TECH LINK

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Seismic Regularization

Summary

PGS has a comprehensive toolkit of regularization and interpolation technology that will help improve the imaging of all types of data and, in the case of 4-D data, the repeatability between data vintages.

This discussion describes the increasing sophistication of solutions, beginning with 4-D and multi-azimuth binning and progressing through to Radon and Fourier regularization.

Introduction

Seismic datasets are generally irregularly sampled in inline midpoint, cross-line midpoints, offset and azimuth. This irregular sampling can lead to both poor levels of repeatability between 4-D surveys and artifacts in pre-stack imaging. Irregular sampling can also limit the effectiveness of high-end 3-D demultiple and imaging algorithms such as 3-D SRME and wave-equation PSDM. To overcome this issue in seismic data processing it is common to use regularization and interpolation. Although precise definitions vary, it is common to describe the process of *regularization* as being that which transfers samples from their irregular recorded location to locations on a regular grid. Extrapolation is generally held to be a process where new traces are created outside the range of the input data, while interpolation entails the creation of new traces "in between" existing traces. In this article we will describe PGS' technology that can be used to undertake these processes.

Figure 1 schematically describes the main areas of seismic processing in which interpolation and regularization have an impact although it is probably true that no significant seismic dataset is processed without the application of at least one interpolation and/or regularization method.

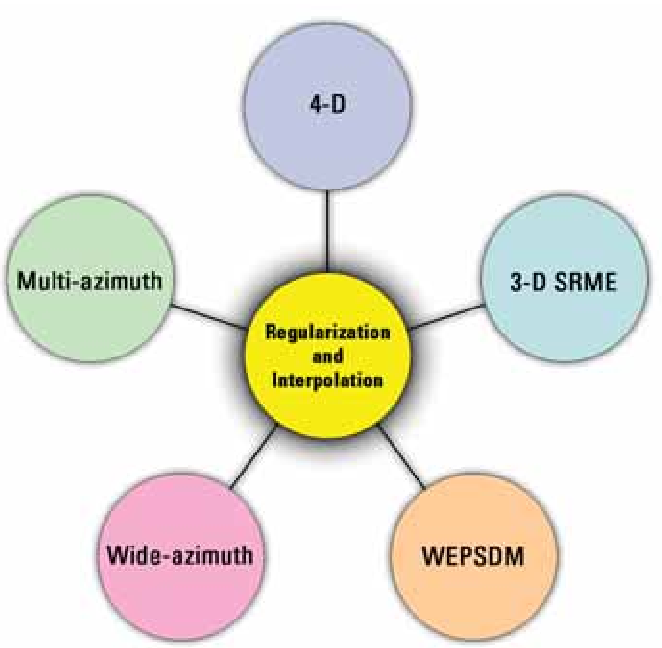

Figure 1: Schematic diagram showing the areas of major use of regularization and interpolation.

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There are several methods for regularization and interpolation, and these have different characteristics. A comparison of some of the characteristics is shown in **Table 1.** Flex-binning used to be the main method in the

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Method	Assumptions	Exact Positions Used	Interpolation beyond Aliasing	Interpolation for 4-D	Characteristics
(Flex)-Binning	Local 1-D assumption	No	No	Good with new capabilities	Cheap
DMO/DMO^{-1} AMO	Model needed	Yes	No	Moderate	Some expensive
***f-k/f-x/f-x-y* Interpolation (dealias, fxintr,fxyintr)**	Limited number of dips present in data	(Flex)-Binning	Yes	Moderate	Fast. Not optimal for larger gaps.
Sparse Radon Interpolation (*Sprint*)	Limited number of dips present in data	Yes	Yes	Good	Fast! Handles conflicting dips & large gaps
Fourier regularization (*reg1d, Reg3da*)	Band-limited data & predominant azimuth	Yes	Partly (in offset direction)	Very good	More costly

Table 1: Comparison of characteristics of the interpolation and regularization technology available from PGS.

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seismic processing industry to handle empty bins, but nowadays it is much more common to use some form of amplitude and dip-friendly interpolation (such as Sparse Radon Interpolation - *Sprint*). DMO, inverse DMO and in particular AMO can be used if a correction of azimuths is needed. *f-x* and *f-x-y* techniques are typically used to interpolate regularly sampled data to a finer grid. *Sprint* is the method of choice in case of larger gaps and can also be used to interpolate to a finer grid, but it does not regularize the existing traces. If the existing traces are also to be regularized (typically put in the middle of the bins), a combination of *Sprint* and Fourier regularization (in two or three dimensions) can be used.

Flex-binning used to be the most commonly used form of regularization, having the advantages of being fast and relatively simple to use. More recently it has been predominantly used to normalize the acquisition differences between surveys of different vintages in 4-D datasets or to optimize the azimuthal coverage within a bin in multi- or wide-azimuth datasets. PGS' binning capabilities come with a wide variety of QC tools allowing easy comparison of different flexed bin sizes. In addition, the selection of each trace can be weighted during the process according to a number of user-specified criteria (for example, by streamer). PGS' binning has the capability to compare two or more surveys. To fill empty bins or to select traces if there are more than one in a bin, it is possible not only to look at the closest trace but also to use a wide variety of additional criteria, in particular offset or azimuth to select the traces that will reduce the difference between the two surveys. Naturally, as noted previously, the main drawback of flex-binning is its inability to handle dipping data.

Pre-stack partial migration (in the form of forward and inverse DMO or AMO) is another common form of data regularization and interpolation. PGS offers either a single-step AMO algorithm, or a split forward and inverse DMO method which allows the inclusion of some form of data QC and manipulation between the two steps of data movement.

f-x and *f-x-y* algorithms can interpolate traces on a regular processing grid. PGS offers a variety of interpolation options including two 2-D interpolation schemes (providing interpolation beyond aliasing) and a fast 3-D interpolation algorithm (again including interpolation beyond aliasing). Note that the algorithms generally work well in the presence of noise and at all dips.

Fourier and Radon regularization methods have a variety of applications, and are often used in combination with Sparse linear Radon interpolation (*Sprint*). These methods take into account the exact (irregularly sampled) cross-line midpoint positions and do not use a geophysical model concerning the data or subsurface and preserve amplitudes. *Sprint* is used to interpolate (fill in) the data in larger gaps, can interpolate beyond aliasing, and is extremely robust in the presence of bad or noisy traces (For example, see **Figure 3**). Fourier regularization is used for bin-centering in the in-line and cross-line direction in common offset volumes. Fourier regularization provides excellent results for data that are sufficiently spatially band-limited, for gaps of one or two traces, as long as the data do not contain bad or very noisy traces. In fact, for well conditioned data Fourier regularization can be used to fill in gaps and regularize in one step. For noisy data and data with large gaps typically a cascaded approach is used where Sprint is used for filling in the gaps, and Fourier regularization for bin centering. Both methods have several options for header interpolation.

Regularization in 3-D is done with a two-step procedure. In the first step the offsets are regularized for each streamer in each shot record using Fourier regularization. In the second step the midpoint-x and y are regularized using multi-dimensional regularization with azimuth correction. This method is based on Fourier and Radon transforms and uses high-resolution inversion techniques for improved robustness (see below). After the second step the midpoints are exactly in the middle of the bins and the offsets are regularly sampled according to a

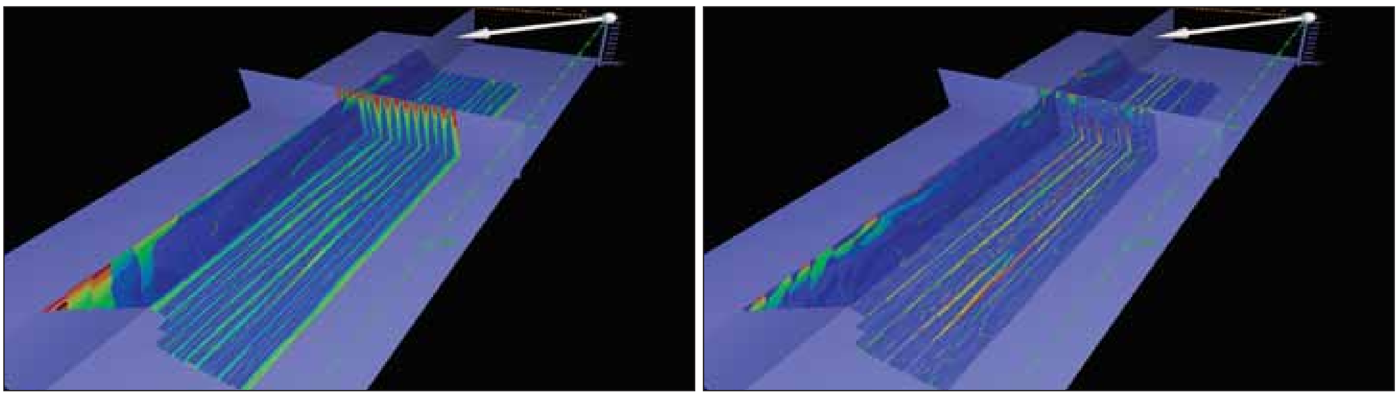

Figure 2: PGS' binning has the capability to compare two surveys. In these plots the azimuth differences between base and monitor surveys (the colour scale in which blue is small or no azimuth difference and red is high azimuth difference) is shown with conventional binning (on the left) and after (on the right) azimuth constrained binning. It is clear that the azimuth differences are strongly reduced by the azimuth constrained binning.

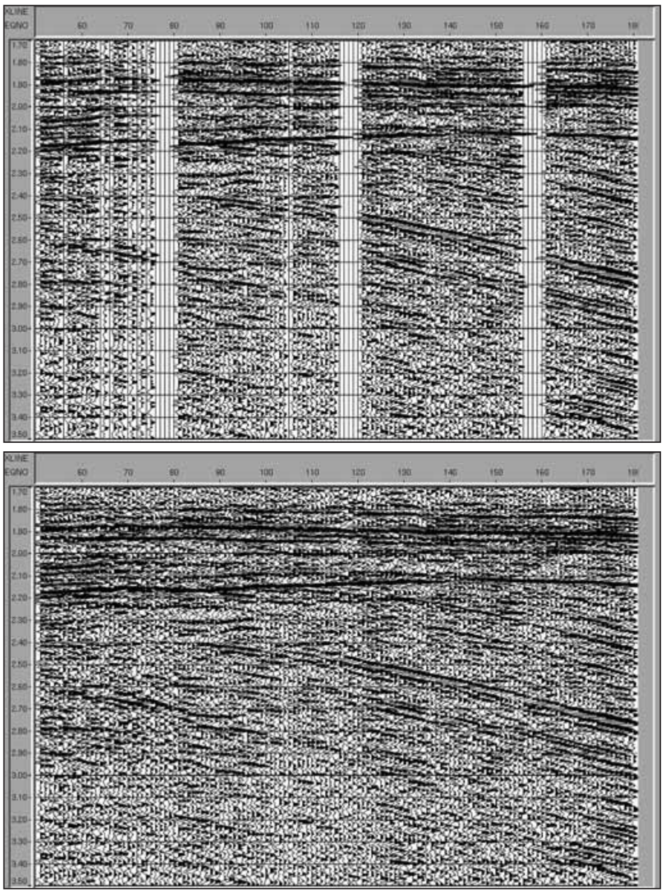

Figure 3: An example of Sprint (Sparse Radon Interpolation) being used to fill in large irregular gaps in a dataset.

user specified range; this results in a constant fold and offset distribution for all bins. The azimuths of the regularized data can also be specified by the user, or alternatively, no adjustment for the azimuths can be done, in which case the azimuths of the output traces are interpolated from the nearest input traces. Full wavefield regularization is particularly suited as a preprocessing step for imaging (see **Figures 4, 5** and **6**) and for matching the sampling positions of base and monitor surveys for time-lapse seismic.

So how does Fourier regularization work? The basis of the regularization methods is that the irregularly sampled data are transformed from the spatial domain to the Fourier or Radon domain, and then the data are transformed back to the regularly sampled spatial domain. The backward transform is straightforward: once the data are in the transformed domain then a standard inverse fast Fourier or Radon transform can be used to transform the data to a regular grid in the spatial domain. However, a standard forward discrete Fourier transform (DFT) will not yield optimal results if applied to irregularly sampled data. To improve upon the standard forward transform a least squares inversion of the inverse Fourier or Radon transformation is used. The inverse transforms require regular sampling in the transformed domain, but not in the spatial domain. Therefore, a high resolution inversion of the inverse-transform can be used to transform irregularly sampled data to the Fourier or Radon domain.

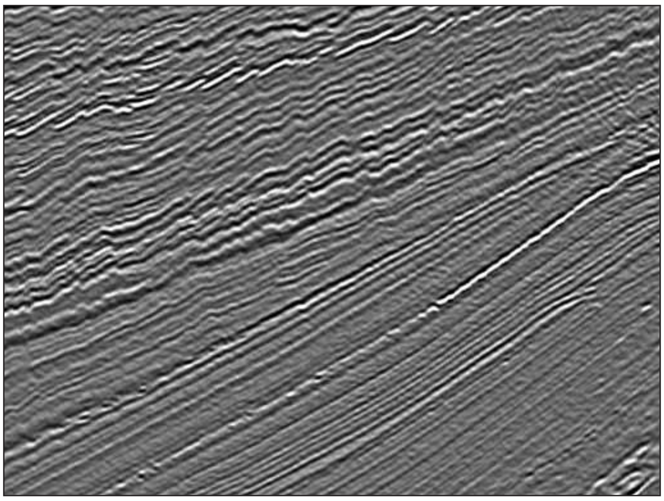

Figure 4: Vertical slice through a complex dataset before any form of bin-centering and hole filling.

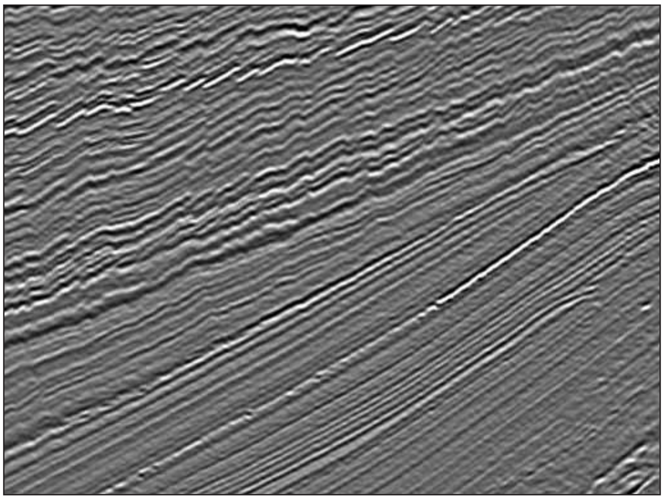

Figure 5: Vertical slice through a complex dataset after bin-centering using three-dimensional Fourier regularization with azimuth correction. Compare with the data shown in Figure 4.

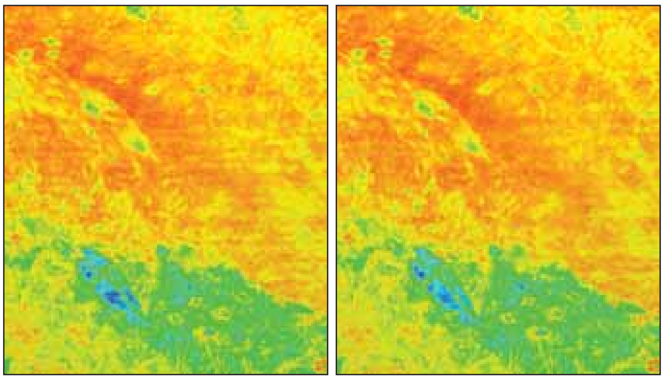

Figure 6: (a) Water bottom amplitude map with no regularization applied. (b) The same water bottom amplitude map after the application of three-dimensional Fourier regularization.

In the 3-D regularization procedure an optional correction for azimuth variation can be made. The azimuth correction is a dip and azimuth dependent time-shift, which can be included in the least squares 3-D linear Radon transform as described in Schonewille (2003). The time-shift is based on the formulation of Chemingui and Baumstein (2000). In contrast to simultaneous binning,

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which rejects many of the recorded data traces, the regularization approach uses all available data to generate an optimum pair of traces.

Regularization for 4-D datasets

For time-lapse data, one commonly applied approach to the issue of irregular sampling is to use some form of 4-D binning to homogenize the sampling in all vintages of the time-lapse data. The irregular sampling in midpoints and offset can also be regularized using Fourier or Radon based regularization, and, as discussed above these can optionally take into account azimuth variation. It can be shown that azimuth variations between vintages do significantly reduce or degrade the 4-D repeatability. If a dipping layer in a homogeneous subsurface is considered, and two traces are compared with the same midpoint and absolute offset, but different azimuths, then the reflection event will shift in time. The time shift is dependent on the dip-angle and direction of the layer, the velocity in the subsurface, the azimuth and the offset. Although these time shifts are small (typically in the order of a few milliseconds), for time-lapse data, where base and monitor surveys are differenced, even a time shift of 1 ms can lead to normalized RMS differences (NRSMD) of 18% (depending on the bandwidth). It is generally the case, therefore, that neglecting the azimuth is not ideal for time-lapse data, and either the azimuths have to be repeated for base- and monitor survey, or a correction for the time-shifts has to be done. In 4-D processing it is common to use statistical measures of the difference between surveys as a quality control measure during processing. The most commonly quoted of these QC attributes in normalized RMS difference (NRMSD); **Figure 7** shows a comparison between NRMSD statistics for various tests on a key horizon in the recent 4-D project. The NRMSD for a simultaneous 4-D binning approach is seen as the top histogram in **Figure 7**; the middle histogram shows the NRMSD when both vintages have been regularized using three-dimensional Fourier regularization with azimuth correction. The bottom histogram in **Figure 7** shows the NRMSD after application of three-dimensional Fourier regularization with azimuth correction and a water column statics correction. It is clear that the NRMSD measure is closer to the ideal situation (NRMSD = 0.0) after the application of a Fourier regularization method as opposed to the conventional simultaneous 4-D binning method.

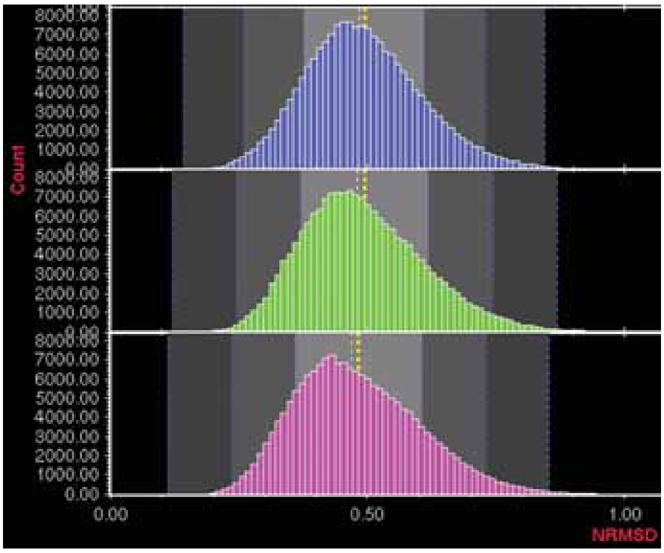

Figure 7: Normalized RMS difference (NRSMD) statistics for the example 4-D dataset for a key horizon on a single fold offset plane. The histograms show the NRMS for the data with simultaneous binning (top), 3-D regularization with azimuth correction (middle) and 3-D regularization with azimuth correction plus water column static solution (bottom).

References

Chemingui, N., and Baumstein, A.I., 2000, Handling azimuth variations in multi-streamer marine surveys. SEG Meeting Abstracts, 1-4.

Schonewille, M., 2003, Regularization with azimuth time-shift correction. SEG Meeting Abstracts, 1917-1920.

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