A new surface-line method for 5D interpolation of orthogonal surveys

Charles Ursenbach, Beng Seong Ong, and David Wilkinson, TGS*

Summary

Existing 5D methods fall into two categories, surface-consistent and subsurface-consistent. In the first, seismic traces are interpolated or regularized into a grid of source and receiver lines. In the second, the target grid is defined by CDP bins and either offset vectors or offset/azimuth pairs. Each of these approaches has advantages and disadvantages. In this study we introduce a novel 5D approach, called surface-line 5D, which bridges these two categories and incorporates certain advantages of each. The target grid in this case is composed of both CDP bins as well as source lines and receiver lines for an orthogonal survey. This is sufficient to maintain surface-consistency, while also focusing on a subsurface CDP grid.

Introduction

Five-dimensional interpolation has become established as a standard technique in seismic processing of 3D surveys. As described in reviews by Trad (2009, 2014), two major categories of 5D interpolation techniques are surface-consistent and subsurface-consistent. In the surface-consistent case, source-receiver interpolation (SRI) is performed on source and receiver positions, while in the subsurface-consistent case, it is performed on inline (IL) and crossline (XL) values and either offset vectors (for offset-vector interpolation (OVI)) or offset and azimuth (for offset-azimuth interpolation (OAI)). Each method has different strengths. For instance, SRI preserves source and receiver identities, which is useful for certain processing steps, and can also be a good preconditioner for wavefield migrations, such as RTM. On the other hand, subsurface-consistent methods preserve structure during regularization, and serve as a useful preconditioner for Kirchhoff migration, amplitude analysis, etc.

In this study we explore a new type of 5D interpolation, which we call surface-line interpolation (SLI) and which straddles the surface-consistent and subsurface-consistent paradigms. In particular, we interpolate using IL and XL as well as source line (SL) and receiver line (RL). As detailed below, this still provides a basis for interpolating missing traces, but with the potential of combining benefits of both standard approaches.

We describe the method for a regularized SLI. We then present results from a land field survey and find that it successfully preserves source and receiver identities and yields surface-consistent results similar to those of SRI. We also describe how it enhances efficiency of interpolation relative to SRI.

Method

We implement the surface-line concept in the context of Minimum Weighted Norm Interpolation (MWNI; Liu & Sacchi, 2004). This begins with a 1D FFT of each seismic trace. Each frequency slice then occupies a 4D space of the remaining variables where the actual interpolation occurs. Binning of the spatial variables to a regular grid is required, as MWNI assumes an ideal acquisition layout. (Application of MWNI to irregular geometries is an important issue but is outside the scope of this study.) Following the notation of Trad (2009), MWNI consists of minimizing a cost function $J = \|\mathbf{d} - \mathbf{Tm}\|^2 + \lambda\|\mathbf{m}\|_{\mathbf{W}}^2$ for each frequency, where $\mathbf{d}$ is input data, $\mathbf{T}$ is a sampling operator, $\mathbf{m}$ is fully sampled model data, and λ is a trade-off parameter. Both terms are L_2 norms, the latter being spectrally weighted.

The MWNI algorithm above applies to all techniques (SRI, OVI, OAI, SLI) described in the previous section. How they differ is in the size and organization of the model space, according to the four spatial variables chosen to represent trace configurations. These determine post-interpolation locations. For instance, in SRI, sources and receivers remain in an orthogonal acquisition pattern, while for OVI the shot and receiver gathers are effectively broken up into very dense shot and receiver lines. For the new SLI method, IL, XL, SL, RL variables are employed, and this preserves the original orthogonal acquisition pattern. How this happens is illustrated below in a discussion of interpolation blocks.

The entire 4D space for a typical survey is too large to interpolate in one operation, so it is divided into overlapping 4D blocks; these are individually interpolated and then summed with appropriate weights. We illustrate below the structure of these blocks, highlighting the effect of each method on source and receiver locations after interpolation.

Interpolation blocks – surface-consistent SRI

For surface-consistent SRI, each 4D block comprises a patch of sources in 2D SL-SS (source station) space and a patch of receivers in RL-RS (receiver station) space. Figure 1 illustrates three such patches.

Interpolation blocks – subsurface-consistent OVI and OAI

For subsurface-consistent interpolation, each 4D block comprises an IL-XL patch of CDPs and a patch of either offset vectors or offsets and azimuths. If the CDP patch is sufficiently small, all traces contributing to it may be included in a single block. This has the advantage of

Surface-line 5D interpolation

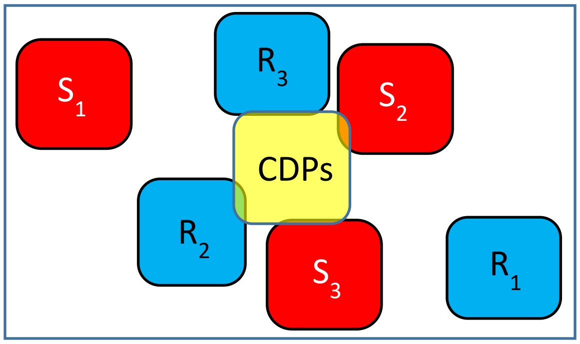

Figure 1: Illustration of three 4D blocks in a 5D surface-consistent interpolation. Each block (indicated by the subscript) is composed of a patch of sources (red square) and a patch of receivers (blue square). All three blocks happen to share the same CDP coverage (yellow square), but other blocks can have different CDP coverage.

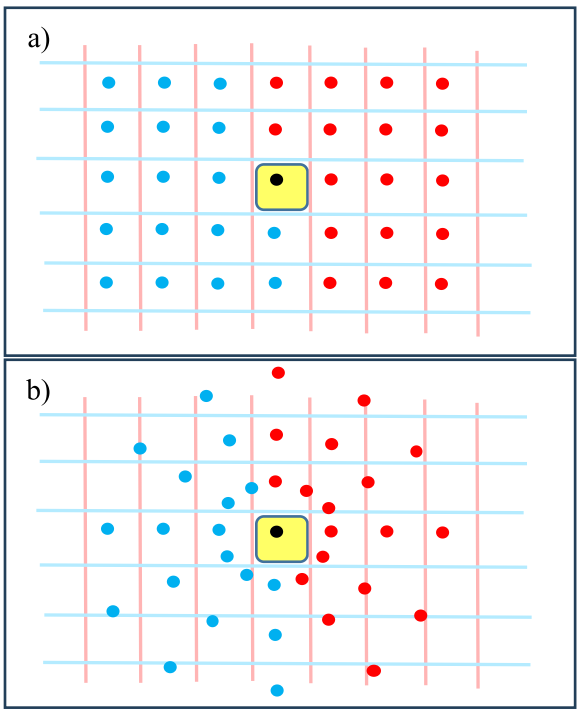

Figure 2: Illustrations of subsurface interpolation blocks for a) offset vector interpolation (OVI) and b) offset / azimuth interpolation (OAI). Original source and receiver lines are shown in light red and blue. Sources (red dots) and receivers (blue dots) are shown for a single CDP location (black dot) in the CDP patch (yellow square) for this block. Each CDP location is associated with a similar set of sources and receivers slightly shifted. For clarity, reciprocity (a common assumption in 5D interpolation) is invoked. These diagrams demonstrate both the advantage that all the traces for a small CDP patch can be included in a single block, and the disadvantage that source and receiver positions are shifted and lose their original identity, even for a perfectly ordered survey.

focusing maximal information on a subsurface region with minimal variation. For such a case, Figure 2a illustrates a block after binning for OVI, and Figure 2b for OAI. For clarity, sources (red dots) and receivers (blue dots) are shown for only a single CDP location (black dot) in the patch. The original source and receiver lines are shown in light red and blue to highlight the disadvantage that, in subsurface binning, sources and receivers are shifted and lose their original identities, even for an ideal survey.

Interpolation blocks – surface-line method

For the new SLI method presented here, each 4D block comprises a patch of CDPs (as in the subsurface case) and a (SL, RL) patch. Each (IL, XL, SL, RL) coordinate corresponds to a single trace. Figures 3-6 contain diagrams to represent the nature of these blocks.

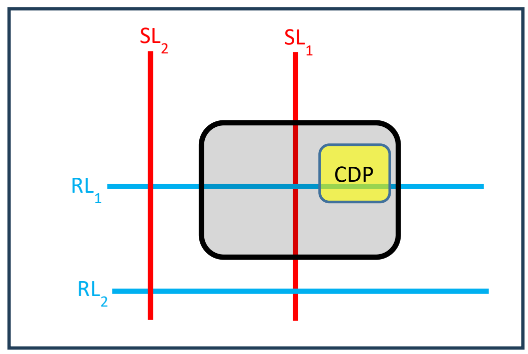

Figure 3: Each interpolation block will contain an IL-XL patch (yellow square). Every (SL, RL) pair is associated with a cross-spread of CDP locations (grey square). If a particular cross-spread includes the IL-XL patch, then the block can contain that SL and RL. In this diagram, RL_1 and SL_1 would be included in a block for the indicated IL-XL patch. RL_2 and SL_2 would not be included, as they have no cross-spread regions that intersect the CDP patch.

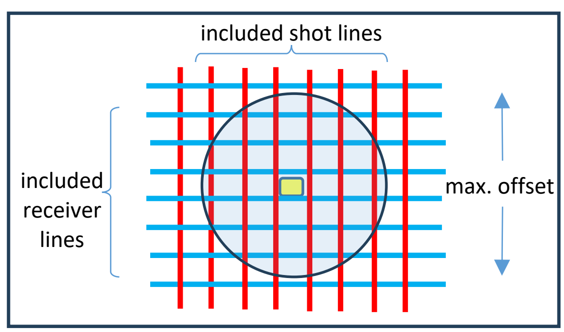

Figure 4: For each 4D (IL, XL, SL, RL) interpolation block, up to [(max. offset) / (SL spacing)] shot lines could be included, as well as up to [(max. offset) / (RL spacing)] receiver lines. These numbers can be small enough that tiling may not be required for SL and RL coordinates.

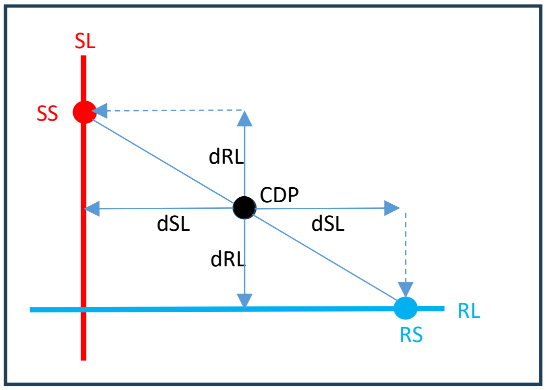

Figure 5: For regularly ordered data, a CDP gather can contain one trace for each (SL, RL) pair. The perpendicular distance from the CDP bin center (black circle) to the RL (dRL) determines a unique shot station (SS) in the opposite direction. Similarly, the distance to the SL (dSL) determines a unique receiver station (RS).

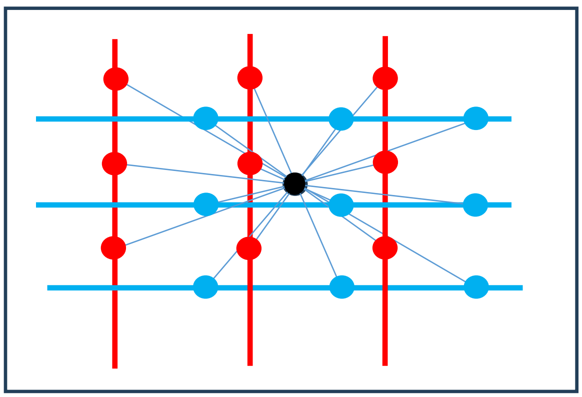

Figure 6: This diagram illustrates a CDP gather composed of one trace for each (SL, RL) pair. The black circle represents a CDP bin location, and red and blue circles represent shot and receiver stations that contribute to the gather. These station locations can each be determined using the method in Figure 5. Each CDP location within an interpolation block's IL-XL patch will contribute a similar gather. This shows that sources and receivers in an ideal acquisition do not need to be moved in binning, and thus retain their surface consistency.

By comparing the traditional interpolation methods illustrated in Figures 1 and 2 to the new surface-line interpolation illustrated in Figures 3-6, we have described the potential of this new method to combine the strengths of surface-consistent and subsurface-consistent methods. In particular, using IL and XL variables allows the interpolation option to focus maximal information on subsurface regions with minimal variation, while at the same time preserving source and receiver locations and surface-consistency. We now present an example using SLI as described above, and discuss the efficiency of SLI.

Results & Discussion

Our data example is taken from the 400 km^2 West Kermit land survey in the Delaware Basin. Figure 7 shows the effect of surface-line interpolation (SLI) on the positions of the resulting traces. Our objective in this case is to fill holes in the original ideal grid, not to infill with new lines (although could also be done). Thus, as expected, missing shots and receivers are interpolated to regularized positions. A key result is that the acquisition pattern is maintained. Line spacing is of course preserved, as SL and RL are variables of the interpolation. However, it is significant that the same is true for station spacing, as anticipated by the discussion in Figure 5.

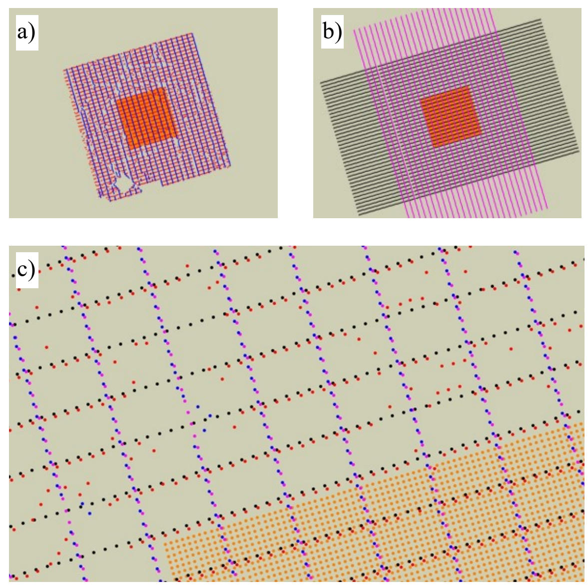

Figure 7: a) Example of input data (red = sources, blue = receivers, orange = target CDP area). b) Corresponding output data from surface-line interpolation. c) Zoom of both input and regularized output for surface-line interpolation (red = input sources, black = output sources, blue = input receivers, magenta = output receivers; for comparison, orange = CDP locations which are the subsurface target for this interpolation). This illustrates that the pattern of the ideal acquisition grid is preserved in surface-line interpolation, even though it does not use the information from source and receiver stations. Rather, station locations are reconstructed after interpolation as described in Figure 5.

Below we display stack images from a portion of the West Kermit survey, comparing the two surface-consistent methods. Figure 8a shows a stack of data input to the interpolation, Figure 8b shows the result of source-receiver interpolation, and Figure 8c shows the result for surface-line interpolation. For further perspective, Figure 9 displays gathers from the center of the stacks in Figure 8.

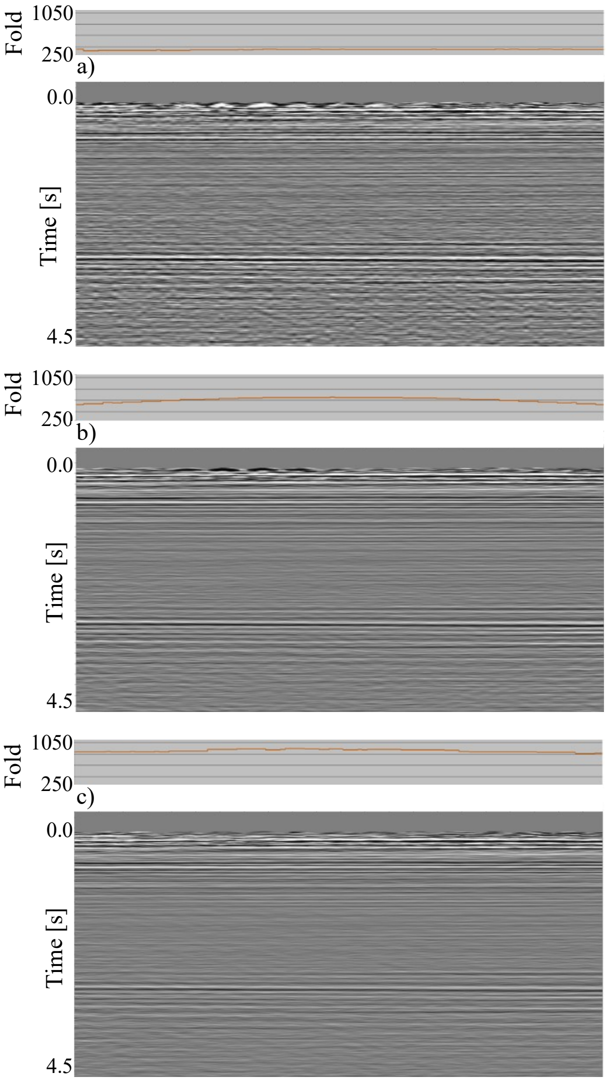

Figure 8: Stacks of three different datasets: a) Input to the interpolation. b) Source-receiver interpolation. c) Surface-line interpolation. The orange curve in the header indicates stacking fold.

The SLI and SRI methods show comparable results in the figures above. However, efficiency considerations show an advantage of the SLI method in general. To show this in a simple way, we compare two hypothetical interpolations in which each interpolation block has n^4 grid points, with n points in each dimension. Given CDP bin width Δ, the area of a target CDP patch in SLI is $n^2\Delta^2$. To determine the CDP patch area for SRI, assume shot and receiver station spacings are 2Δ, and line spacings are $2p_S\Delta$ and $2p_R\Delta$, where p_i is the ratio of line and station spacing. Then the shot and receiver patch areas would be $4p_Sn^2\Delta^2$ and $4p_Rn^2\Delta^2$. By geometry, the area of the CDP patch generated by these would be $[(2\Delta\cdot n+2p_R\Delta\cdot n) / 2]\ [(2\Delta\cdot n+2p_S\Delta\cdot n) / 2] = (1+p_R)(1+p_S)n^2\Delta^2$.

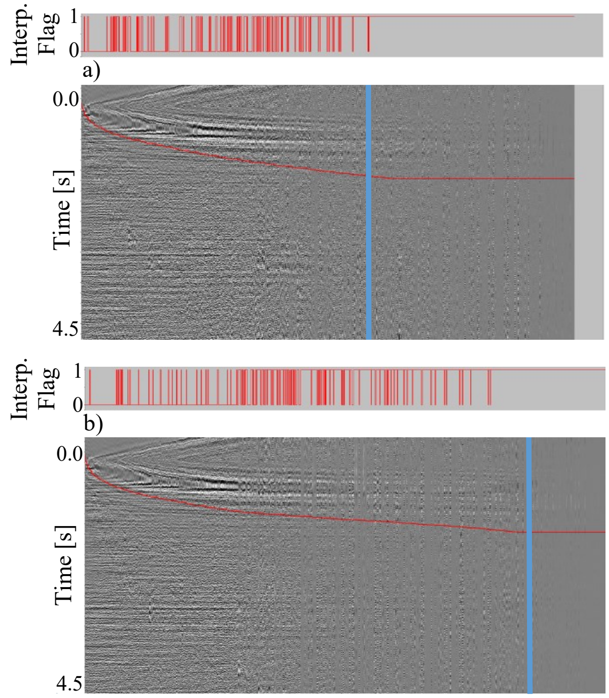

Figure 9: Prestack gathers for a) source-receiver interpolation and b) surface-line interpolation. The red curve in the header is 0 for original traces and 1 for interpolated traces. The red curve over the data indicates the stacking mute. The blue vertical lines indicate the offset cutoff used for stacking. In the surface-line case, low amplitude traces past the blue line correspond to extrapolated far offsets observable in Figure 7b above.

In Figure 7c $p_S = 4$ and $p_R = 6$, so in this hypothetical case the CDP area for SRI would be 35 times as great as for SLI. This ratio will vary with actual block parameters, but in normal cases will be markedly greater than unity. The significance of this is that interpolating over a smaller subsurface region with the same number of input traces increases the ability of the algorithm to faithfully interpolate traces, especially in more structured areas. OVI and OAI possess this advantage of focusing maximal information on a minimal subsurface area; SRI has an advantage of preserving surface consistency; and SLI bridges these interpolation methods, combining the advantages of each.

Conclusions

We have explored a hybrid approach to 5D interpolation that bridges the surface-consistent and subsurface-consistent paradigms. We have demonstrated that interpolation using IL, XL, SL and RL variables yields surface-consistent results comparable to those of traditional source-receiver interpolation. Furthermore, this approach has interpolation efficiencies of subsurface-consistent algorithms. This motivates further investigation into this novel method.