B-07 Model-driven data interpolation vs. velocity knowledge uncertainties.

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Abstract

Model-driven data interpolation performed by continuation algorithms (i.e., 3D SMO – Shot MoveOut), exploits the redundancy of the prestack data to regularize/densify survey geometries. Their usual Kirchhoff-type kernel implies that the accuracy of interpolation results is directly linked to the coverage of the operator itself [2], then coverage must be properly defined. A simple scalar index (e.g., fold of coverage) is not enough as it does not account for uneven dip illumination.
Moreover, the sensitivity of the continuation operators to velocity model errors depends on the continuation distance. Its analytical expression derived in [4] allows the definition of a criterion (interpolation strategy) to automatically select the most appropriate input gather. Interpolation strategy represents a trade-off between high dip coverage and low sensitivity to velocity knowledge uncertainties. Furthermore, the proposed criterion can be exploited as a support for the design of the survey, as it depends on survey geometry only.

Introduction

During the acquisition stage, obstructions, cable feathering, economic constraints and many other factors cause seismic data to be sampled in sparse and irregular fashion. This introduces noise/artifacts that can limit the resolution of the final image.
Model-driven seismic data interpolation can improve the quality of the seismic processing as it leads to dense/regular surveys without increasing the acquisition costs. Data Continuation algorithms [4] (i.e., SMO, AMO – azimuth moveout, DMO – dip moveout) are prestack model-driven operators that interpolate prestack data, by transforming the geometry of the seismic traces. Although the continuation operators can be reduced to be velocity independent, the underlying assumption is that the NMO correction is performed with the correct velocities. The analysis of the sensitivity of continuation operators to velocity uncertainties (although it is a usually neglected topic) is of outmost importance to achieve high quality interpolation results for real acquisition geometries.

Continuation operators' coverage spectrum

The Kirchhoff-type implementation is preferred for all the algorithms that have to deal with irregularly sampled data. As the practical implementation of any Kirchhoff integral operator leads to the computation of a numerical integration over a sampled hypersurface, the quality of a seismic acquisition geometry with respect to the processing sequence can be evaluated by the analysis of the stacking surface. However, the concept of coverage must be updated to a definition of fold that is consistent with the stacking performed by continuation operators. The definition of coverage for 3D SMO, Cov_{SMO} (or for any continuation algorithm) can be given by extending the *DMO Coverage Spectrum* introduced by Ferber [3]. Cov_{SMO} depends on the fraction of traces that interfere constructively to interpolate the data. This depends on the dip and azimuth of the events to be imaged, and it should take into account the finite bandwidth of seismic data. Let $t_{SMO}(\Delta\mathbf{S},\Delta\mathbf{R};h_2,t_2)$ be the SMO time and $t_{NMO}(\mathbf{S}_2,\mathbf{R}_2;\theta,\alpha)$ the two-way *NMO*-corrected traveltime (where the target event is characterized by its dip θ and azimuth α, and subscripts 1,2 indicates input and output traces respectively). The definition of *SMO Coverage Spectrum* is [4]:

$$Cov_{SMO}(t_2,\mathbf{S}_2,\mathbf{R}_2;\mathbf{S}_1,\mathbf{R}_1,\theta,\alpha)=\sum_{\forall(\mathbf{S}_1,\mathbf{R}_1)}\left\{\Delta t_{SMO}(\Delta\mathbf{S},\Delta\mathbf{R};h_2,t_2)<1\big/4f_{MAX}\right\} \quad (1)$$

the time shift $\Delta t_{SMO}=|t_{SMO}-t_{NMO}|$ depends on the geometrical parameters only and f_{MAX} is the maximum (or dominant) frequency of the seismic data. Differently from [3], we assume that any input trace contributes to the hit-count (1) if Δt_{SMO} corresponds to less than a quarter of the wavelength (i.e., the maximum acceptable phase error is π/2 rad).
The coverage is helpful to:

1. evaluate a seismic acquisition geometry with respect to the SMO processing sequence (this highlights the areas of poor dip illumination);
2. analyze SMO impulse response to compute the required dip coverage as a function of f_{MAX}. This aspect is illustrated in fig. 1 for the continuation of a horizontal reflector ($\theta=0^o$): the attainable vertical resolution (in Hz) is computed when considering only displaced reflections (or equivalently displaced prestack isochron tangencies [2]).

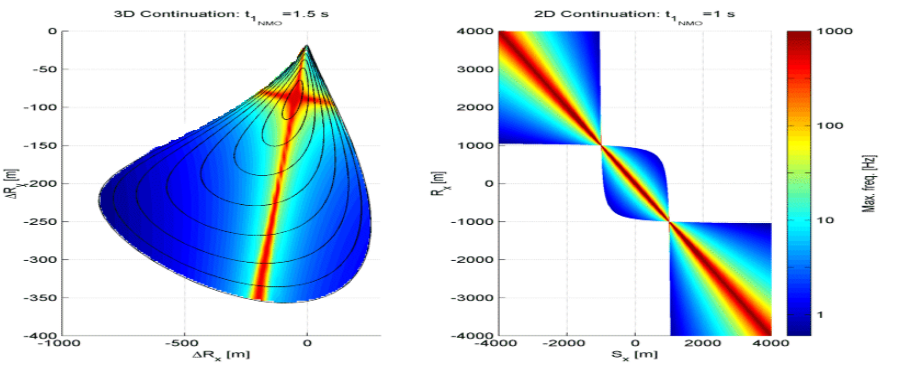

Figure 1. Maximum frequency of the seismic data that contributes constructively to the horizontal reflection (t_{NMO} =*const*) for displaced isochron tangencies: 3D SMO (left) and 2D SMO (right).

Sensitivity to velocity model errors

The structural shot continuation operator 3D SMO is velocity independent, as the velocity correction can be carried out as a standard NMO correction. Indeed, if *NMO*-corrected data show residual moveouts, 3D SMO becomes velocity dependent even if the velocity v does not appear explicitly. In practice, the velocity model is estimated from the data with a degree of uncertainty. Moreover, the analytical formulation of 3D SMO implies a constant-velocity model: lateral velocity variations are interpreted as velocity model errors. Thus, the analysis of the sensitivity of the continuation operators to velocity model errors is of outmost importance to understand the limits of their applicability. The analytical expression of the traveltime error $\Delta^2_{SMO}=t_2'^2-t_2^2$ (t_2' and t_2 are the output traveltimes obtained by the wrong

($v_{err}=\varepsilon \cdot v_{true}$) and correct ($v_{true}$) velocities respectively), due to the incorrect knowledge of the velocity is [4] (γ_{SMO} indicates the SMO time scaling):

$$\Delta_{SMO}^2 = \frac{\varepsilon^2 - 1}{\varepsilon^2} \cdot \frac{1}{v^2} \left(4h_2^2 - 4h_1^2 \cdot \gamma_{SMO}^2 \right) \quad (2)$$

The sensitivity of the 2D and 3D SMO to velocity model errors depends on the offset difference between input and output traces (the maximum frequency of the seismic data that can be correctly handled by 2D SMO is shown in fig. 2 for $v_{err}=95\%\ v_{true}$).

The maximization of Cov_{SMO}, with the constraint that the data can be reliably interpolated in presence of velocity knowledge uncertainties, requires a proper selection of input gather (interpolation strategy). Interpolation strategy plays a key-role to increase the accuracy of continuation algorithms output, as shown in fig. 3. The corresponding operator coverage values, also sketched in fig. 3 (top row), prove how interpolation strategy dramatically improves the imaging results. The input gathers are restricted only to those data that are required for complete illumination (coverage spectrum) and are less sensitive to velocity model errors.

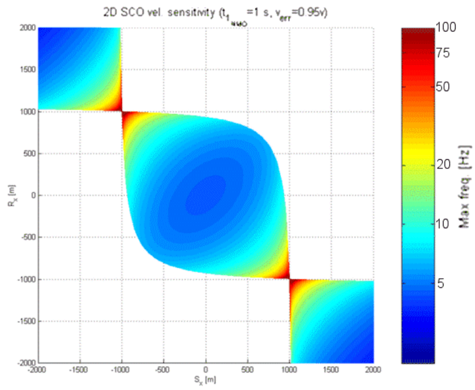

Figure 2. Maximum frequency of the seismic data that can be correctly handled by 2D SMO (the corresponding phase error is π/2) for $v_{err}=0.95v$ (input trace geometry [$S_{1,x}$, $R_{1,x}$] =[-1000 m, 1000 m]).

Survey design by continuation operators

A fundamental issue related to seismic processing is how to parsimoniously choose an optimal distribution of sources which is able to extract the maximum subsurface information. Actually, if seismic data can be estimated by the neighboring traces (under the hypothesis of a partial knowledge of the velocity model), 3D SMO processing can partially relax the spatial requirements for the acquisition in field, thus allowing a reduction of the acquisition costs. The equivalence of the acquired traces and the 3D SMO interpolated traces has been proved for imaging purposes by the comparison between estimated and real data [2]. Thus, the *SMO Coverage Spectrum* (constrained by a velocity model error) can be proposed as a criterion for evaluating acquisition geometries. The aim of the proposed analysis is not the design of an acquisition geometry from scratch, but by the analysis of the Cov_{SMO} we can:

1. evaluate the need of a re-shooting in the field;
2. compare the actual acquisition geometry to its nominal design (thus evaluating the effects of sources and/or receivers mispositioning);
3. evaluate the expected resolution for the interpolated data.

The "3D SMO interpolability" criterion is interesting because (as the operator itself) it depends on acquisition geometry only. With respect to other approaches for the evaluation of acquisition geometries [1], it does not need a detailed velocity macro-model, but it depends on a simple estimate of the uncertainty of the knowledge of the velocity field.

Conclusions

The sensitivity of continuation operators to velocity model errors has been analyzed by deriving the corresponding analytical expression. This allows to define an interpolation strategy that enhances the results of model-driven interpolation algorithms. The input gathers are automatically selected as a trade-off between illumination requirements (maximization of the *SMO Coverage Spectrum*) and minimum sensitivity to the velocity model errors. The results on field data prove how the proposed data selection algorithm plays a key-role to improve 3D SMO prestack interpolation. Since it depends on geometry only, it can be also proposed as a criterion to evaluate the feasibility of re-shooting in the field.

References

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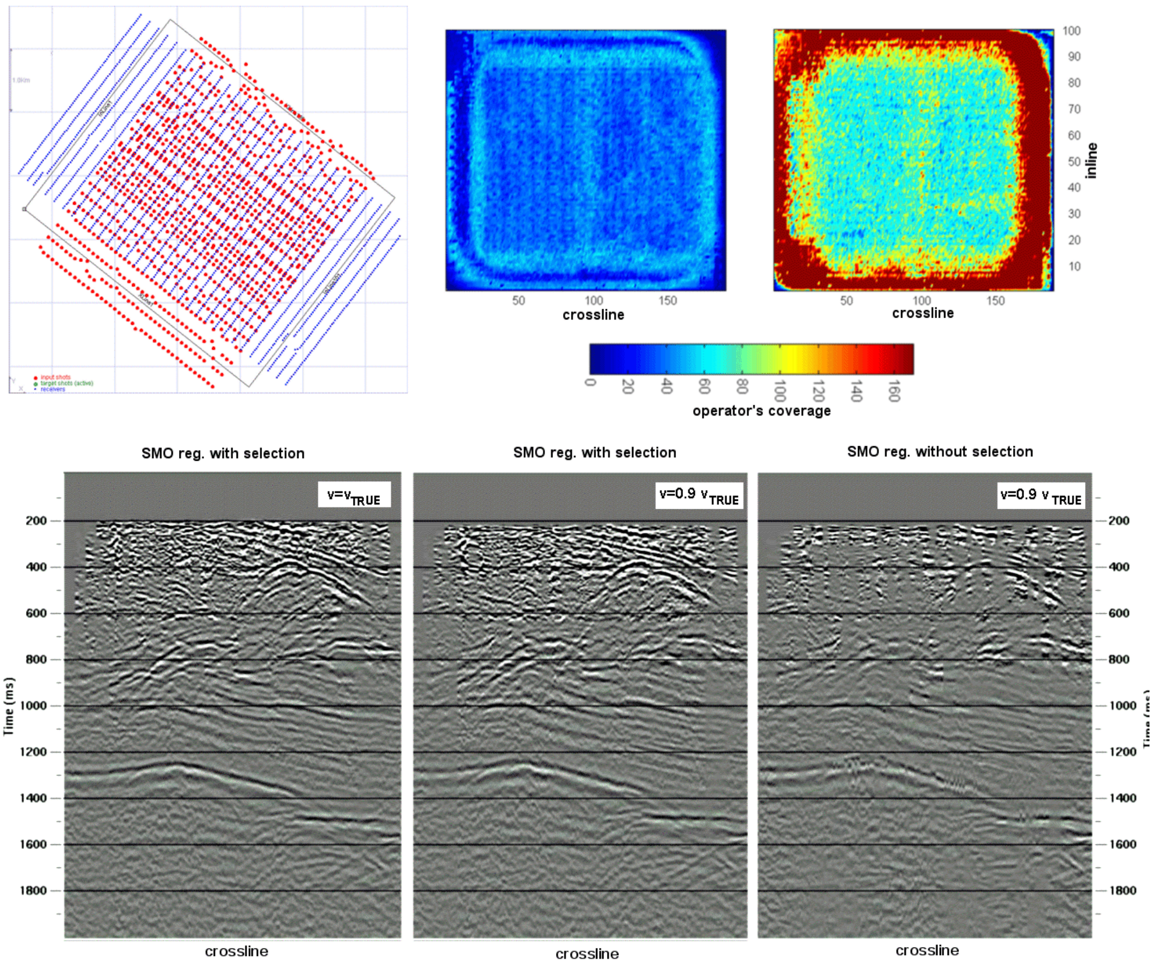

Figure 3. Top-row – *Left:* acquisition geometry. ***Middle:*** operator coverage at t=1 s, when applying the proposed interpolation strategy. ***Right:*** operator coverage at t=1 s, without applying the proposed interpolation strategy. **Bottom-row -** selected inline from common offset/common azimuth volume ($|\mathbf{h}|$ =360 m, $\alpha=0^o$), created by 3D SMO. ***Left:*** benchmark data, obtained by using the correct velocity field $v_{rms}(x,y,t)$. ***Middle:*** interpolation results obtained with the wrong velocity $v_{err}(x,y,t)$ and the interpolation strategy (based on eq. (2)), that assures both minimum sensitivity to velocity model errors and dip illumination. ***Right:*** interpolation results obtained with the wrong velocity $v_{err}(x,y,t)$ **without** data selection.