Factors Affecting Frequency Content in preSDM Imaging

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Abstract

It is sometimes remarked that pre-stack Kirchhoff depth migrated images have a lower frequency content than their time-domain counterparts. Here we assess the various factors that influence frequency content during migration, with the object of assessing the reasons for potential loss of bandwidth in migrated data.

We demonstrate that there is no inherent reason for the bandwidth of Kirchhoff (or depth) migrated data to be worse than other migrated data, and offer recommendations for ensuring optimal frequency content in the processed output image.

Introduction

'The depth migration has lower bandwidth': this complaint has often been heard, and examples can be found where it appears to be true. Is this observation an indication of some inherent limitation of Kirchhoff 3D preSDM or simply of 'bad practice' or economic 'expediency'?

In the following work, we outline the nature and cause of various factors that have an impact on the frequency content of a migration, and try to assess if these factors affect depth migration more than time migration, or Kirchhoff migration more than alternative schemes.

The analysis covers the following topics:

- **Spurious Differences**	
- **Aliasing**:	Temporal; Spatial
- **Wavelet Changes During Migration**:	Frequency, Velocity & Offset Dependent
- **Kirchhoff Migration as a Stacking Process**:	Travel-Time Sampling Errors; Sensitivity to Velocity Error; Acquisition Footprints

Spurious Differences

Some aspects of this work deal with 'statements of the obvious': but it could be instructive to re-state them anyway. For example, a common element of confusion in time versus depth comparisons is the degree of post processing. A final time product (with its associated deconvolution and spectral balancing) will naturally look better in terms of signal content, than a raw preSDM result. Consequently, it is important to perform the appropriate post-processing on the output from the preSDM before drawing conclusions. In the case of designing spectral balancing operators, we must ensure that the preSDM output spectrum extends well beyond the signal spectrum.

In addition, whereas a frequency domain finite-difference algorithm explicitly limits the frequency range (FMIN & FMAX parameters), a Kirchhoff scheme (which is usually time domain) does not inherently limit the frequency range. However, in preparation for anti-alias filtering, or variable depth step, some Kirchhoff schemes may also select a frequency bandwidth. Thus, in comparisons, we must first ensure that we have migrated that same frequency content

Temporal Aliasing

For time-sampled data, we have a Nyquist frequency, and if we resample the data say from 2 to 4 ms, then we must first pre-filter the time data in order to avoid aliasing the signal with energy beyond the new Nyquist.

Likewise, during depth migration, we resample data to depth, and must take care that we do not alias temporal frequencies that are not adequately sampled by the output depth step.

This is not usually a problem for finite difference depth migration, as we band-limit the data explicitly during. However, for Kirchhoff migration, we have no explicit time-frequency cut-off so must ensure that upon output we do not permit aliased energy to survive.

To accomplish this, we must pre-filter the input time data: to calculate the frequencies permissible in the output depth data, we need to know: *DZ* (the output depth sample rate) for the migration, and Vi(t) the interval velocity function. The maximum temporal frequency that can be imaged for a given dz is:

$$F_{nyq} = v/(4^{*}DZ)$$

For example, for typical shallow marine data, imaged with a 10m depth step, we would need to pre-filter the input data to about 35Hz in the shallow.

This problem of not having pre-filtered the data to guard against temporal aliasing is only important when we image at a 10m depth step (or greater) or in the very shallow parts of a marine section, where we have low velocities. Deeper in the data, or with a 5m (or variable) depth step, the problem is not as severe. For land data, the problem does not usually occur, as we have high near-surface velocities. However, in dune areas, we can have very low surface velocities, so the problem can be even worse.

Recommendations

Estimate the global minimum 1D velocity function that is representative of the 3D velocity field. Compute the corresponding Fmax for the depth step to be used in the migration. Pre-filter the data with the appropriate low-pass filter.

Parameter testing (design of aperture, spatial anti-alias filter, etc) must be performed only on data that have been appropriately pre-filtered.

Spatial Aliasing

During migration, data is moved out along the impulse response to increasingly higher dips, prior to summation to form the output image. For a given inter-trace distance, a given frequency will become aliased for a given dip. In order to prevent the aliased frequencies from being summed into the output image, we apply an anti-alias filter during migration.

This will limit the frequency content of dipping reflectors. This observation is true for all migrations, but is more pronounced in Kirchhoff migration, where we explicitly apply an anti-alias filter.

For finite difference schemes (as usually applied in time migration) we do not usually have explicit control of the operator, but aliased frequencies will be rejected as evanescent energy.

Sometimes the design of the anti-alias operator is sub-optimal, as the effect of tapers is not properly taken into account, and the filter kills too much high frequency energy. Thus, omitting the anti-alias filter can sometimes give a better result, especially deeper in the section where high frequency aliased energy is less of a problem.

Recommendations

Produce a test line with the anti-aliasing turned-off, so as to be able to assess any potential damage done to steep dips by the choice of anti-alias parameters. Adjust the anti-alias parameters accordingly.

Wavelet Changes During Migration:

Frequency Dependent Changes

In general, migrating an event of a given dip will lower the frequency content of that event. This lowering of frequency on dipping events is common to both time and depth migrations, but care must be taken to choose the low-cut of display filters so as to preserve the post-migration frequency content of the data.

This also has a corresponding effect on the design of deconvolution operators. It can be observed that using a deconvolution whose parameters have been chosen by testing on a time migrated image, will give a sub-optimal result when used on a depth migrated image.

Recommendations

Deconvolution tests and parameter selection should preferably be done on the depth migrated data (converted back to time) rather than applying deconvolution operators with parameters selected from previously existing time migrated data.

Velocity Dependent Changes

On a time migrated section, the wavelet is seen in its domain of measurement: namely time. So, ignoring the effects of dispersion and attenuation, the wavelet will appear stationary down the trace. That is to say, its phase and frequency content should not change.

On a depth migrated image however, the wavelet is seen in depth, and its wavelength changes in accordance with the velocity contrasts it sees. The wavelet is stretched as it passes through an interface with a high velocity contrast.

Consequently, the wavelets appear to be of lower frequency in the deeper parts of the section in the depth image. This stretch effect can be removed by a vertical stretch back to time, and if we do this, the frequency content of the wavelet should be similar to that of a time image.

Although we have stated that converting back to time will 'back out' the vertical wavelet stretch, on real data, life is not so simple. Due to the persistence of RMO, the depth domain wavelets are not perfectly aligned in the CRP gathers. Thus upon stacking, we degrade the wavelet character. This distorted wavelet is then converted back to time with a model whose velocity interface sits 'somewhere' within the distorted wavelet. Thus a residual low frequency element remains in the wavelet after conversion back to time. If the input data are in minimum phase, then this effect can be lessened somewhat, as the energy of the wavelet is front-loaded. There is also the interplay with where the horizon boundary sits within the wavelet.

Recommendations

Strive towards a good wavelet compression sequence prior to migration.

Offset Dependent Changes

A more problematic, and fundamental problem related to depth imaging, is the offset dependent stretch of the wavelet in depth (Tygel, et al, 1994, 1995). This is analogous to the NMO stretch in time processing (Barnes, 1995).

In the depth domain, the severity of the stretch is proportional to the incidence angle, reflector dip, and to the velocity. Hence the effect is very noticeable for the farther offsets. In addition, the effect stands out at high velocity contrast layers, especially after a velocity inversion, as in this case, the down going rays refract back to the vertical, thus reducing the angle of incidence of subsequent reflections. Consequently the stretch at the base of the high velocity layer appears more pronounced in comparison to deeper events. Hence the effect is most noticeable at unconformities, carbonate, and salt interfaces.

Because the stretch can both increase and decrease with depth, such events are difficult to mute out with a standard processing mute, as the mute functions often must be simply monotonic. To deal with depth stretched wavelets, we need to design an automatic stretch dependent mute.

Recommendations

Stacking mutes should be selected after preSDM. Consequently the pre-migration mute should be left quite wide. Ideally, an automatic stretch mute, with a parameter to select the stretch threshold could be implemented.

This recommendation is only valid for offset Kirchhoff migration. In a shot migration (as used in a full wave equation scheme) energy is mixed between offsets during the migration, Thus, the mutes must be applied prior to migration.

Kirchhoff Migration as a Stacking Process.

If we think of the migration as a sum over hyperbolic trajectories (in time migration) or over more complex asymmetric trajectories (in depth migration), then we can see that summing over an incorrect trajectory will lead to mis-stacking, which translates into a lack of frequency content.

Assuming we have the correct model, there will be 3 main influencing factors on image quality:

- correct sampling of the velocity field (ergo – travel times)
- correct sampling of the input data on the acquisition surface
- adequate sampling within the Fresnel zone at the image point

Travel-Time Sampling Errors

There are various theoretical approximations made in ray-tracing or other travel time computation schemes (such as how we treat the curvature of a ray in a velocity gradient). However, a more mundane and damaging effect relates to how we sub-sample the travel times for storage.

In practice the travel time calculation is performed by considering a five-dimensional problem:

- the 2D surface acquisition grid sampled at say 125m * 125m, representing both the source and receiver positions, and
- the 3D subsurface volume sampled at say 100m * 100m * 50m.

For each surface location on the 2D grid, we compute the one-way travel time to each of the nodes in the 3D subsurface volume. In general the cost of computation increases as the cube of the depth (solving to a depth of 2km costs 8 times more than solving for a depth of 1km). Given that in general an input trace will not lie on the surface nodes used for calculation, we must read the travel time tables associated with the four nearest neighbours and then interpolate. Also, given that the desired output points will not lie on the 3D volume nodes, we must also interpolate those values between nearest neighbours.

These interpolations introduce some error. To avoid them, ideally we should compute travel times for the true surface locations of all shots and receivers, and do so for all desired output depth samples (i.e. at the seismic sampling, typically 25m * 25m * 5m). However, the volume of space required to store all travel times is very large (e.g. For a 10km * 10km * 10km volume, this would typically be 400 terabytes).

In the near surface, the travel time isochrons tend to have greater curvature, as the wavefield has not spread-out too much. If we sample the travel times on a surface grid of say 200*200m, and then interpolate these values down to 25*25m during the migration, we will have some interpolation error. If we use a simple linear interpolator to resample the travel times to the migration output grid spacing, then we will usually see a grid pattern artifact in depth slices through the resulting images. (N.B. In practice it is the slownesses that are interpolated).

Recommendations

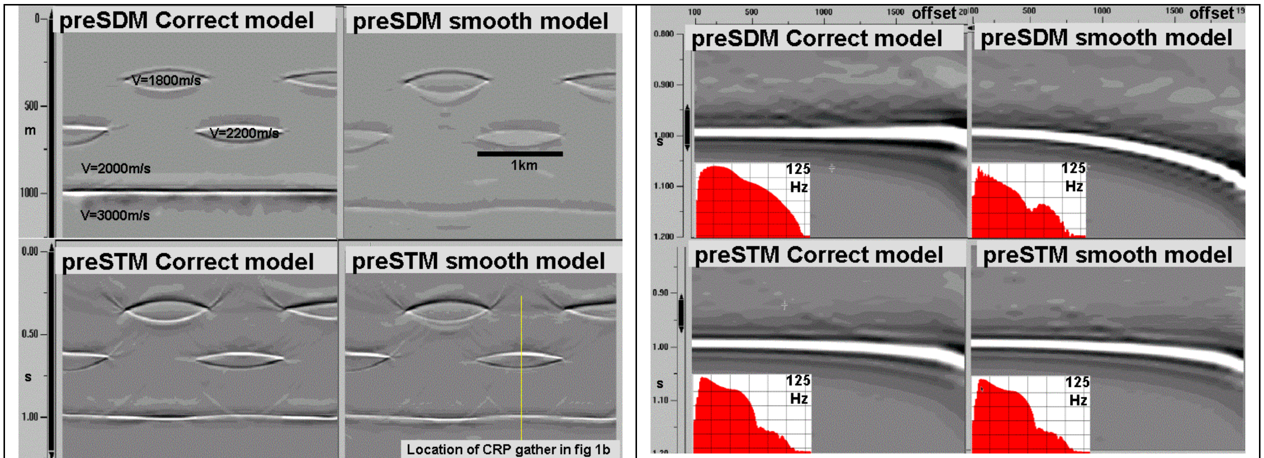
QC the degree of artifact by inspecting 3D depth slices through the final image. The artifact is usually strongest at shallower depths. If necessary, use a non-linear interpolation and/or use the smallest ‘affordable’ grid;

Sensitivity to Velocity Error

As we have noted, an error in the travel times, due to whatever cause, results in mis-stacking in the Kirchhoff summation. This not only leads to a loss of stack power, but also to a loss of frequency content (Jones, et al, 1998). Both time migration and depth migration will suffer from loss of amplitude and frequency due to this mis-stacking.
However, depth migration is more sensitive to lateral velocity change (in fact, time migration ignores it to the extent that time migration operators are symmetric) Due to this greater sensitivity to velocity, a depth migration will suffer more than a time migration for a given velocity error (see fig 1.)

Recommendations

Output all CRP gathers from the 3D preSDM final run. Then obtain a dense RMO velocity correction field - eg use an automatic velocity analysis tool to continuously analyse velocity along lines spaced at 200m: gathers can be converted back to time for this. Velocities can be output every 100 or 200m along the lines, to yield a 200m * 200m RMO correction grid, after appropriate editing and smoothing.



Migrated images for exact and smoothed models | *Migrated gathers and associated amplitude spectra*

Figure 1: Synthetic data with small-scale length velocity anomalies are migrated first with the exact model, then with a smoothed model using both preSTM and preSDM algorithms. The preSTM result is similar with both models. PreSDM is worse with the smoothed model. The preSDM looses more frequency content that preSTM for small velocity errors.

Acquisition Footprints

A Kirchhoff migration assumes that the input data are regularly sampled in x, y, and offset, so that the resulting wavefield can be adequately reconstructed during imaging. If we have a gap in the input, there will be an amplitude anomaly in the output, as the corresponding Huygen's 'secondary wavelets' will not sum appropriately.

In the case of acquisition footprints, time processing is helped by bin-centred DMO and subsequent interpolation prior to migration. Finite Difference preSDM requires regular bin-centred input, so we avoid the problem as with time imaging

Recommendations

Perform regularization/interpolation prior to Kirchhoff preSDM.

Conclusions

3D preSDM is still considered an 'expensive' process, consequently pressure is always on to 'save money'. However, if money is 'saved' by not outputting full bandwidth gathers, then more money will be lost by having to work with sub-optimal images.

All gathers should be output from a preSDM: these gathers should be subjected to the full conventional processing expected for any high-fidelity time-processing sequence (e.g. careful mute selection, wavelet deconvolution, signal spectral balancing, residual anti-multiple, etc).

A series of recommendations have been given in the body of the text. Following the majority of these recommendations should safeguard against most of the factors that act to degrade depth image quality.

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