Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

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Summary
Three dimensional seismic data are acquired in five dimensions namely; shot-x, shot-y, receiver-x, receiver-y and time. These five dimensions can also be represented by inline, crossline, offset, azimuth and frequency. For narrow azimuth data, the dimensions reduces to four, as azimuth is assumed to be nearly constant. 5D interpolation techniques can interpolate simultaneously all space dimensions. Although interpolation is not a replacement for acquisition; nevertheless, 5D interpolation has proved to be quite successful in recent years. Seismic surveys usually have irregular area where data cannot be acquired due to various known or unknown reasons. Therefore missing data must be approximated from the acquired data or interpolated using an intelligent interpolation scheme either in time domain or any other domain. The 5D or 4D interpolation methods provide an opportunity to fill the data gaps. The interpolation methods also pave a way to reduce acquisition costs and further more improve the resolution of seismic images. In the present paper, the authors have used 4D interpolation to fill an acquisition gap for an area in Cauvery basin. Although the gap is unusually large, an attempt has been made to create an approximate data in the gap. The four dimensions used for interpolation are inline, crossline, offset and time/frequency. The fifth dimension, azimuth is dropped from the study because the acquisition gap occurs in the northern part where sufficient azimuths are not available. The algorithm is very slow for three and more dimensions (CGG Documentation). It is found that even 4D interpolation has provided reasonable results. For 4D interpolation, a module called “FREND” is used from the M/s CGGs software and the results are presented.

Introduction
Exploration for the development of hydrocarbon reservoirs may be efficiently done with the help of seismic data, which must be properly processed in order to allow interpretation of subsurface features. Generally, seismic data is acquired by using active seismic sources to inject seismic energy into the subsurface which is then refracted and/or reflected by subsurface features and recorded at seismic receivers. In many cases, the seismic survey is unable to acquire the data in a perfectly uniform manner, resulting in irregularly sampled data. This may be caused, for example, by obstructions in the survey area, errors in placing sources and receivers, cable feathering in marine acquisitions, and/or the use of non-uniform survey geometries such as coil shooting. These examples are not meant to be limiting; one skilled in the art will be aware that other causes exist. Some conventional methods for handling irregularly sampled seismic data include flex-binning, 3D linear interpolation, and local slant-stack interpolation. These methods may render the seismic data inappropriate for certain types of seismic processing such as tomography. Described herein are implementations of various approaches for a computer-implemented method for regularization of seismic data.

Theory and Method
A computer-implemented method for regularizing irregularly sampled seismic data, wherein the irregularly sampled seismic data has at least five dimensions including a first spatial dimension, a second spatial dimension, an offset dimension, an azimuth dimension, and a time or depth dimension; each trace of the irregularly sampled seismic dataset is assigned to a representative bin; each of the traces of the irregularly sampled seismic dataset is mapped to an offset vector tile (OVT) with a calculated center azimuth; an azimuth sector with all offsets of interest and a narrow range of the center azimuths from the OVTs is assembled; the azimuth sector is rotated from an original orientation to align the first spatial dimension and the second spatial dimension with an inline direction and a crossline dimension determined from a seismic acquisition geometry for the irregularly sampled seismic dataset; a subset of traces is selected from the rotated azimuth sector based on a single crossline value to create an irregular 3D

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Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

volume; the irregular 3D volume is regularized; the regularization is repeated for all crossline values to generate a regularly sampled azimuth sector; the regularly sampled azimuth sector is rotated back to the original orientation; and the operations are repeated for each azimuth sector to generate a regularly sampled seismic dataset. The regularization may include interpolation by an algorithm such as an anti-leakage Fourier interpolator. The regularly sampled seismic dataset may be used to characterize the subsurface by further processing such as tomography.

Most of the seismic processing methods require a uniform sampling. Regular sampling is also an important element of true amplitude preservation in processing. Irregular sampling can affect data analysis and introduce noise, phase and amplitude distortions and a degraded final image. Issue of an inadequate and irregularly sampled data is one of the most important problem in seismic data processing particularly while dealing with onshore datasets. Several techniques can be selected to reduce the problem of irregular geometry. The most powerful are 3D, 4D, 5D interpolation techniques, 3D interpolation, 3D flexi binning and local slant-stack interpolation.

The benefits of prestack interpolation are:
- Improves imaging
- Reduces migration smiles
- Enhances S/N
- Improves offset-azimuth distribution and
- Preserves amplitude relation for AVO and AVAZ.

In the case of merging datasets of different vintages regularization and interpolation can compensate the acquisition geometry differences.

In the time domain simple interpolation methods such as flexibining are used. These time domain methods fail as the distance between the traces exceeds the nominal dimensions of the bin. A class of algorithms such as Minimum Weighted Norm Interpolation (MWNI), Anti Leakage Fourier Transform (ALFT) and Matching Pursuit (MP) are based on the Fourier theory in the F-K domain by computing the estimated spectral frequency content of irregularly sampled data. All the algorithms have different flavours.

Five dimensional (5D) interpolation has been in the industry for several years and has been widely accepted and used. Multidimensional sampling is not easy to visualize and understand because different dimensions are linked through physics in complex ways. The seismic frequencies can only take a limited bandwidth along each dimension and are connected across dimensions namely inline, crossline, offset, azimuth and time or frequency in the seismic volume. The mechanism behind interpolation is to first remove artifacts produced by poor sampling such as aliasing and other types of noises from the spectra and then invert the spectra to predict seismic data at arbitrary locations. 5D interpolation requires algorithms that can generate large number of traces simultaneously. The first algorithm used in 5D was MWNI (Lin and Sacchi,2005, Trad, 2009). MWNI is still a popular algorithm because of its efficiency and amplitude preservation. These features come as a consequence of using regular grids after 4D binning which permits the use of Fast Fourier Transforms (FFTs). This enables the algorithm to infill large gaps since it can handle large datasets simultaneously. The main issue of irregular data sampling is that there are leakages which arise as Fourier basis functions are no longer orthogonal. As a result there is a cross talk between different spatial frequencies in the measured spectrum which is refered as leakage. In other words energy from one Fourier coefficient leaks onto others. Since time dimension is sampled regularly, there is no leakage between frequency slices, The transformation from data to spectra is performed by an operator with close to orthogonal properties (Trad, 2009), it achieves an almost perfect fit to the input data in few iterations, which leads to excellent amplitude preservation. By contrast, algorithms that use discrete Fourier transform on irregular grids instead of FFTs have operators that are more difficult to invert.

In the present paper, the authors have used 4D interpolation to fill an acquisition gap for an area in Cauvery basin. Although the gap is unusually large, an attempt has been made to create an approximate data in the gap. The four dimensions used for interpolation are inline, crossline, offset and time/frequency. It is found that 4D interpolation has provided reasonable results. For 4D interpolation, a module called “FREND” is used from the M/s CGGs software. The module has two options to regularize/interpolate seismic data, one in F-K domain and the other in Tau-P domain. The F-K domain can handle 2-4 dimensions whereas the Tau-P domain 2-3 dimensions. In the present study, the seismic data has been regularized and interpolated in F-K domain using 4D interpolation.
Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

During regularization process, two approaches can be used:
Regularize seismic data to a survey different from the original that is to bin centers where the mid points are not naturally places, which means that the original measurements will be modified, for example the shot and receiver coordinates
Stay close to input geometry by keeping the original traces in order to minimize the distortions and interpolate. The objective of reconstruction of pre stack data is to fill the gaps in acquisition geometry, regularize data to bin center on a regular grid and improve offset distribution.

The important parameters to interpolate data in 4 dimensions are:
Interpolate in a domain or choose a domain in which seismic events look simple and sampling is dense
Use long operators to provide the algorithm/mathematical engine with enough information to predict the new traces in large gaps.
Adapt to the acquired geometry to avoid data movement for large distances from recording locations.

For 4D interpolation, the module FREND uses Anti Leakage Fourier Transform (ALFT), proposed by Xu et al 2004. ALFT is an iterative procedure for computing the spectrum of irregularly sampled data. The ALFT estimates Fourier components in two ways
Beginning with the one with the maximum energy and proceeding down to the one with the minimum energy (Fig.1)
After each coefficient is estimated, it is effectively removed from the input data.
To be more specific, the ALFT minimizes spectral leakages with the following steps:
1. Compute all Fourier coefficients with irregular transform
2. Select the Fourier coefficients that have maximum energy
3. Subtract the Fourier coefficients in step 2 from the input data
4. Use this new data as input for steps 1, 2, 3 iteratively until all coefficients are found.

In effect we first solve for most energetic Fourier coefficient assuming that it causes most severe leakage. To attenuate all aliases and leakages of this component onto other Fourier coefficients, data component corresponding to it must be substracted from the input data.

Inspite of being an efficient technique for irregular sampling, ALFT has its disadvantage in the computational cost.

![Fig.1. Irregular Frequency transform showing maximum energy peaks and spectral leakage from main events. The result of ALFT which has significantly reduced the spectral leakage.](image)

**Case study**

The following example shows interpolation scheme for some data gap from Cauvery basin.

It is common for 3D seismic data acquisition to have large data gaps with missing shots or receivers or both because of surface logistics or other reasons.
The land dataset used in this example was acquired using an orthogonal geometry with a bin size 20m X 40m. A large but irregularly shaped acquisition gap exists in the data. The gaps are 1000-1500m in diameter before interpolation. In the present study, the global method of interpolation strategy which uses all of the data simultaneously up to the aperture limit defined and models with many degrees of freedom. Therefore this algorithm is slow and harder to implement when constrained with processing system capabilities. Nonetheless, the method can interpolate large gaps by using information supplied from distant data (Trad, 2009).

In the example, a large operator size of 41 bins has been selected as spatial block size for the three dimensions namely inline, crossline and offset. These parameters have been optimized after several tests.
The large operator is justified because the dips in the subsurface are less than moderate in the time zone of interest which is 2.0 to 3.0 msec TWT. It is allowed the algorithm to decompose all the energy for maximum filling in the gap during mapping and
Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

inverse transform process. In some places the near offsets are not filled up. However, the far offsets which are essential for deeper events are interpolated and regularized.

Usually the time dimension is well sampled and only the spatial dimensions need to be interpolated. In the present study, 41 X 41 inlines and crosslines, 1000-1500m offsets are used as operators as the data gap is large. These large windows are required to deal with very sparse data.

After extensive testing, we have chosen 4 dimensions namely inline, crossline, offset and frequency with NMO corrected data.

4D interpolation is to be used after preconditioning of 3D seismic data and as the last stage before prestack time/depth imaging.

Interpolation acts as a random noise attenuator, because it can only predict coherent energy. Coherent noise on the other hand can barely be distinguished from amplitude variation and data complexity unless strong assumptions are imposed. However, it is advisable to suppress ground roll and all types of multiples before interpolation.

Seismic data is processed in overlapping spatio-temporal blocks. After temporal FFT, each frequency slice is transformed into spatial frequency domain with an irregular transform. The reverse transform reconstructs the energy to the bin centre or specified coordinates. For each dimension, processing block size in number of bins, taper size in number of bins are very important to fill the large gaps. Wave number percentage is a crucial parameter to avoid aliasing in the interpolation dimension along with apparent velocity of steepest dip in this dimension.

Minimum and maximum frequencies are selected from the signal bandwidth available in the data are needed for computation dips. It is very important to apply tapering both before and after interpolation to avoid ringing and edge effects between adjacent windows.
Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

Fig. 5. Inline 2550 before and after bin centering and interpolation. Purple lines indicate gaps in the data.

Fig. 6. Inline 2600 before and after bin centering and interpolation. Purple lines indicate gaps in the data.

Fig. 7. Inline 2626 before and after bin centering and interpolation. Purple lines indicate gaps in the data.

Fig. 8. Inline 2650 before and after bin centering and interpolation. Purple lines indicate gaps in the data.

Fig. 9. Inline 2700 before and after bin centering and interpolation. Purple lines indicate gaps in the data.

Validation of results

The interpolated volume is not migrated but stacked to have an idea how the data looks like in the data-gap area. Few 2D lines are passing through the data gap area (Fig.10) and the results after interpolation is compared with 2D stack data. Some inlines are reconstructed from the interpolated volume and with reference to the location of 2D lines and the results are compared. Fig.11 to Fig.13 shows that the results after interpolation are in good agreement with that of 2D data particularly.
Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

Fig. 10. 2D lines passing through the data gap depicted by the polygon

Fig. 11(a). 2D Line No:1

Fig. 11(b). Reconstructed line along 2D line No:1. The data in the black box is interpolated data.

Fig. 12(a). 2D Line No:2

Fig. 12(b). Reconstructed line along 2D line No:1. The data in the black box is interpolated data.

Fig. 13(a). 2D Line No:3

Fig. 11(b). Reconstructed line along 2D line No:1. The data in the black box is interpolated data.
Four dimensional interpolation of a 3D seismic dataset from Cauvery basin, India

Future Study

It is proposed to carry forward this work for interpolating the data using 5 dimensions including azimuth to see whether the near offsets can be filled up in the gap area for shallow information.

Conclusion

Regularization and interpolation is very important in optimizing land seismic datasets for imaging. The irregular sampling and data gaps commonly found in land surveys generate migration artifacts that makes the resulting images uninterpretable. By interpolating in 4D space, amplitudes can be reasonably predicted even in the large acquisition gaps for structural interpretation. One of the main advantages of using ALFT over other algorithm is that whole seismic data can be input in a single step rather than seperating it in different classes such as offset and azimuth. This saves the processors time and effort considerably.

References


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