Inverse CRS

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Abstract

The CRS method is a powerful tool to produce high-quality stacked images of multi-coverage seismic data. As a result of the application of CRS, not only a stacked section, but also a number of attributes defined at each point of that section, is produced. In this way, one can think of the CRS application as a transformation from data space to attribute space. However, as the CRS method is purely kinematic, it should be completed by amplitude information, that we propose to obtain from the zero-offset (ZO) section and common midpoint (CMP) gather. In this paper, we propose an algorithm for an (approximate) inverse CRS transformation, namely one that (approximately) transforms the CRS attributes back to data space. The CRS transform pair established in this way may find a number of applications in seismic imaging and data processing, in the same way as other well-known transformations, e.g., Fourier, Radon, tau-p, etc.

Introduction

CRS (Common Reflection Surface) is a recent data-driven time imaging process (see Hubral, 1999; Jäger et al., 2001 and also references therein) that has been originally proposed as an alternative to the classical NMO-DMO chain (see, e.g. Yilmaz, 2001) to build seismic stacked, zero-offset (ZO) time images of the subsurface. As already discussed elsewhere (see, e.g., Perroud and Tygel, 2005), the CRS method has both advantages and disadvantages with respect to its competitors. In fact, the adoption of the CRS method by the geophysical community has been until now only limited, because the classical NMO-DMO chain already provides good-quality robust results, so the need for a change is not obvious. However, CRS does not provide only zero-offset images, but also a set of wavefield attributes (emergence angles and wavefront curvatures) that have been exploited in several applications. These include, e.g., velocity model building (Della-Moretta et al., 2006; Klüver, 2006), multiple attenuation (Prüssmann et al., 2006), residual statics correction, (Koglin et al., 2006), among others.

CRS can be seen as a transformation from the data space (seismic amplitudes as a function of position and time) into attribute space (wavefield attributes as a function of position and time). Note that data space position variables include both midpoint and offset coordinates, while the attribute space position variables consist in the midpoint coordinates only. In this way, the attribute domain is much smaller, even if several attributes exist per mid-point. For example, in the 2D case, the number of CRS attributes is three. The CRS method provides also a generalized hyperbolic moveout expression that allows for traveltime estimations for reflection event at any midpoint and offset in the vicinity of a reference position where the attributes have been estimated.

The representation of the data in the new (attribute) domain is not complete, since it is purely kinematic. We miss the amplitude of the seismic events, that are necessary for a full representation of the data. In this sense, it can be stated that the CRS transformation, on its own, induces a loss of information that cannot be reversed. To establish a transformation that could allow going back from the attribute space to the data space, we need to add some dynamic information. Our purpose here is to demonstrate that this goal can be achieved if we have, in addition to the CRS attributes at a given reference point (or reference trace), also data from two trace gathers in its vicinity. These are (1) the true-amplitude ZO gather and (2) the CMP gather centered at the reference midpoint. The chosen ZO and CMP traces should be sufficiently close to the reference midpoint, so that the validity of the CRS approximation of any reflection traveltime is valid in this range. We propose then to call Inverse CRS this new transformation. Since the (forward) CRS transformation is essentially an approximate process (namely, it is realized upon the use of the hyperbolic traveltime approximation), the proposed inverse CRS transformation should also not be expected to provide exact (loss-free) results. One of our goal is therefore to evaluate in which range these losses can be considered as insignificant.

In the following, we describe the Inverse CRS transformation, as well as the algorithm that allows one to build a trace at any midpoint and offset. As indicated above, both the ZO and CMP sections in the vicinity of the reference trace are assumed to be available. For illustrative purposes, we apply it to two simple synthetic cases of a dipping planar and a circular reflector.

THE INVERSE CRS TRANSFORMATION

The problem to be solved can be formulated as follows: to build the unknown data trace at a given midpoint position and offset, in the vicinity of a reference trace, for which we know (a) the CRS attributes, (b) the ZO gather and (c) the CMP gather. The known ZO and CMP gathers consists of traces located in the vicinity of the reference trace. The construction of the unknown data trace means filling the “right” amplitude (i.e., a valid approximation of it) at all time samples. We therefore need to estimate both time and amplitude for all events that can be identified in the known part of the data. We shall describe below how these are estimated. As far as possible, we want this transformation to be macro-model independent, so we shall try to use in the process data-related quantities only.

Equation for traveltime

Traveltime estimation can be achieved directly using the CRS traveltime approximation. For an event such that the ZO traveltime at the reference point is t(0, 0), we can evaluate the corresponding traveltime t(m,h) at any neighboring midpoint position m and half-offset h, from those in the CMP gather t(0,h) and ZO section t(m,0), obtained themselves using the CRS attributes known at the reference trace (located at midpoint m = 0), using the formula:

$$t^2(m, h) = t^2(m, 0) + t^2(0, h) - t^2(0, 0). \qquad (1)$$

This approximation is valid as long as the CRS traveltime approximation is. For example, it is exact for a dipping plane reflector with an homogeneous overburden.

Equation for amplitude

Although it has been relatively straightforward to predict the traveltime above, this is not the case with amplitude. This is so because CRS provides kinematic attributes only. As a matter of fact, full account of amplitudes involves many factors, such as angle-dependent reflection-transmission coefficients, geometrical spreading, medium attenuation, source wavelet, etc. Determination of all these quantities is, of course, unfeasible. Nevertheless, as shown below, a reasonable approximation can be achieved.

We suppose we have full knowledge (traveltime and amplitude) at each sample of the two specific ZO and CMP gathers. More specifically, we consider that for each event that we select with time t(0,0) and amplitude A(0,0), the traveltime and amplitude pairs (t(0,m),A(0,m)) and (t(0, h),A(0, h)) that refer to the ZO and CMP gathers, respectively, are known. The question now is how to evaluate the unknown amplitude A(m, h) relatively to these known (data-driven) quantities. Our main assumption is that the predicted traveltime, t(m, h), and amplitude, A(m, h), are supposed to be valid only in the neighborhood around the reference trace, so the CRS traveltime equation should provide a good approximation. Concerning the amplitude, we further assume that the physical quantities such as velocities, densities, are also more or less stationary in this neighborhood. As a consequence, we may restrict the analysis to the main laterally variable factors, which are geometrical spreading and reflection angle, that can significantly change with lateral change of the depth of the reflector.

Taking into account these two factors, and classical approximations for their evaluation, we arrived at the following equation to evaluate the amplitude at position m and half-offset h:

$$A(m, h) = \{A(m, 0)t^{\alpha}(m, 0) + [\, A(0, h)t^{\alpha}(0, h) - A(0, 0)t^{\alpha}(0, 0)\,]\, t^2(0, h) / t^2(m, h)\,\} / t^{\alpha}(m, h), \qquad (2)$$

where $\alpha = 1/2$ for the case of 2D in-plane spreading only and $\alpha = 1$ in the case of 3D spreading.

Note that this formula leaves unchanged the amplitude within the ZO gather (h = 0), as well as within the CMP gather (m = 0).

The evaluation of the unknown quantity, A(m, h), relies only on quantities that are data-dependent, which can be picked from the two given specific configurations or computed from the CRS attributes. No other information is required, as long as the stationarity of model physical parameters in the vicinity of the reference position is a valid approximation.

General Algorithm

We shall now assemble the above obtained steps as building blocks of an algorithm that will produce a new data record at midpoint position m and half-offset h starting from the given ZO and CMP gathers in the neighborhood of the reference trace:

• First compute the CRS attributes for all samples of the record at the reference position (m = 0) using the CMP gather and the ZO gather, together with the corresponding coherence values. This has to be done only once for all data traces to be built in the vicinity of the given reference trace.

• Start a loop on time samples, t(0, 0), with amplitude, A(0, 0), from the record at the reference midpoint, m = 0, and half-offset, h = 0. Each time sample will be taken as a possible reflection event if its CRS attributes have coherence values that are high enough. Otherwise, go to the next sample.

– Compute t(0, h), t(m, 0) and t(m, h) from t(0, 0) and its CRS attributes using the traveltime equation 1.

– Pick A(0, h) at time t(0, h) in the CMP gather and A(m, 0) at time t(m, 0) in the ZO gather, using interpolation from surrounding data samples, and compute A(m, h) using the amplitude equation 2.

– All obtained pairs of time and amplitude should be stored for future use. Note that calculated times are not necessary monotonously increasing. In the case there are more than one CRS groups of attributes for the same time sample (conflicting dips), this process has to be carried out for each CRS attribute group.

• End of the loop on time samples.

• Order the time-amplitude pairs by increasing times and interpolate the amplitudes at the data time-sampling rate.

The above algorithm, which builds a single data trace, can then be used in a loop on midpoint, m, and fixed half-offset, h, to build a common-offset (CO) section. In addition, in an outer loop on half-offset, h, it can be further used to build the full dataset.

Note that with this scheme, a given reflection event is built sample by sample, so that we do not have to make any assumptions on the signal wavelet, only that it has been adequately sampled. Preprocessing steps such as filtering or deconvolution that enhance the signal-to-noise ratio and signal resolution can be applied on the ZO and

CMP gathers. This can be done either before or after the application of the algorithm.

SYNTHETIC EXAMPLES

Two simple models will be tested to check the efficiency of our algorithm. They are shown in Figure 1. The models consist of (1) a dipping planar reflector, within a homogeneous overburden, for which the traveltime equation is exact, and (2) a circular reflector, tangent to the dipping plane at the normal incidence point for the reference position, for which the traveltime equation is only approximate. The choice of these models reflects our assumption that the earth subsurface has to be locally simple enough so that the CRS traveltime equation provides a good approximation. The synthetic data have been computed by a ray-tracing calculation with 2D inplane amplitudes, convolution by a ricker wavelet, and addition of white noise with a signal-to-noise ratio of 10.

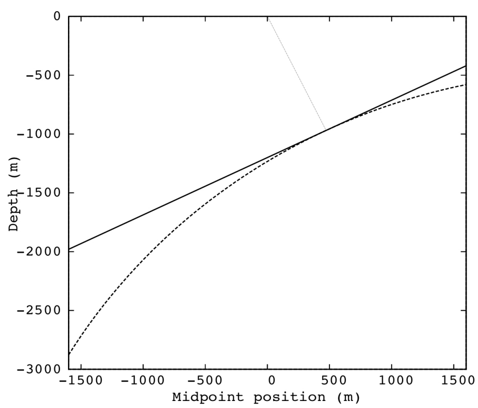

Figure 1: The two simple synthetic models used to test the inverse CRS algorithm.

Dipping planar reflector

Our first test was to compare the theoretical traveltime and amplitude values at any midpoint position, and offset, in the vicinity of the reference position, with the traveltime and amplitudes values obtained with the above equations.

This comparison is shown in Figure 2, which reveals a very good agreement in most of the investigated range. The biggest discrepancy arises for the lowest amplitudes. These correspond to largest offsets, as well as incidence angles close to the critical angle. Under this situation, the approximation we have used is not appropriate. However, the area were the two set of values can be identified represents more than 90% of the full range. Note than in this case, the difference exists only in the amplitude value.

Figure 3 shows the two specific configurations that have been used to build the full dataset: the ZO gather on the top and the CMP gather at the bottom. From the traces in these two gathers, the CRS attributes at the reference midpoint m = 0 have been extracted, together with their coherence values. Traces were then build following the algorithm detailed above, for all midpoints and offsets. The build traces are compared to the synthetic data in Figure 4, for small, medium and large offsets. We can see how the build trace compares well with the synthetic data in the vicinity of the reference midpoint, but differences appear when offset or distance to the reference midpoint increase. To evaluate how far we can go, a map of the relative mean quadratic error is shown in Figure 5. The contour at 0.2 provides a conservative estimation of the area where the approximation is very satisfying. It appears that it covers an extent approximately equal to the reflector depth, both in the offset and mid-point direction. Note that the noise is suppressed by the process when there is no coherent signal, which is when CRS attributes coherency is less than a given threshold.

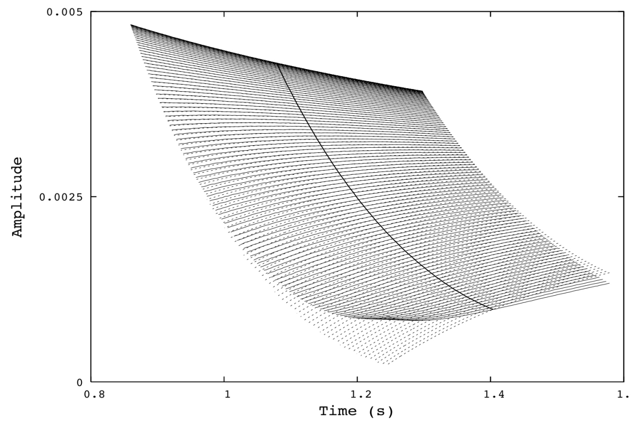

Figure 2: Comparison of traveltime and amplitude along all CO sections between the theoretical values and the Inverse CRS equations, in the case of the dipping-planar reflector. The black lines represent the ZO and CMP sections where there are no differences

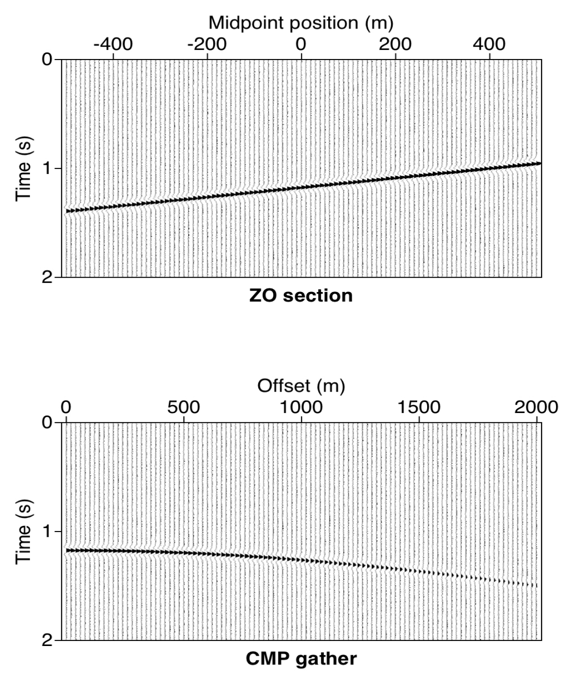

Figure 3: Synthetic data for the dipping planar reflector.

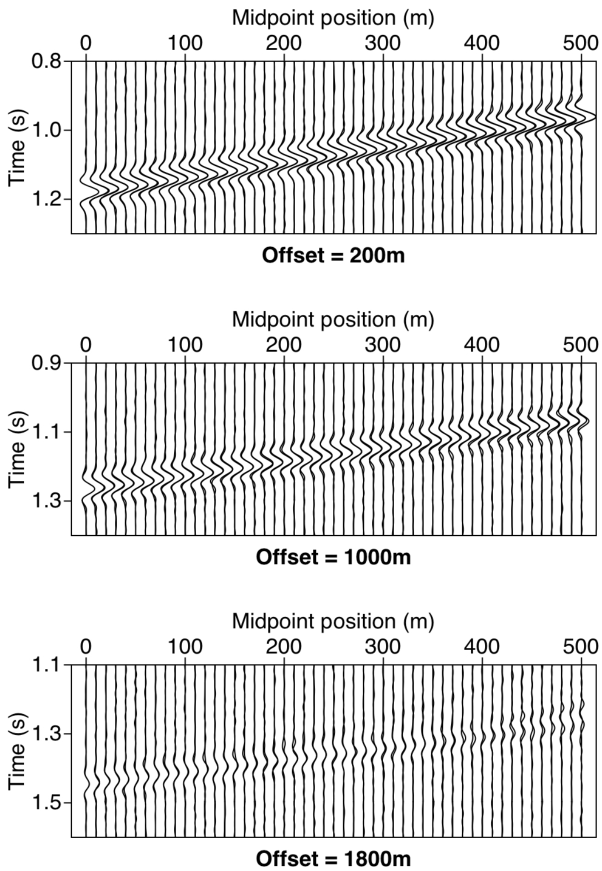

Figure 4: Dipping reflector: comparison of the build traces with the synthetic data for small, medium, and large offsets, with the reference midpoint located at position 0.

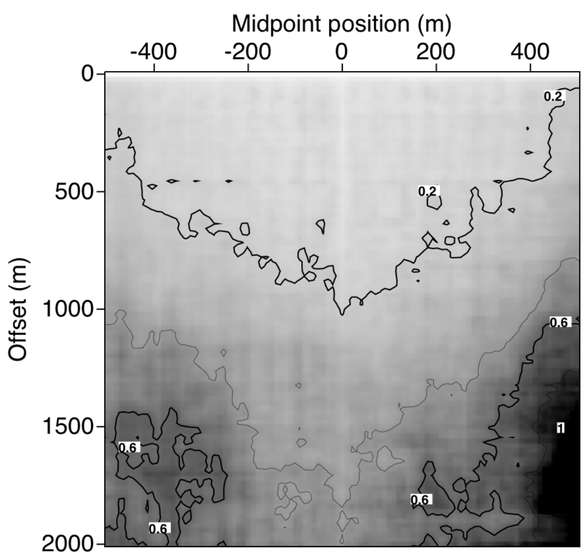

Figure 5: Dipping reflector: map of the relative mean quadratic error introduced by the process.

Circular reflector

The same results (Figure 6 to Figure 9) were obtained for the circular reflector. Note that in this case, the CRS traveltime formula is only approximate, so the differences between the build traces and the synthetic data become significant for shorter offsets, or distance from the reference midpoint.

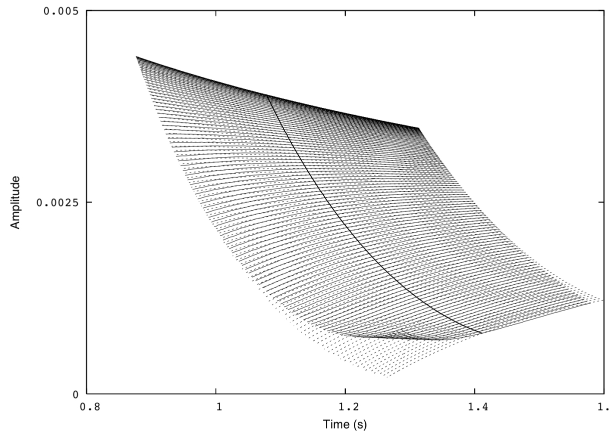

Figure 6: Comparison of traveltime and amplitude along all CO sections between the theoretical values and the Inverse CRS equations, in the case of the circular reflector.

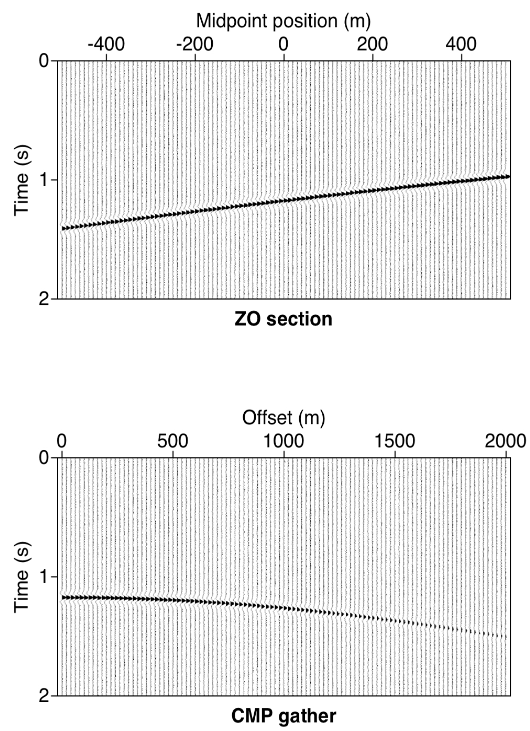

Figure 7: Synthetic data for the circular reflector.

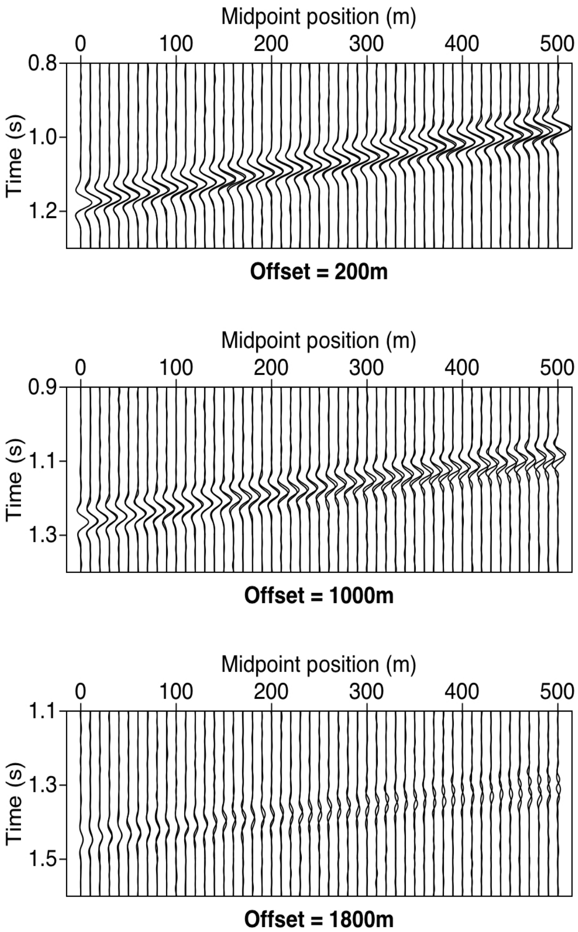

Figure 8: Circular reflector: comparison of the build traces with the synthetic data for small, medium, and large offsets, with the reference midpoint located at position 0.

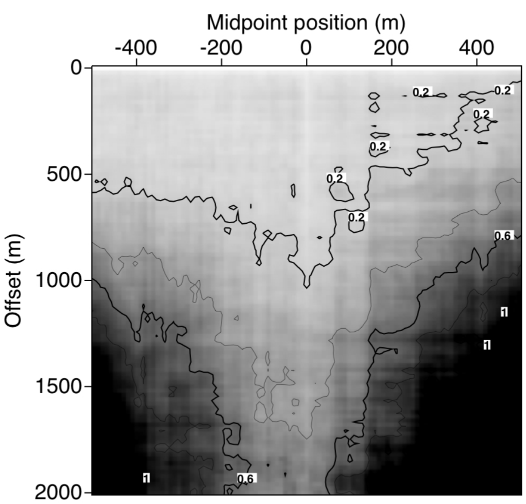

Figure 9: Circular reflector: map of the relative mean quadratic error introduced by the process.

Conclusions

At the present stage of this on-going research, we have proposed an algorithm that is able to build seismic traces from a very limited set of real data, namely a CMP gather and a ZO section, together with the CRS attributes that can be obtained from them. First tests of this algorithm provide satisfaying results for the two types of reflector geometry investigated, dipping-plane and circle. An area where the used approximations are acceptable was defined, whose extent is similar to the reflector depth in the first case, and a little less in the second case. Further tests are on the way using real seismic data. Applications of this technique could be numerous, from noise suppression, data compaction, trace interpolation, etc...

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