Abstract
The final stage of a migration process is usually the imaging condition, which brings together elements of the upcoming and downgoing wavefields for each shot gather in order to form an image contribution. This procedure suffers limitations due to the approximations made in representing the physics of the system, but in addition to that, the final summation of all shot contributions necessarily assumes that the subsurface parameter model was perfect, such that all image contributions align perfectly for summation (within a Fresnel zone), as well as having recorded data that are noise free and adequately sampled. In this work, we assess the effect of unresolvable velocity errors on the final image, and present a case study example of a technique for compensating for these errors via techniques borrowed from astronomical image processing applied to each of each of the many thousands of elemental traces that contribute to the final image.
Introduction
Regardless of the model building procedure we employ, there will always be remnant error in our estimation of subsurface parameters: this is a basic tenet of inverse theory. With contemporary waveform inversion procedures, these errors may only be of a scale length of tens of metres, but they will still affect our ability to form a high resolution image. As we move towards higher resolution imaging, whether due to the contributions to bandwidth gained from deghosting or from high frequency RTM imaging, such small scale parameter errors will inevitably limit the final resolution of the image.

There are several classes of error that affect the image. Firstly we have the physics of the problem. In any computational technique, we make simplifying assumptions concerning the physics involved in the process, and then need a suitable numerical technique to realize that physics. Most if not all, contemporary imaging techniques assume an acoustic earth model (i.e., all rocks are fluids, and cannot support shear propagation), and the majority of imaging algorithms deployed for very complex geological environments use shot migration algorithms for two way propagation (such as reverse-time migration: RTM; Hemon 1978, McMechan 1983; Whitmore 1983; Baysal et al., 1983). Typically, a convolutional imaging condition is used for RTM imaging (Claerbout 1971). The limitations of these techniques are well understood (Yoon et al., 2004; Schleicher et al., 2007; Arntsen et al., 2010; Leveille et al., 2011) and many workers have outlined techniques to compensate for the failings of the approximate (‘bad’) physics employed. The techniques include interferometric imaging (Sava & Poliannikov 2008), least squares migration (Schuster 1997; Nemeth and Schuster 1999), and deconvolutional and illumination compensated imaging conditions. More recently, some workers have moved to address the issue of residual model error via phase or trim-static alignment of individual image contributions (‘optical stacking’ or ‘adaptive optics’: e.g., Etgen et al., 2014a, b; Albertin and Zhang 2014; Jones et al., 2015). It is this aspect that we consider in this work.

Methodology and Synthetic Examples
Consider the contribution to an image from a single shot gather: the product of the downgoing source wavefield and the upcoming receiver wavefield at each propagation time-step, integrated over all propagation time, constitutes the image contribution from this individual shot (after various forms of normalization, e.g. Jones 2014).

If we were now to consider just one surface location and collect all the individual shot contributions to this point, we would have an elemental contribution gather. Many of these contributions are useful signal (namely those that fall within a Fresnel zone of the image point), but most will be migration noise. Usually the contributions to the image from individual shots are summed ‘on the fly’ or at best in shot-offset-azimuth tiles (Xia et al., 2013, Tyson et al., 2015). We can assess the effect of model error on these image contribution gathers by migrating synthetic data with and without model error. To assess the effect on this elemental gather of velocity errors, we have perturbed the model used to create the data with a checkerboard pattern with a cell size of 100*100m, and velocity perturbations of +/-1%. These small-scale velocity perturbations are taken to represent the degree of velocity uncertainty likely to be present after a comprehensive velocity model building exercise. Figure 1a and 1b show the velocity model used to create the synthetic shot gathers and an RTM image using the correct model. Figures 1c and 1d show the model after perturbation and the associated RTM image. As expected, with these small velocity errors there is very little visual image degradation, and other than in the near surface, the degradation is difficult to see. However, closer inspection will show a slight loss of bandwidth even in the deeper section.
Figure 1: a) model used to create synthetic shot gathers. b) RTM using the correct model. c) Model with a +1% interval velocity perturbation on a 100m *100m grid (the yellow circle indicates the location of the elemental gather shown later). d) RTM image formed using the perturbed model.

After migrating with the correct model, the image contribution gather is flat for reflectors within the Fresnel zone (Figure 2a), where events would sum to form the final image. However, for RTM using the perturbed model, we can see that the hitherto flat central portion of the gather now has a trace-to-trace jitter of about +/− 10m (Figure 2b). This jitter and general distortion of the waveform results from the small-scale velocity errors introduced into the migration model. In a real tomographic (and/or WFI) iterative model updating project, we would expect there to always be some residual (and more importantly - unresolvable) velocity error in our final model. However, we should be able to ameliorate the resulting image degradation by performing localised wavelet shaping and phase adjustment of these jittering elemental waveforms within the Fresnel zone. In this way, we could recover some of the potential image resolution lost due to unresolvable and more general model error.
Results for a Field Data Example
Here we will consider data from an offshore deep water environment where we have a complex salt canopy near the sea bed (Tyson et al., 2015; Kobylarski et al., 2015), demonstrating how the resolution of the sub-salt sediments is improved. Due to the complex nature of salt behavior, it is often the case that we will have significant velocity error in our description of the subsurface, resulting from both inadequate inversion of available data and from inappropriate description of the associated physics (e.g. Jones and Davison, 2014).

Discussion
It is well known that the imaging conditions used for RTM give rise to artefacts that can be ameliorated via various pre- and post-stack signal processing techniques. However, perhaps of more concern is the effect on image degradation of unresolved and unresolvable velocity error. Velocity errors of a scale length comparable to the wavelength of sound being used to illuminate the subsurface can significantly limit the resolution available to us.

Assessing and compensating for these small errors can facilitate enhancing the images obtained during conventional RTM so as to extract the maximum amount of information available from the computational effort. However, to do this requires modification of the latter stages of the imaging process: namely the final integration over each shot migration’s contribution to the image.

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