High frequency random noise attenuation on shallow seismic reflection data by migration filtering

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Summary

High frequency random noise can be attenuated in the F-k domain using Stolt F-k migration. F-k migration algorithms routinely used to effectively migrate data can be used to attenuate high frequency random noise. The attenuation of high frequency random noise in the F-k domain is facilitated by defining the trace spacing interval significantly larger or velocity significantly lower than actual.

Evaluation of this noise attenuation technique on real data conclusively shows significant improvement in data coherency and a decrease in high frequency random noise with no noticeable migration effects or artifacts. The method seems especially useful in situations where migration produces artifacts, high frequency random noise is present or where techniques such as spectral balancing have left an elevated level of background noise.

Introduction

Migration is an inverse operation involving rearrangement of data sample elements to compensate for dipping or nonuniform bedding and collapse diffractions. (Sheriff, 1994). Simple constant velocity F-k migration (Stolt, 1978; Chan and Jacewitz, 1981) is accomplished through: 1) Conversion of traces from time to depth using a constant velocity. 2) Two-dimensional Fourier transform. 3) Migration (reallocation) of data values from the two dimensional array in the F-k domain. 4) Inverse Fourier transform.

Besides correcting for dip distortion and collapsing diffractions F-k migration acts as a low pass filter effectively narrowing the bandwidth. This bandwidth narrowing is a result of the frequency domain mapping downward toward lower Kz (Chan and Jacewitz, 1981) (Figure 1). In most cases involving shallow reflection data the bandwidth is already relatively narrow, so migration on a section with minimal dip dramatically reduces resolution.

The way the F-k migration algorithm affects a specific area in the F-k domain can be modified by redefining the input parameters. Thus, we can use a simple technique to emulate a sophisticated filtering process. Similar results could probably be achieved by applying a complicated F-k filtering routine designed to remove a specific area of nonunique slope in the frequency domain. That area as defined by F-k migration algorithms is a thin horizontal wedge positioned at the highest values of K_z. The wedge thins as K_x approaches 0 and thickens with increasing K_x. Migration filtering is a very subtle and simple process that shifts and compresses data values in the high frequency range.

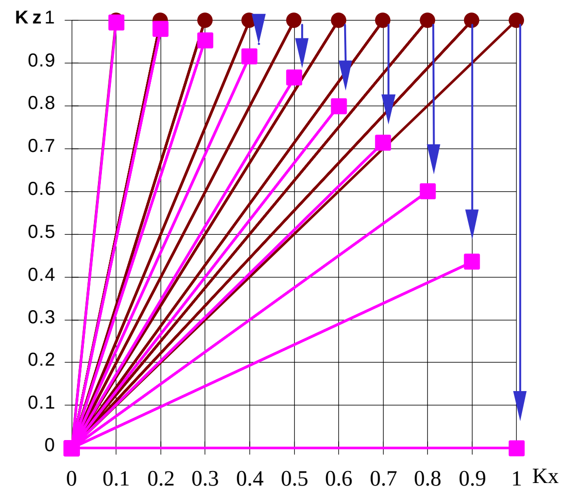

Figure 1. Migration in the F-k domain. Data values are reallocated down the vertical axis and thus change the dip of slopes. The arrows show the migration of the values from the topmost row. The area covered by the arrows (top right corner) is filled with zeros since there is no data to migrate to those locations. That explains the bandwidth narrowing that occurs after F-k migration

Theory and Method: F-k Migration Filtering

All events in the depth domain with a dip α_b when transformed to the F-k domain are represented by a single line of same slope α_b. (Chan and Jacewitz, 1981). To remove optical distortion (i.e., correct for distortion or point source scatter) and establish the true event location and slope, migration must map each element of a line in the F-k domain with slope α_b to a line with slope α_a. After adjustment of a line's slope in the F-k domain the line is transformed back into x-z space to contribute to numerous events with slope α_a. (The number of events in the depth section with slope α_a after migration is the same as the number of events with slope α_b before migration). This slope adjustment of lines in the frequency domain is analogous to an expanding fan (Figure 1). For simplicity, that process can be denoted as α_b-α_b-α_a-α_a. Adjustment of line slopes in the F-k domain are controlled by the formula:

$$\alpha_a=\sin^{-1}(\tan\alpha_b). \qquad (1)$$

In the frequency domain the mapping is performed by the formula:

$$F(K_x, K_z) = K_z/\sqrt{(K_x^2+K_z^2)}*F(K_x,\sqrt{(K_x^2+K_z^2)}), \quad (2)$$

(Chan and Jacewitz, 1981), where K_x is the horizontal wave number and K_z is the wave number of the depth z after time to depth conversion using a velocity V. A key observation in this process that some of the new locations (K_x, ,$\sqrt{(K_x^2+K_z^2)}$) are outside of the data set (at the highest K_z values). Since these new locations are filled with zeros the inverse F-k transform narrows the bandwidth (Figure 1). Another observation is that for small α_b the change due to migration is small (the difference between α_b and α_a). For small α_b, $\alpha_b \approx \alpha_a$ (when $\alpha_b \leq 15°$, $\alpha_b - \alpha_a < 1°$).

Migration filtering takes advantage of the previous observations. Migration filtering can most easily and effectively be applied to a data set by increasing the true trace spacing. Let us consider increasing the space interval K times.

$$dX_g=K*dX_a \quad (3)$$

where dX_g is the greater spacing interval, and
dX_a is the actual spacing interval.

All the events in the depth domain with a dip α_b when transformed to the F-k domain are represented now by a single line with a false slope α_{b1} instead of α_b. The dependence of α_{b1} on K is given by:

$$tg(\alpha_{b1}) = tg(\alpha_b)/K \quad (4)$$

$\alpha_{b1} < \alpha_b$, for K>1 (as we would assume further on). Since $\alpha_{b1} < \alpha_b$ the migration change would be smaller than appropriate based on actual trace spacing. Migration in the F-k domain would change α_{b1} to α_{a1} less than compared to the change from αb to α_a, when using normal trace spacing interval. The angle transform of dips from the F-k domain back into the depth section would be analogous to (4):

$$tg(\alpha_{a1}) = tg(\alpha_a)/K, \quad (5)$$

where α_{a1} is dip in the F-k domain after migration and
α_a is dip in depth section after migration.

Simply, migration filtering can be denoted as α_b-α_{b1}-α_{a1}-α_a. Migration filtering uses an exaggerated trace spacing, which transforms all the dipping events from the depth section into lines with smaller dips in the F-k domain. Because dips are smaller than when actual trace separations are used migration in the F-k domain changes line dips less. When transformed back into the depth section those events would be less migrated. The idea of migration filtering is to use a sufficiently large value of K that the slope change due to migration in the F-k domain is insignificant ($\alpha_{b1} \approx \alpha_{a1}$, and αb≈αa due to that). Even with a large value of K downward mapping is performed in the F-k domain at the highest K_z values. Therefore some locations get filled with zeros and a filtering process results.

Lets consider increasing the space interval ten times, K=10, $dX_g=10*dX_a$. For simplicity of explanation we will consider further on only the first quadrant in the F-k domain and we have chosen K_x and K_z to vary from 0 to 1. We assume also that all true dipping events in the depth section vary from 0 to 45° and that all that are greater than 45° are noise (Chan and Jacewitz, 1981). Since the wave number K_x is inversely proportional to dX, if we use dX_g instead of dX_a the range of K_x will change to 0–0.1. All true events on the depth section will have dips ranging from 0 to 45°(α_b), which equates to dips that range between 0 and 5.7106°(α_{b1}) in the F-k domain (formula 4). Migration changes insignificantly the dip of events between 0-5.7106° (0-5.7392°(α_{a1})) (formula 1). After the inverse Fourier transform the events in the depth section will range from 0 to 45.144°(α_a) when K-10 (formula 5) (Table 1). The migration effects in either domain are negligible.

Unmigrated true dips in the depth section α_b	F-k domain dips before Migration using K=10 α_{b1}	F-k domain dips after Migration α_{a1}	Dips in the depth section after inverse Fourier transf. α_a
5.7106	0.5729	0.5730	5.7109
11.3099	1.1458	1.1460	11.3121
16.6992	1.7184	1.7191	16.7063
21.8014	2.2906	2.2924	21.8172
26.5651	2.8624	2.8660	26.5937
30.9638	3.4336	3.4398	31.0094
34.9920	4.0042	4.0140	35.0582
38.6598	4.5739	4.5886	38.7496
41.9872	5.1428	5.1636	42.1031
45.0000	5.7106	5.7392	45.1440

Table 1. List of dips from the depth section, after Fourier transform into the F-k domain using K=10 ($dX_g=10*dX_a$), after migration in F-k domain and after inverse Fourier transform back into the depth section.

Migration filtering when used with a big K (K=10) does nothing negative in terms of the integrity and analysis potential of the data. For all intensive purposes the data is not migrated and should not be used as if it were. For the extreme case of a 45° dip α_b in the depth section the dip change is only 0.31%.

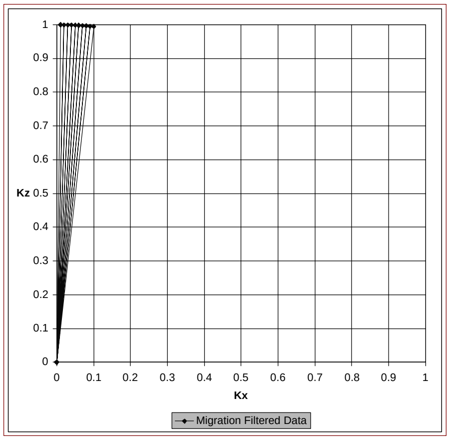

Figure 2. Changing space interval from dX_a to dX_g=10*dX_x scales the K_x axis from the range 0-1 into the range 0-0.1 and changes slopes of the dips in the F-k domain.

The actual process we wish to exploit occurs when the values from the very top K_z row are shifted down as a function of K_x. The space left by this shift is filled with zeros since there is no data to be shifted into those locations according to formula (2). The largest shift is at the largest value of K_x decreasing (rapidly and non-linearly) as K_x decreases (Figures 1 to 3). Migration filtering basically opens a small crack (wedge) of locations at the very top part of the F-k domain. This wedge, which generally contains the highest frequency data, is filled with zeros effecting filtering the data. This same wedge can be selected within the F-k domain using filtering software and removed. However, migration filtering retains all data by simply shifting it as opposed to deleting it.

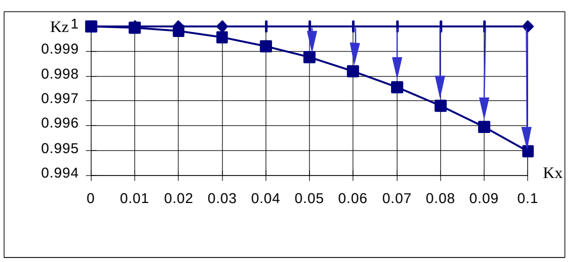

Figure 3. A zoomed image of the selected area from Figure 3 showing data sample shifting by Migration in the F-k domain. The top row is shifted to new locations. The area covered with arrows is filled with zeros thus forming a wedge.

Migration removes dips greater than 45° in the F-k domain (Chan and Jacewitz, 1981; formulas 1 & 2). In this example (using K=10) the slope of 84°(α_b) in the depth section becomes 45° (α_{b1}) in the F-k domain. It is then obvious that noise having dips greater than 84° in the actual x-z space will be removed (Table 1).

The accuracy of migration filtering is minimally dependent on the accuracy of the velocity. Lets look at the effects of choosing 50% higher velocity on an extreme true 45°(α_b) dip from the depth section. When converting from time into depth section the true 45°(α_b) dip will change erroneously into 63.3°(α_b). Nevertheless, by applying migration filtering using K=10 (dX_g=10*dX_a) that 63.3°(α_b) dip will become 11.3°(α_{b1}) in the F-k domain and it will become 11.53°(α_{a1}) after migration. After the inverse Fourier transform that dip will be 63.9°(α_a). The dip change (less than 1%) is insignificant (i.e., filtering is effective and there is virtually no true migration taking place in the depth domain). If the velocity is smaller than true, the dip in the frequency domain would be smaller and would just decrease the effect of filtering. A suitable single velocity should be chosen that will be a generalized velocity for the section.

Results

Prior to migration filtering, coherent reflections are quite interpretable and possess a reasonably good signal-to-noise ratio for shallow reflection data (Figure 4).

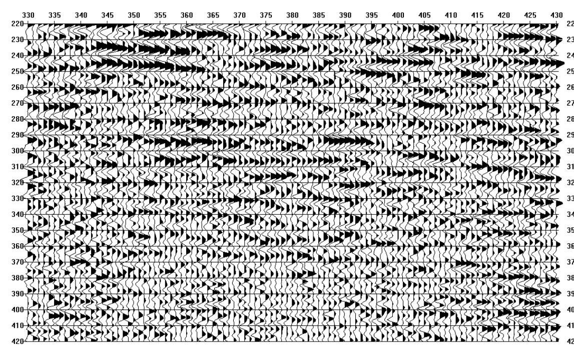

Figure 4. Data before migration filtering.

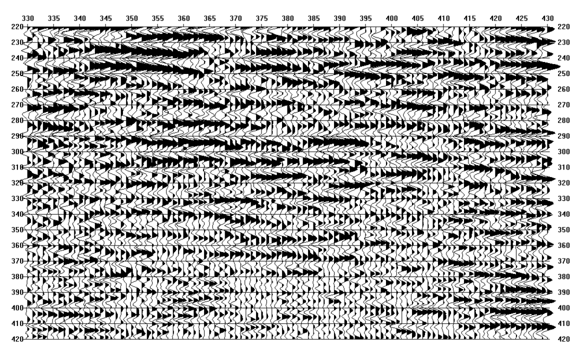

Figure 5. Data after migration filtering using K=10.

After migration filtering using K=10 the enhancement of reflections previously degraded by noise is evident (Figure 5). CMPs 331-333 and 342-346 at time 400-405 ms are examples of notable improvement in event coherency and signal-to-noise ratio. Improvement is evident in the waveforms of existing reflection wavelet between CMPs 360-390 at time 360-370. Migration filtering improves the signal-to-noise ratio and the interpretability of many reflections on the section.

If we apply migration filtering using K=5 the bandwidth is reduced and events are moved in the direction of their true position (Figure 6). The bandwidth is reduced even more and events are moved even closer if we apply migration filtering using K=2 (Figure 7).

On the other hand higher values like 20 times the true trace spacing do not change the section at all.

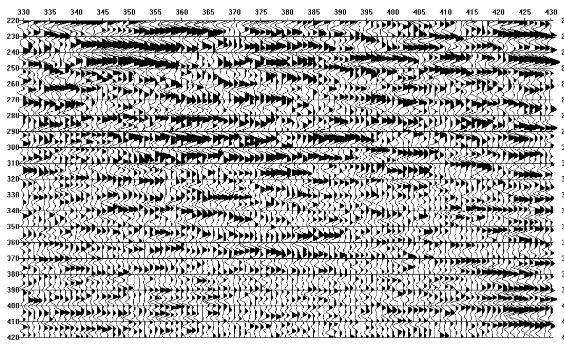

Figure 6. Data after migration filtering using K=5.

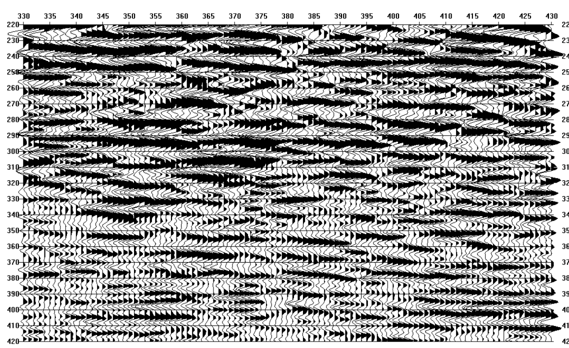

Figure 7. Data after migration filtering using K=2.

Discussions and Conclusions

Migration software can be used as a migration filter to improve the data quality by filtering high frequency random noise, increasing signal-to-noise ratio and improving of the data coherency without narrowing the bandwidth of reflection events.

A reasonable question that may arise is why use migration filtering since migration performs the same filtering anyway?

Under most 2-D shallow seismic circumstances it is reasonable to consider migration a marginally useful technique.

First, F-k migration severely reduces the bandwidth of near-surface seismic data and for that reason is not recommended. Second, shallow reflectors are sometimes close enough to the earth's surface and the velocity is low enough that migration provides little if any change in the image (Black et al., 1994). Third, often identifying the highly varying laterally and vertically velocity function, typical for the near surface, and migrate data properly is unrealistic. For any of the above reasons migration would not be applied to near surface data. However, migration filtering can contribute to data improvement.

There are many advantages of migration filtering over F-k filtering, including its ease of use. It can be accomplished using the most simple F-k migration software (such as a constant velocity F-k migration, included in the least expensive processing packages), and it preserves the high frequency data values as opposed to deletion. The same technique can be applied to shot gathers before stack as well.

References

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