SEPARATION AND IMAGING OF SEISMIC DIFFRACIONS

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Introduction. Diffracted and reflected seismic waves are different physical phenomena originating from different kinds of subsurface features. Usually, in seismic exploration, the focus is on seismic reflections because they carry most of the information about subsurface.

However, sometimes the goal of seismic processing consists in identifying small subsurface features (e.g. faults, fractures and rough edges of salt bodies) or small changes in reflectivity. In all these cases it is diffracted waves which contain the most valuable information (Kanasewich, and Phadke, 1988; Landa and Keydar, 1998). Over the last decade there has been an increasing interest in using diffractions as a direct indicator of different kinds of discontinuities. The energy carried by diffractions can be also used to refine velocity models (Harlan et al., 1984; Landa et al., 2008; Reshef and Landa, 2009). Tsingas et al. (2012) proposed to use diffraction imaging as a tool for helping interpretation in fractured reservoirs.

Typically diffracted energy is one or even two order of magnitude weaker than reflected one and often it is not easy to distinguish the diffracted events in a full dataset or to identify the image of diffractors in a full seismic migrated image. Therefore, diffractions have to be separated from reflections for imaging or other kind of processing and this still represents one of the main issues when handling diffractions.

Several approaches were proposed for the separation of reflections and diffractions, and several different domains were used for this purpose.

Khaidukov et al. (2004) take advantage of the different propagation properties of the waves. The recorded wavefield is focused back to the imaginary source location in a pseudo-depth domain and then the reflections are muted out. After defocusing of this muted data they obtain a wavefield where reflection events have been suppressed. Taner et al. (2006) show how to separate reflections and diffractions using plane-wave constant p sections. In this domain reflection energy can be filtered out by the method of plane-wave destructors (PWD) (Claerbout, 1992; Fomel, 2002). Separation of diffractions and reflections and imaging of diffractions by dip-filtering via the same PWD operator, but this time in the post-stack migrated domain, is discussed by Fomel et al. (2007).

Separation in the post-migration dip-angle gathers, where reflections always have a concave shape (Audebert et al., 2002) and diffraction have a different shape (horizontal if migration was performed with the correct velocity) has been proposed by Landa et al. (2008) and Reshef and Landa (2009).

In this work we analyze separation of diffractions in the migrated image domain via two algorithms belonging to the last two mentioned methodologies. First we analyze the peculiarities of the separation via dip-filtering of the migrated image. We introduce a different filtering technique based on the local image gradient. Then we illustrate the properties of the dip-angle common image gathers and we analyze the behavior of this domain in the context of separation of diffractions. Finally, we propose to combine these methodologies in an original technique that aims to take advantage of both. The effectiveness of the method has been tested on both synthetic and field datasets. Here we show an example on the synthetic Sigsbee dataset.

Separation of diffractions via dip-filtering in the depth image domain. The first studied technique is a variation of the method proposed by Fomel et al. (2007) which performs separation of diffractions by dip filtering in the post-stack domain.

The use of dip-filtering in the depth migrated image domain as a method for separating diffractions is based on the underlying assumption that, in a migrated section, reflections are imaged as strong coherent events with a dip that changes with continuity. On the contrary diffractions are imaged as very localized coherent events that do not show any identifiable dip.

Thus, once the events that show clearly identifiable and slowly variable dip are removed, the remaining coherent events are interpreted as diffractions.
The result of dip filtering is an image that shows an approximation of all those events that do not follow the dominant trend of dips. Therefore we can use this result as an estimation of the migrated image of the diffractions. Even in the case of incorrect migration velocity the diffractions can be identified and separated by this methodology because they appear as little “smiles” (in the case of overestimated migration velocity) or “frowns” (in the case of underestimated migration velocity) and they still do not follow the dominant trend of dips. This peculiarity means that, after the separation of diffractions, this domain could be suitable for a velocity analysis based on the focusing of diffraction events.

Fomel et al. (2007) use the method of plane-wave destructors (Claerbout, 1992; Fomel, 2002) for dip filtering. In our study we use a different filter based on the gradient squared tensor (GST) as a tool for dip estimation (van Vliet and Verbeek, 1995), because of the easier parametrization, the lower computational complexity, and the presence of a dip coherency output.

GST exploits the eigenvectors of the dyadic product of the gradient vector with itself \((g \cdot g^t)\) to estimate the local slopes. The additional feature of dip estimation by the GST method is that it gives the coherency of the local estimate as an auxiliary output, originally called “anisotropy” (van Vliet and Verbeek, 1995). The value of the local dip coherency varies from 0 to 1. A value of 0 corresponds to a perfect isotropy: no dominant dip has been clearly identified, therefore the estimated dip value is not reliable. A value of 1 means that the local neighborhood of the examined point exhibits the same behavior; therefore the estimated dip is very reliable.

Local gradients, GST eigenvectors and local dip coherency can be used to build very accurate dip filters (Hale, 2007), which can be used to properly enhance or remove events showing a certain dip, respectively emphasizing coherent events or revealing underlying information (residual image).

This methodology works quite well in eliminating reflection events. However, the residual image can also contain noise, effects of uneven illumination, edge effects due to limited migration aperture and other kinds of spurious events besides the desired diffractions.

**Separation of diffractions in the migrated dip angle domain.** The second methodology studied consists in separation of diffractions and reflections in the dip angles domain at the depth point.

Among the well-known reflection angle common image gathers (CIGs), it is possible to obtain, as an output of the migration process, the so called dip-angle CIGs which show the image of the events as a function of the imaged reflector’s dip (i.e. the dip of the vector obtained by summing the incident and the reflected slowness vectors). The dip-angle CIGs have been used as a tool for equalization of illumination in depth migrated images, for true amplitude migration (Audebert et al., 2000), for optimal migration aperture estimation (Bienati et al., 2009) and for velocity analysis (Reshef and Ruger, 2005).

In this domain we are essentially looking at the direction in which the incident energy is sent back. In the case of a reflector the wavefield follows the Snell’s law, therefore it is sent back in a single direction, which is univocally identified by the actual reflector’s dip. In the case of a point diffractor the incident energy is sent back in all directions. In the dip angle domain these directions are identified by the stationarity of the events’ moveout. The stationary points are preserved when summing over the dips according with the stationary phase principle.

To be more precise, when migrated with the correct velocity, a diffraction appears as a flat horizontal event if the dip-angle CIG is located exactly above the point diffractor, and as a dipping event if the CIG is relative to an horizontal position near the diffractor. On the contrary the reflections appears as concave events where the apex indicates the actual reflector’s dip. The different behavior of diffractions and reflections in this domain can be exploited for the separation of diffractions e.g. by means of dip filtering of flat horizontal events.

The moveouts of reflection and diffractions are different and clearly recognizable even in the case of migration with wrong velocity. In this case the imprint of a reflection is still a
concave event. The analytical expressions of reflection and diffraction moveouts in constant velocity media can be found in Landa et al. (2008).

In particular, in the zero offset case, the imprint of a flat reflector in the dip-angle gather located at \( x \) is the following:

\[
z(x, \alpha) = \frac{(z_0 \cos \alpha_0 + x \sin \alpha_0) v_M \cos \alpha}{v - v_M \sin \alpha_0 \cos \alpha}
\]

Here \( v \) is the medium velocity, \( v_M \) is the migration velocity, \( \alpha \) is the dip angle, \( \alpha_0 \) is the actual reflector’s dip. The reflector is described by the equation: \( z(x) = z_0 + x \tan \alpha_0 \). Note that, if the migration is performed with the correct velocity (\( v_M = v \)), then the stationary point occurs at the actual reflector’s dip: \( \alpha = \alpha_0 \).

The shape of a diffractor point in the dip-angle gather located at \( x \) is:

\[
z(x, \alpha) = \frac{v_M \cos \alpha [(x - x_0) v_M \sin \alpha + D]}{v^2 - v_M^2 \sin^2 \alpha_0}
\]

where \( D = \sqrt{z_0^2 (v^2 - v_M^2 \sin^2 \alpha) + (x - x_0)^2 v^2} \). Thus, when migrating with the correct velocity, the shape of a diffraction point in the gather located exactly above is a horizontal flat line which corresponds to illuminating the diffractor uniformly from all directions. If the gather is not located just above the diffractor the shape is a curve with no stationary points.

It is possible to take advantage of the local discrepancy between reflection and diffraction events and use dip-filtering in this domain, in order to separate diffractions which do not follow the dominant trend of dips.

Being substantially a pre-stack domain, the dip-angle gathers are more prone to noise with respect to the post-stack image domain and this can lead to an incorrect dip estimation which causes artifacts in the dip-filtered gather and in the subsequent migrated image of the diffractors (i.e. the stack over the dip angles). On the other hand the dip-angles domain has the advantage that the shape of diffractions is clearly identified and other kind of spurious events cannot be mistaken for them. Diffractions look significantly different from reflections in the common-image gathers and unlike reflections, they are affected by velocity errors in the conventional way. These two characteristics mean that also this domain could be used to perform effective migration velocity analysis by using the moveout of diffraction events.

**Combined separation technique.** The aim of our work was to unify the two methodologies mentioned above in order to exploit the peculiarity of each. The input data is depth migrated image in the dip-angle CIG domain. The algorithm is made of the three following steps:

1. local slopes are estimated on the stack image through a filter based on the gradient square tensor method;
2. dip filtering of each constant dip angle image is performed. It removes strong coherent events with continuously variable slopes calculated at step 1. In this way, being the filter a linear operator, we obtain the contribution of each common angle panel to the final residual consisting in all events, including seismic diffractions, that do not follow the dominant slope pattern. After this step we have eliminated the reflection but, besides the diffractions, there are still spurious events due to migration artifacts, uneven illumination or noise;
3. each dip-angle CIG is then further processed, this time in a way that emphasizes the coherent events through the local coherency of the filter. Indeed, in the dip angle domain, the diffracted events are strong coherent events (horizontal events if migrated with the correct velocity), on the other hand the remaining spurious events do not usually show a clearly identifiable dip. Therefore by applying a mask proportional to the local coherency of the dips estimated in the dip angle CIGs the true diffractions are emphasized compared with the spurious events.
If the energy of the reflections has been correctly removed in the dip filtering step it is possible to emphasize only the true diffractions with a low computational effort. This is also a drawback of the algorithm: also the residual reflections which survive to the dip filtering step (e.g. due to an incorrect dip estimation) could be emphasized through the application of the mask, being coherent events as well.

**Example.** As an example we show the synthetic Sigsbee 2A dataset released by the SMAART JV consortium.

This model contains a sedimentary sequence broken up by a number of normal and thrust faults. In the sedimentary sequence are embedded two dozens of point diffractors, regularly

![Diagram with labeled arrows and columns showing angles and depth with images illustrating the process]

**Fig. 1** – Migrated image of the Sigsbee 2A synthetic dataset: image 1-a is a zoom of the zone with the diffractor point. The black arrows b c and d point to the location of the dip-angle common image gathers of images 1-b, 1-c and 1-d respectively.

![Diagram with labeled axes and columns showing angles and depth with images illustrating the process]

**Fig. 2** – From left to right: first, a dip-angle CIG located exactly in correspondence of two diffractor points. Second, a dip-angle CIG in the same location after removal of reflection via dip-filtering. Third, local dip coherency estimated on the previous CIG. Fourth, enhancement of diffraction on the second dip-angle CIG.
positioned at two different depths. As an additional issue, there is a complex salt structure found within the model that causes illumination problems when migrating the data.

In Fig. 1 a part of the migrated section is shown in the image at left. The 3 arrows on top of the image indicate the locations of the three dip-angle CIGs shown in the images at right. In particular panel 1c is located exactly above two isolated diffractor points. The diffractions are clearly visible in panel 1c as two strong horizontal events embedded in a pattern of concave events. Being this gather located on a sedimentary sequence, it is noticeable how the apex of the concave events are positioned approximately at the same lateral position in the gather. This is what we expected for a sequence of approximately parallel events. Images 2b and 2d show two dip-angle gathers located at the right and at the left of the same point diffractors. Also in these gathers diffractions are easy to distinguish from the dominant pattern of concave reflections. Here they appear as dipping events whose slopes are determined by the horizontal distance between the location of the gather and the location of the diffractor.

The images of Fig. 2 illustrates, from left to right, the effect of three steps of the proposed procedure in the dip-angle gathers. First the original dip-angle CIG, on a location exactly above two point diffractors, is shown. The diffractors are quite noticeable as the strong horizontal events. Also the concave events corresponding to reflections are easily identifiable. The second image shows a CIG correspond to the same location, this time after dip-filtering on the common dip images: the concave events corresponding to reflections have been correctly removed while the diffractors have been properly preserved. However, several other events with no easy interpretation are present in addition to the two evident diffractions. In the third image from left the estimated local coherency computed on the previous CIG is shown. It is quite evident that the two strong diffractors are clearly identified as large zones of high coherency. Finally in the last image the regions of high coherency have been emphasized leading to an enhancement of the actual diffraction events.

In Fig. 3 we show a depth migrated section of the Sigsbee 2A dataset in the zone of the point diffractors. In the left image the result of the depth migration is shown. In the image at right the migrated image of enhanced diffractions is shown (i.e. the stack over dip angles of the enhanced CIGs). It is noticeable that most of the reflectors have been properly removed and that diffractor points have been highlighted.

Conclusions and future works. Diffractions are reliable indicators of small structural and lithological elements of the subsurface. However, since they are order of magnitudes less
energetic than reflections, it is necessary to separate diffraction from reflections in order to perform diffraction imaging and processing.

We analyzed separation of diffractions by dip-filtering in the post-stack domain and separation in the dip-angle gathers. Then a strategy for separation of diffractions from reflections in the depth migrated images has been developed, based on a combination of the previously analyzed algorithms and taking advantage of the virtues of both. The strategy has been tested with promising results on both synthetic and field data. Although separation of reflection and diffraction energy can never be exact, the proposed methodology achieves the practical purpose of enhancing diffractive response of small subsurface discontinuities. Here an example of separation of diffraction in the synthetic Sigsbee 2A dataset is shown. Future works will be focused on the study of methodologies for the actual use of diffraction for velocity analysis, both in the post-stack depth migrated image and in the dip-angle gathers.

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