5D leakage: measuring what 5D interpolation misses

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Summary

5D interpolation methods have proven to be capable of overcoming the constraints of actual data acquisition in a wide range of situations. However, in general the interpolation methods work by making some type of assumption about the simplicity or sparsity of the underlying model that describes the seismic data, so there is a legitimate concern about whether any information or resolution is being lost during the interpolation process. To address this concern, we present a simple, general method of measuring 5D leakage. 5D leakage is the noise, and possibly the signal, that 5D interpolation is not able to correctly interpolate due to the fact that the data do not completely conform to the simplicity constraints used by the interpolation algorithm. Using the MWNI algorithm, we show with real data examples that 5D leakage can contain complex (quickly varying) aspects of the data such as noise, diffraction patterns and acquisition footprint. In general, the slowly varying aspects of the signal (especially the reflections) are not part of the measured 5D leakage so most important aspects of the signal appear to be reliably interpolated.

Introduction

The primary purpose of 5D interpolation is to reduce the generation of migration artifacts during prestack time migration by improving the prestack sampling characteristics of the 3D dataset. There are several algorithms for performing 5D interpolation but we will focus on the minimum weighted norm interpolation (MWNI) algorithm here. A large amount of interpolated data can be generated by any 5D interpolation method. The MWNI method of 5D prestack interpolation (Trad, 2009) generates the new data by using two constraints, a least-squares fitting constraint on the input data and a weighted L2-norm constraint that favors the large "sparse" Fourier coefficients in the construction of traces between existing input traces.

MWNI is able to generate excellent results. However, all interpolation methods have limits. With MWNI and other interpolation methods there is the possibility that small details in the data can be lost since each method interpolates data by focusing in one way or another on interpolating the major components of the data correctly, with "major components" being defined differently for each method. There are several reports on the value of using 5D interpolation as a means of obtaining improved AVO inversions (e.g. Downton et al, 2008). However, it is also well known that 5D interpolation can act as an attenuator of both random noise and systematic footprint noise. Since there is nothing inherent in 5D interpolation to distinguish between signal and noise, there is a lingering question of whether each algorithm sets the demarcation line between signal preservation and noise attenuation correctly.

In this paper we tackle the question of whether MWNI is capable of losing resolution during the interpolation process, and we give a concrete answer. The answer, not surprisingly, is yes, some resolution can be lost during the 5D interpolation process but of course the amount of loss depends on the complexity of the data and on the acquisition parameters. We present a general method for measuring this 5D leakage quantitatively in any situation, and we suggest that it be generated as a by-product of any 5D interpolation process as a means of quality control.

The need to assess the fidelity of 5D interpolation

Figures 1 and 2 show a typical example of stacks before and after prestack 5D interpolation with MWNI. We see the normal enhancement of the stack due to noise attenuation. The improvements are most easily seen in the shallow events since the obvious noise in the first few hundred milliseconds has been essentially removed, and the continuity of events has been greatly improved. The impact on the deeper parts of the stack is less obvious, but there is nonetheless a certain amount of noise attenuation that can be observed, although the characteristics of the signal appear to be relatively well preserved.

One part of the stack where we might question the integrity of the 5D interpolation is in the middle part of the section, between about 600ms and 1000ms, where a heavily karsted feature has generated a large number of diffractions. The 5D interpolated stack has a smoother appearance than the original stack in this area, so although the major features seem to have been preserved, it also appears that the diffractions may have been attenuated. Diffractions are generated by edges, and sharp edge definition is basically what the interpreters need for resolution. So it is obviously desirable that diffractions be preserved through the interpolation process.

Fig.3 shows an example of a CDP gather from this 3D dataset after 5D interpolation. The data in the gather show a great deal of integrity in terms of character changes along the flat events, noise and multiples. The parameter choices in the 5D interpolation were chosen with the utmost care to generate as good an interpolation as possible. However, there is still some character difference between the original

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input traces shown in Fig. 4 and the interpolated traces in Fig. 3. The original traces appear to be somewhat noisier than the interpolated traces. This is to be expected since MWNI invokes a sparseness (simplicity) criterion on the Fourier coefficients that is used to generate the new traces. So if noise is incoherent from trace to trace, we expect 5D interpolation to have trouble interpolating all of the characteristics of the noise.

The question remains, however, whether all of the signal in the original traces has been correctly interpolated. Is it just noise that distinguishes interpolated from input traces or is it something more?

The flip-flop method for measuring 5D leakage

Our simple procedure for measuring the parts of the input data that 5D interpolation is failing to interpolate (the 5D leakage) is a method that we call the flip-flop method. The flip-flop method consists of first performing a normal 5D interpolation, eliminating the original input traces from the newly 5D interpolated dataset, and then interpolating the data in the original input trace locations using just the 5D interpolated data. i.e. we have flip-flopped the input data and interpolated data in the interpolation process. The difference between the original input traces and the interpolated data at the input trace locations obtained by the flip-flop method is a measure of the residue, or leakage, from the 5D interpolation process. Notice that the interpolation method that is used to interpolate the original traces from the newly interpolated traces does not have to be the same method that was used in the original interpolation, and there may be good reasons not to use the same method. Normally the first interpolation (MWNI in this case) is interpolating many traces from a few traces and the second interpolation (the flip-flop interpolation) is interpolating a few traces from many traces. So it is not obvious that the same algorithm is best suited to these two different situations.

Fig. 5 shows the same CDP gather as in Fig.4 after applying the flip/flop method to the entire 3D dataset. In this case, MWNI was used for both the original 5D interpolation and the flip-flop interpolation. Notice that the traces in the original input locations after the flip/flop interpolation are now more similar to their neighbors than before (compare Fig. 5 to Fig. 3). Fig. 6 shows the difference between the traces in Fig. 4 and Fig. 5 at the original input locations.

The traces in Fig. 6 are a measure of the 5D interpolation leakage. They may look like they consist of nothing but random noise, but stacking up these traces shows the remarkable result in Fig. 7 along one inline. We see the obvious noise at the top of the section, as expected, but we also see a clear image of many diffractions between about 600ms and 1000ms. Just as remarkable is the almost total absence of flat events. Fig. 7 is a picture of exactly the aspect of the signal that we would expect MWNI to have difficulty interpolating successfully. Diffractions are subtle features of the signal that take many low-amplitude wavenumbers to describe. Flat events are simple features of the signal that take a smaller number of high-amplitude wavenumbers to describe. Hence, the leakage display in Fig. 7 tells us that simple flat events are being interpolated well by MWNI but that diffractions may leak through the interpolation process. Figures 8, 9 and 10 show a comparison of a timeslice at 679ms from the stack of the uninterpolated traces, the 5D stack, and the 5D leakage stack, respectively. The correspondence between the channel-like features in the 5D stack and 5D leakage stack is obvious. It appears that the 5D leakage is greatest at locations in the dataset where edges in the geology occur. Rapid spatial changes in the data require many Fourier coefficients to describe, so some of the smallest Fourier coefficients are being inaccurately estimated by MWNI.

Footprint attenuation

A common observation is that 5D interpolation can attenuate the acquisition footprint that is often observed in 3D datasets, especially at early times. An example of footprint attenuation is shown by the reduction of periodic linear noise between the timeslices before and after 5D interpolation in Figures 11 and 12.

The footprint in Fig. 11 is generally understood to be due to the stack responding to noise (probably shot-generated or backscattered noise) in a periodic fashion because of the periodic offset sampling that is inherent in the acquisition geometry. Therefore it may be that footprint attenuation occurs during 5D interpolation because interpolation has made the offset and azimuth sampling the same within all CDP gathers. This explanation assumes that the noise causing the footprint has been correctly interpolated by 5D interpolation. A counter-argument is that 5D interpolation has simply failed to interpolate the noise correctly that causes the footprint because its spatial variation is too rapid. With our measure of 5D leakage, we can try to resolve which argument is right.

Fig. 13 shows the 5D leakage from the 5D interpolation process. The footprint exists in the 5D leakage stack almost as much as in the stack of the input data in Fig. 11. If the interpolation had in fact interpolated the noise correctly, then that noise would have been accurately distributed through the interpolated traces after 5D interpolation. Therefore, the subsequent flip-flop interpolation of the original input traces would have interpolated that noise back to its original locations at the input trace locations,

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and that noise would have subtracted out of the difference traces (the 5D leakage traces). The fact that the footprint appears strongly in the leakage shows that the 5D interpolation in this case has not been fully able to interpolate the noise that causes the footprint: the noise is too complex (highly variable) to be predicted by the interpolator.

Although our present example clearly shows that the footprint is caused by noise which 5D interpolation has failed to interpolate accurately, we stress that other datasets may exhibit a footprint that is caused by an aspect of the signal that the algorithm *is* able to accurately interpolate (e.g., AVO, NMO, multiples). In such cases we would also observe footprint reduction after interpolation, but this reduction would be attributable to the homogenized offset and azimuth sampling rather than to a failure to interpolate the noise.

Discussion

The images of 5D leakage that we have included here are perhaps a surprising measure of how much information loss, in some situations, can occur during 5D interpolation. Nevertheless, 5D interpolation gives excellent results in most situations so the fact that 5D leakage exists should not necessarily be interpreted as a negative aspect of 5D interpolation. All interpolation methods have limitations, so all that we are doing is providing a method of defining what the limitations of 5D interpolation are. We have always known that 5D interpolation is not capable of working perfectly, yet it has been frustrating to be unable to know the exact limitations of the results. But now, with this measure of 5D leakage, we have a quantitative measure of the signal and noise that 5D interpolation fails to interpolate, so we are in a better position to assess the results of 5D interpolation.

Conclusions

We have presented a method for measuring the aspects of the signal and noise that are not interpolated correctly during 5D interpolation. This technique involves an additional interpolation step whereby data at the original input data locations are interpolated using just the newly interpolated data from a normal 5D interpolation. It appears to provide an accurate measure of the energy leakage in the 5D interpolation process and it can be used to assess the output of any 5D interpolation algorithm (or any prestack interpolation algorithm, regardless of the dimension of the interpolation variables). Data examples were used to illustrate how 5D leakage may contain random noise, diffracted energy and coherent footprint noise.

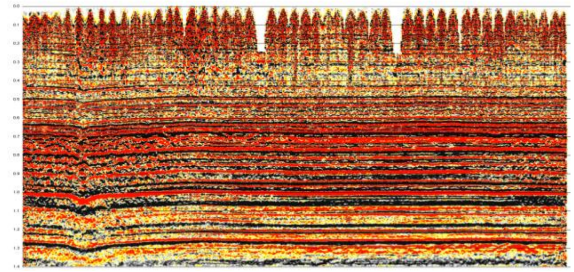

Figure 1: Inline of 3D stack before 5D interpolation

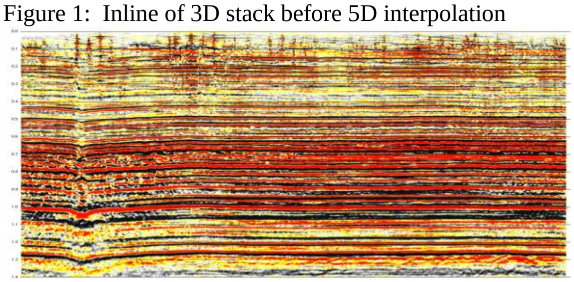

Figure 2: Inline of 3D stack after 5D interpolation

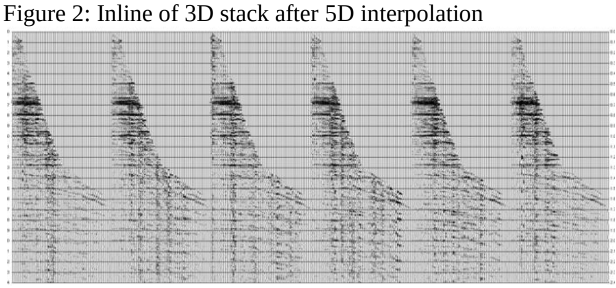

Figure 3: CDP gather (organized in six azimuth sectors) after interpolation.

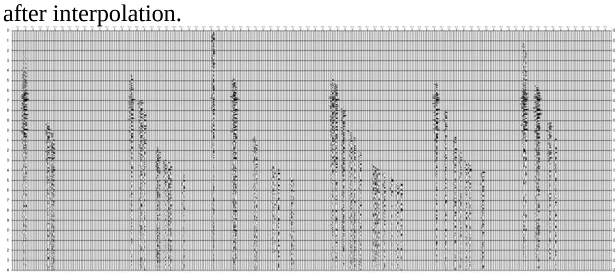

Figure 4: CDP gather before interpolation showing location of live input traces plus unoccupied trace locations.

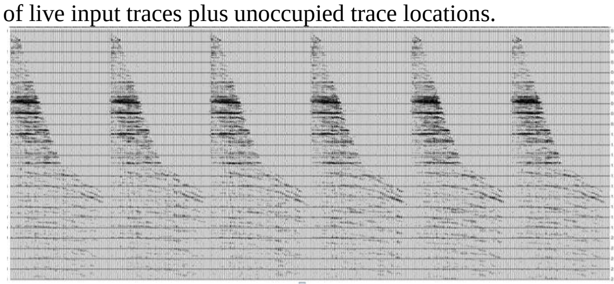

Figure 5: CDP gather after interpolating traces in the input trace locations with the 5D interpolated traces.

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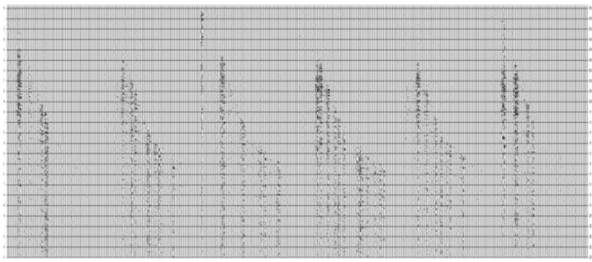

Figure 6: 5D leakage traces = difference between original input traces and traces at the input locations interpolated using the 5D interpolated traces.

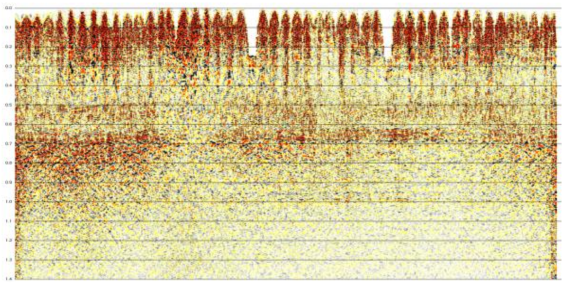

Figure 7: Stack of the 5D leakage showing noise, diffractions and an almost total absence of reflections.

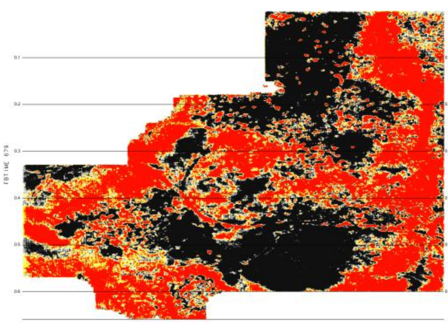

Figure 8: Timeslice of 3D stack before 5D interpolation.

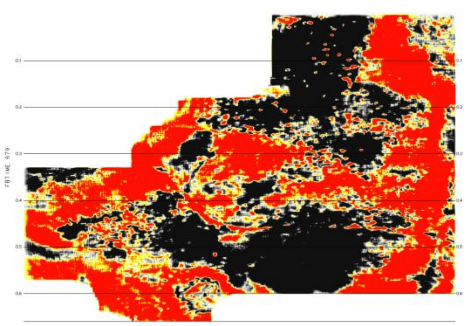

Figure 9: Timeslice of 3D stack after 5D interpolation.

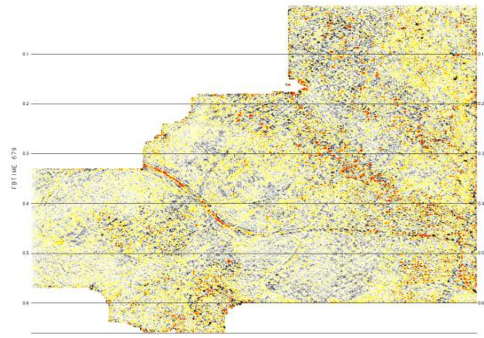

Figure 10: Timeslice of 3D stack of 5D leakage traces.

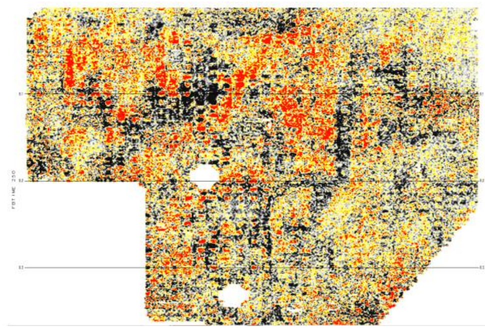

Figure 11: Timeslice before 5D interpolation showing footprint

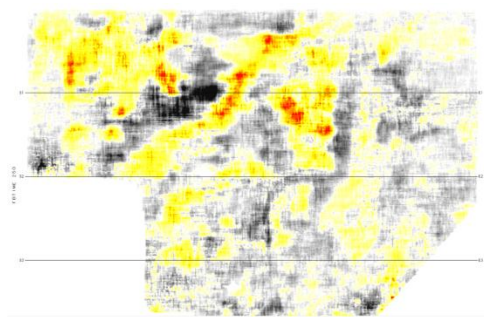

Figure 12: Timeslice after 5D interpolation.

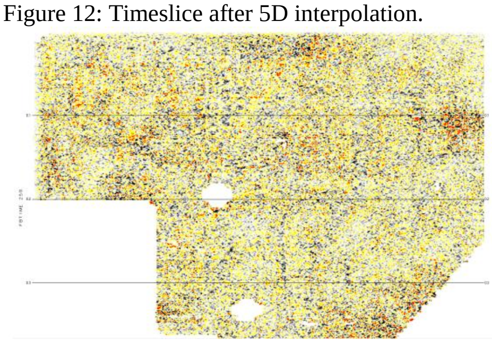

Figure 13: Timeslice of 5D leakage showing mostly footprint noise.

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EDITED REFERENCES

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