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Time domain localized interpolation of pre-stack 3D seismic data with dip scan in 5D space

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The method

To interpolate a seismic trace at shot position (X_s,Y_s) and receiver position (X_r,Y_r), we collect a suite of input traces with shots at (x_s,y_s) and receivers at (x_r,y_r), such that their L_1 norm of distance from (X_s,Y_s, X_r,Y_r) in 4D, d_4, is within a user specified limit R_4, or:

(1) $R_4 >= d_4 = | X_s - x_s | + | Y_s - y_s | + | X_r - x_r | + | Y_r - y_r |$

With such input traces, a small time window, (t_1,t_2), of the trace is interpolated to (X_s,Y_s,X_r,Y_r) from (x_s,y_s,x_r,y_r) by a low order 4D polynomial, along the dipping plane in 5D, that maximizes semblance of trace segments cut from input traces.

Repeat the above for many consecutive overlapping time windows to cover the whole trace in time, and a full trace gets interpolated.

The above mentioned dipping plane in 5D is defined by move out time correction dt:

(2) $dt = d_{xm}(X_m - x_m) + d_{ym}(Y_m – y_m) + d_{xo}(X_o – x_o) + d_{yo}(Y_o - y_o)$,

in which, X_m / x_m is CMP-x of interpolated/input trace, … and Y_o / y_o is offset-y of interpolated/input trace; $d_{xm} /d_{ym}/d_{xo}/d_{yo}$ are slopes in the four spatial dimensions, and should be scanned up to +/-N times in a small step size, dt (in second/m), while N*dt should be large enough to cover maximum dips exhibited in the data.

Likewise, the above mentioned 4D polynomial is also in CMP-x/y & offset-x/y.

The dip scan in 5D is prohibitively time consuming: all combinations of slopes number $(2N+1)^4$, and with a moderate N=3, the combination of dips is $7^4=2401$, and that is done for each time window (t_1,t_2), and independently for each pre-stack trace to be interpolated.

We have found a time saving way to do the 5D dip scan. Briefly, 3D dip scan (CMP-x & CMP-y slopes) is performed and top dips of highest semblance are picked. Then 5D dip scan is performed in a small neighborhood around these top dips picked in the 3D dip scan.

Reasons for 5D dip scan

We can think of the following:

1. Velocity function is never perfect, but 5D dip scan will still be able to capture and retain signal with residual moveout.
2. Data may exhibit anisotropy, and the offset & azimuth dependent 5D dips will track such signals properly.

3. AVAZ & VVAZ effects are azimuth dependent, and they can be now more properly modeled than scanning dips in 3D only, and the interpolated pre-stack traces can be a more trustworthy replacement of the raw input.

It should be noted, however, 5D dip scan can only improve the interpolation of the signal, but cannot correct the above mentioned problems. For example, less than perfectly NMO'ed events will remain not flattened.

Limitations of 5D dip scan

The linear nature of a plane in 5D as defined by time move-out correction (eqn.2) suggests that it only works in a small neighborhood of interpolated trace position, same as how a truncated Taylor series works. This can be achieved by choosing a small R_4 in eqn.1.

A note on semblance

Instead of the usual semblance:

(3a) $\Sigma_t\{\Sigma_x A(t,x)\}^2/\Sigma_t\Sigma_x A(t,x)^2/N_x$,

for robustness, we use an L_1 norm version of (3a):

(3b) $\{\Sigma_t|\Sigma_x A(t,x)|/\Sigma_t\Sigma_x|A(t,x)|\}^2$,

in which, the power of 2 is only necessary for (3b) to exhibit similar shades as (3a). It has been observed that, with L_1 norm semblance, interpolated traces contain less impulsive noise.

A note on choice of four spatial dimensions

In the above, we use CMP and offset x/y's as the 4 spatial variables. Mathematically, however, any two of (x,y) vector of : shot, station, CMP and offset, uniquely define a pre-stack 3D trace. With the 4D polynomial interpolator, we have chosen CMP-(x,y) and offset-(x,y) as spatial coordinates, with polynomial order between 1 and 3. Higher order polynomials offer higher spatial resolution, but poorly distributed input may cause instability. Below order-1, we also have order-0, which is simply an inverse 4D distance weighted summation.

In 5D dip scan, we have also chosen to use the same CMP-(x,y) and offset-(x,y) as spatial coordinates. The reason is twofold:

1. The time/ CMP-(x,y) dips are structural dips we observe on stacked sections, and such dip-scan is done only once for all the interpolated traces of one CMP gather;
2. The time/ offset-(x,y) dips reflect effects like VVAZ etc., and this is done for each individual trace in one CMP gather. Such dips can be converted to velocity corrections, which form the basis of VVAZ analysis.