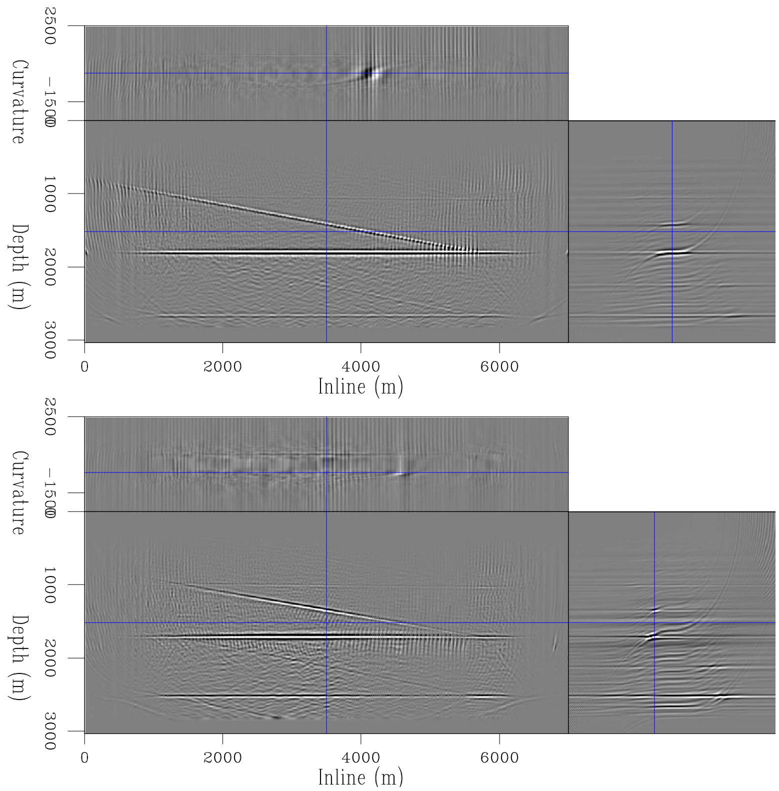

Figure 3: The angle domain image with the correct velocity model after a single hyperbolic transform (top) and the slow velocity image after a single hyperbolic radon transform. [**CR**]

clear transform noise and a spreading over curvature values for all events. To improve this focusing a simple gradient based inversion can be used instead of a direct adjoint methodology. By using this transform, it's adjoint and a conjugate directions solver this gradient based inversion can be easily constructed (Claerbout, 2001).

Figure 4 shows the result of applying one instance of this radon transform and the result after applying ten iterations of this radon based inversion to the image obtained with the correct velocity model. It is immediately clear that the latter of these served to greatly improve the focusing of these events in curvature space, and that curvature based filtering will remove the overlapping data. The reverse transforms can then be applied and the separated data constructed. Figure 5 then shows these two panels but for the image obtained with a velocity model which was 10% too slow.

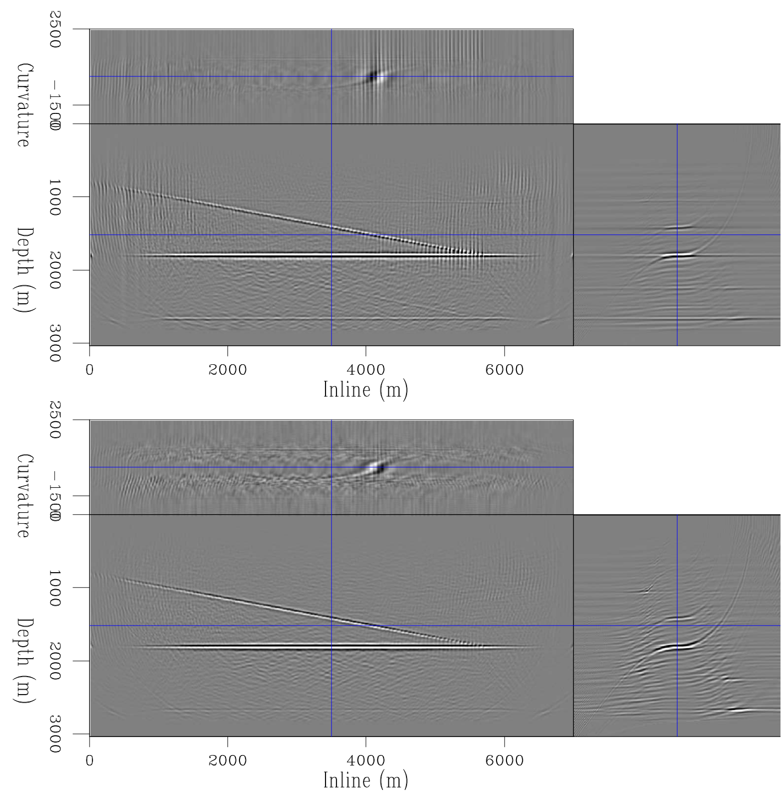

Figure 4: The angle domain image with the correct velocity model after a single hyperbolic transform (top) and after ten linear iterations of the transform (bottom.) Note the focusing at zero curvature (corresponding to a flat angle gather.) [**CR**]

Again, the inversion was able to more tightly focus these events for given values of curvature. This focusing now occurs at a non-zero value of curvature, however the relative differences in curvature values between primary and overlapping data are the same. Thus these events can still be filtered according to their curvature, even though these data were imaged with an incorrect velocity model. The events do not focus at an exact curvature value because a hyperbola does not describe these shapes exactly. However, within a range of curvature values the overlapping events are still localised, meaning penalisation or filtering can be used.

CONCLUSIONS

It is demonstrated herein that it is possible to untangle linearly blended data in the image domain. Migrating these data into ADCIGs serves as the first step, resulting in a space where it is possible to distinguish between primary data and overlapping data. A hyperbolic radon inversion can then isolate these events into given measurements of curvature; certain curvature values can then be removed or penalised, effectively removing energy associated with overlapping shots. The remaining energy can then be transformed back to ADCIGs and then demigrated, with the final output being the separated dataset. This separation scheme does not depend on a well constratined velocity model.

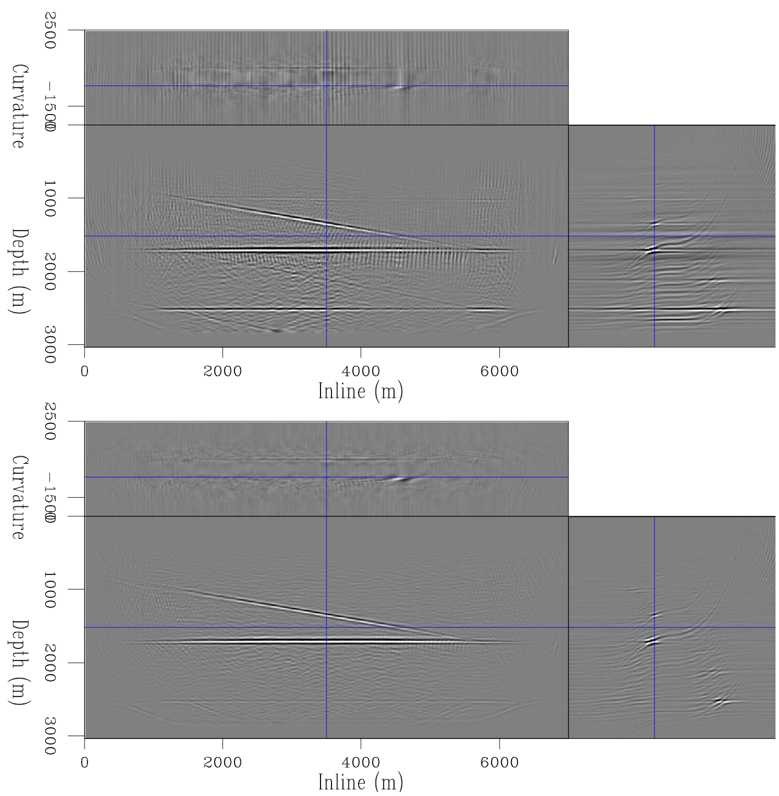

Figure 5: The angle domain image with the incorrect velocity model after a single hyperbolic transform (top) and after ten linear iterations of the transform (bottom), note the focusing is now at non-zero curvature. [**CR**]

FUTURE WORK

While the hyperbolic transform does focus these events over a smaller range of curvature values, the events in the angle domain can not be exactly described by hyperbolae. This is even more true for data acquired over a more complex model. It would be better to decompose these events into parabolic curvature and tangent values, this will be attempted next.

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