Coherency enhancement on 3D seismic data by dip detection and dip selection

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Summary

Historically, 3D land data has been noisy when compared to 3D marine data. Recently we have witnessed the advent of high density recordings with folds in excess of 300 that help to reduce noise on the final images. However, low fold land 3D, mostly old vintage, is still commonly seen in processing shops and on interpreter's workstations. To pull signal from such post-stack data and, more challengingly, from even noisier pre-stack offset class data, is a challenge that this paper aims to address.

Introduction

Despite the advances in imaging techniques the main idea, "the power of stack", that Mayne (1962) introduced in relation to common reflection point stacking almost half a century ago, still seems to be the main workhorse for enhancing/detecting signal in low signal-to-noise ratio (SNR) data. It is well known that a fold of N brings about a signal enhancement by a factor $N^{1/2}$. When stack volumes of modern processing are still noisy enough to prohibit an intelligent interpretation of the data, as is sometimes the case with offset class data, one can resort to stacking along dip directions to pull the low amplitude signal buried under high amplitude noise. More specifically, if a small space window (of size N_x traces along x-direction and N_y traces along y-direction) around a location of interest (x,y) is considered then stacking this small cube along a dipping plane (dip p_x and dip p_y) of the signal acts as if fold has increased by a factor N_x*N_y. This corresponds to a signal enhancement by $(N_x*N_y)^{1/2}$. If all dips on the data are available through mechanisms like semblance analysis then all significant events can be enhanced along their planar dips (producing signal) and then this signal can be added back to original data by a user controlled amount to bring about the desired signal enhancement. Alternatively, if there are undesired but strongly coherent events on this data, then the signal model obtained in a specified dip range can be subtracted (not shown here) from the input volume to attenuate undesired dips.

Towards Spiky Tau-P Forward Transforms

Identification of various waves, arriving in a small set of sensors at angles corresponding to propagation angles, was first done by Rieber (1936). This was the first directional decomposition of seismic data, although it was done through the use of electrical analog processes. Slant stack of digital data along various dip directions (see, for example, Stoffa et al., 1981, Tatham et al, 1982) is the same as Rieber's method but achieved digitally. Slant stack, however, involves an inverse transform. Slant stack later became linear tau-p transform in an effort to make it invertible. Exact mathematical formulation of tau-p transform is given by Tatham (1984). Tau-p transform is known to enhance low temporal frequencies and a process, known in the industry as rho filter (time derivative), is generally applied to either forward slant stack, or, to inverse slant stack, or sometimes to both but with half strength. A rho filter response is a linear ramp in the frequency domain, being zero at DC and 1 at the temporal Nyquist. In Tatham's tau-p formulation, it naturally occurs as a result of change of variable from k to p (from wave-number to ray parameter) in the continuous infinite integral over space since k=f*p. Note that seismic data is neither continuous nor of infinite extent in space and this causes truncation effects due to finite spatial aperture of seismic data used in tau-p transforms. This effect was soon realized, and spatial tapers on input data were considered to lessen these artifacts. Further studies revealed that tau-p transform done in this manner for finite and discrete offset data was not an invertible transform. Least squares tau-p transform, later known as linear Radon transform (see Gulunay, 1990, Kostov, 1990), implicitly handled the rho filter issues, and truncation effects to some degree. Radon transforms, being based on the least squares fit idea, involve matching of input data to the dip model selected and use matrix inversions which are costly. Radon transform is invertible in the sense that forward + inverse of the data matches the original input data with great precision. However, it soon became clear that the Linear Radon transform was not sharp enough as two distinct events (dips) in the input domain interact in the forward domain. This means that trying to remove one of them results in some damage to the other one. This observation led to the development of a new process called high resolution Radon transform (see for example, Herrmann et al. 2000). Such methods aim to reduce the forward transform into spikes in the p direction. Between the development of linear Radon and linear high resolution Radon in the industry, Schneider et al (1996) presented a semblance weighted linear tau-p method to clean up noisy 3D data where they inverse transformed all p samples (traces) of linear forward tau-p transform after multiplying them with semblance, a process which obviously sharpens tau-p transforms.

Data construction from peak slant stack amplitudes

If the aim of High resolution Radon transforms is to make the tau-p response as spiky as possible then one can resort to just picking the peak amplitudes on the tau-p response and zero the rest as long as p-responses do not interfere.

To illustrate and so differentiate the method that we are proposing in this paper let us study Figure 1. This figure depicts a cube with two simple dipping events. The temporal wavelet residing on the events is shown as a spike but it can have any bandwidth and shape.

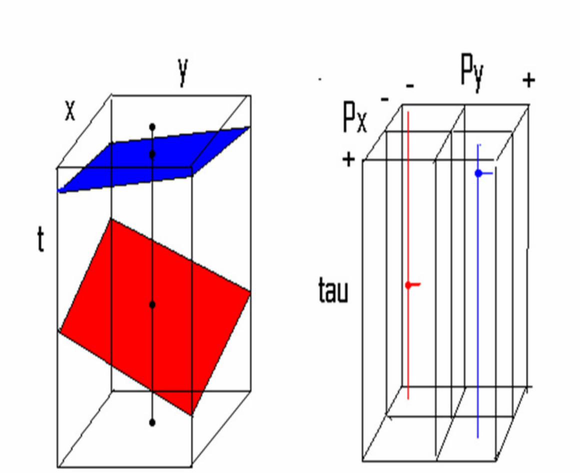

Figure 1 Two dipping planes and their desired 3D tau-p transform.

Although we depicted the plane waves to collapse on two (p_x,p_y) points (but at different times tau) the tau-p transform of these plane waves is never quite a spike along p directions. This is because seismic data has a finite spatial extent causing loss of sharpness in the forward domain. In this particular application where we are going to be very local to support the plane wave assumption, the size of the data cubes is around 10, or so, traces in the inline and in the crossline direction. Therefore severe data truncation effects and loss of p resolution are expected. This well-known phenomenon is depicted in Figure 2.

Note that each event has a horizontal smear which is due to truncation effect at zero offset, and a slanted one which is due to the maximum (finite) offset. Although the amplitude of these smears (or. "wings") is small when compared to the amplitude at the points where they cross each other (blue dots in Figure 2), they nevertheless cause problems when one wants to keep one event and delete the other one.

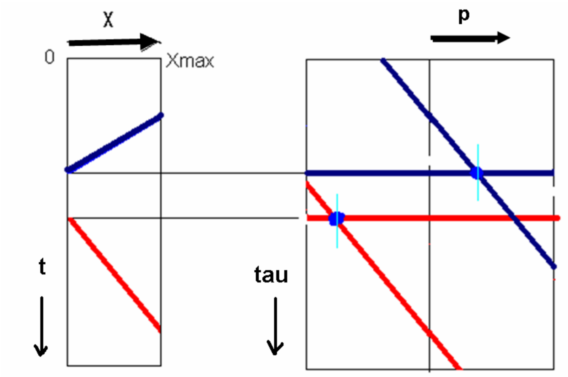

Figure 2 Finite spatial aperture causes data smear in the forward tau-p domain.

Inverse transforming all of the p-samples around these points (dots) also cause the amplitude distortion (hence the need for the rho filter or least squares or high resolution Radon) on the inverse data. Some of this distortion can be suppressed by methods like semblance weighting (Schneider et al. 1996). Note that, assuming p sampling is fine enough, the wavelets residing on the events (left hand side of Figure 2) are identical to the wavelets residing on the corresponding peak p traces (i.e. correct p traces, where the arms cross each other). This observation leads us to suggest using only one p trace (one (p_x, p_y) point in 3D) per event where events are forced to be distinct (a dip separation is imposed on them while picking events). Note also, however, that there will be many events for one input cube and they all can be picked by the method. Obviously picking the peak p trace causes loss of lateral amplitude variations (resolution) but it bypasses the wavelet spectral distortion issues (i.e. such a method does not need rho filters). One can argue that if one can not see any events on the input data then one may not care if lateral resolution is lost or not.

Of course these p_x-p_y points where energy concentrates must be detected to be selected, but this can be done automatically by checking if points are significant local maxima on some function. This function could be the semblance cube. It is possible to obtain a semblance value at each output point by obtaining a squared amplitude sum at each tau and along each dip direction (each p_x,p_y pair is a direction) while creating the summed amplitudes (slant stack) corresponding to right hand side of Figure 1. Each semblance value is indeed the measure of the coherency of the interpolated samples on the plane corresponding to the tau-p_x-p_y (like the red or blue plane in Figure 1) value we are at. The semblance cube can then be used to detect the most coherent tau-p_x-p_y points in the volume, or most energetic p_x-p_y traces. The method, although not as powerful in that mode, can also be used for 2D lines or for 3D lines in two pass mode (inline and then crossline or vice versa).

Field data example

We illustrate this process on a multi-vintage merged transition zone 3D survey as shown in Figure 3.

The data were acquired with many different source types and configurations over an area that included some environmentally sensitive zones towards the coastal margins. This resulted in severe access problems, with the consequence of a highly irregular shooting and recording geometry which was compounded by a lack of far-offset data, due in part to the multi-vintage acquisition, which could otherwise be used to undershoot this poor access area (Figure 4). Additionally, the individual source effort in this area had to be reduced to respect the environmental considerations. Explosive sources, where they were permissible, were only a fraction of the nominal charge elsewhere on the survey, and similarly the vibrator sources had to be used on reduced drive levels. The net result of these local limitations to the acquisition was very low fold data of exceptionally poor SNR.

After careful initial processing, which paid particular attention to phase-matching the many different sources and receivers, the resolution of surface-consistent statics through a cascaded refraction and reflection solution, and a variety of pre-stack de-noise strategies, the data were processed through a Kirchhoff pre-stack time migration. The resultant post-migration offset cubes could then be used for 3D de-noising which, due to the acquisition, was not possible earlier in the processing sequence. The 3D coherency enhancement algorithm described here was used to good effect in this area Elementary blocks of 12 x 12 traces in windows of 500ms were selected, with 50% overlap in time and space. 50% of the model was added back to produce the final image.

A time slice (at 972 ms, and, corresponding to the area shown in Figure 4) for the offset class 700-799m is shown in Figure 5. Noisy character of data is evident in the time slice. Figure 6 shows the same time slice after the data went through coherency enhancement method described in this paper. Suppression of noise took place leading to a clearer picture of the time slice. Vertical sections (crossline 30) before and after the process are shown in Figures 7 and 8 respectively. Random as well as coherent noise suppression (of dips exceeding what is allowed during the forward tau-p_x-p_y transform) is evident in Figure 8.

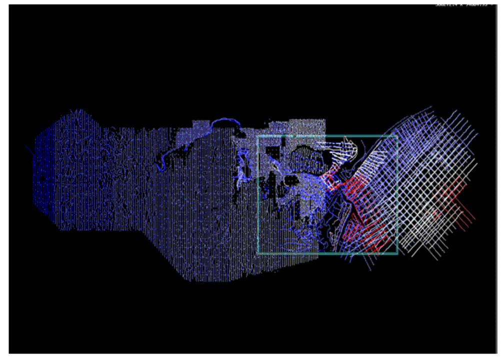

Figure 3 Surface map of the merged surveys

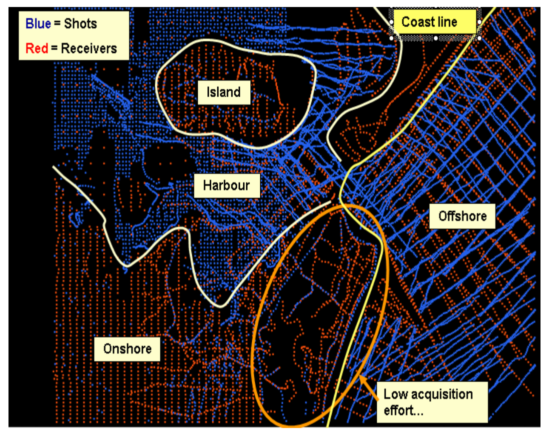

Figure 4 Zoom of the surface map corresponding to the rectangle of in Figure 3. It corresponds to 300 inlines (horizontal axis) and 200 crosslines (vertical axis) shown in Fig 5.

Conclusions

Low fold 3D seismic data, especially, offset class cubes, that are encountered in land or transition zone surveys can benefit from the signal enhancement method described here. The method is based on transforming the data in small time space cubes into forward tau-p domain and then selecting the most coherent events in that domain. Once such events are identified (automatically) then they are inverse transformed by only keeping one p (or p_x-p_y) sample point per event. That is, the inverse tau-p transform is nothing but the propagation of distinctly separated p traces back to input offsets (back projection) and blending with the input.

We described the method and illustrated its use on an offset class of a merged 3D survey volume.

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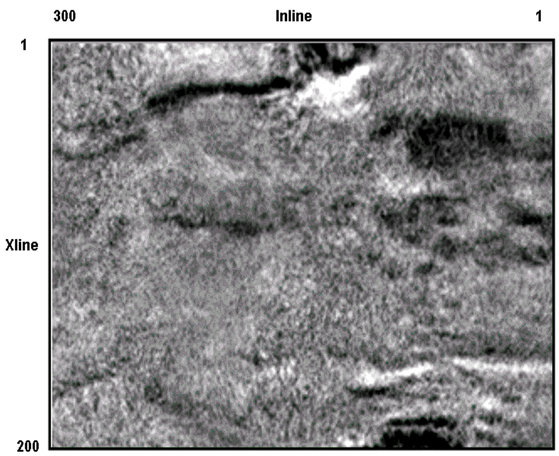

Figure 5. A time slice (at 972 ms) of the one offset class (900m-999m) of the merged survey

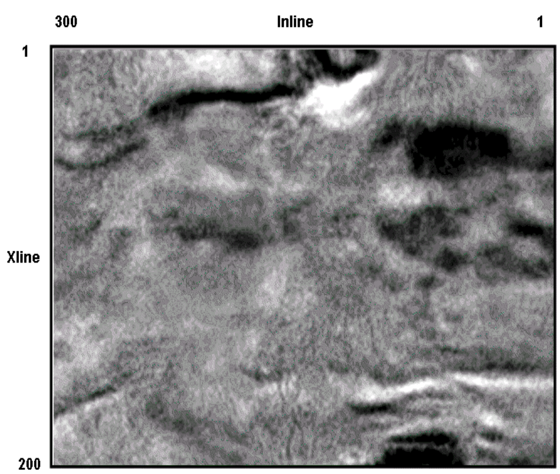

Figure 6 Same time slice after 3D coherency enhancement

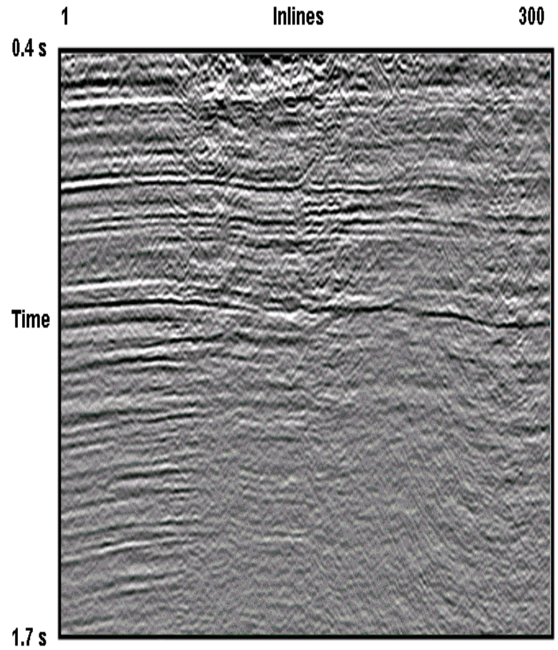

Figure 7 Crossline 30 before 3D coherency enhancement

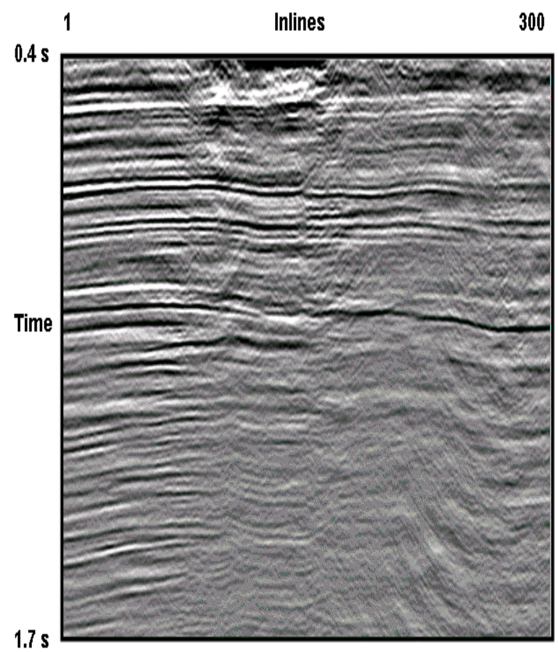

Figure 8 Crossline 30 after 3D coherency enhancement

EDITED REFERENCES

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