Controlled Directional Receptivity -- A Russian Method of Pre-Stack Migration

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Qualitative Discussion

It is well known that the Soviet Union is one of the world's largest producers of oil. Not so well-known, however, are the methods that Soviet geophysicists use to find this oil. Recently I was given the opportunity to talk with Dr. Zavalishin of the Gubkin Institute in Moscow about one of these methods -- Controlled Directional Receptivity (CDR).

The principles of CDR were laid down by Rieber, an American, in the late 1930s, but the technique was fully exploited only in the Soviet Union. Over the past forty years the principles of CDR have been applied in many different ways for many different purposes. The variation that I shall describe here is used to convert a series of common-shot gathers into a migrated depth section, and is thus a type of migration without stack. The discussion that I had with Dr. Zavalishin was mostly qualitative, However, in the second part of this article I will attempt to explain the method as quantitatively as possible, using the various mathematical formulas I was able to glean from printed material which Dr. Zavalishin generously provided. In addition, although this method is claimed to be useful in areas with vertically- and horizontally-varying velocity, I will only discuss the constant-velocity case.

To begin with, let us assume that we are shooting with a split-spread geometry. Let us place a shot at position x_1, giving us a shot record $V_1(x, t)$, where x is the receiver position. In the same way, let us put a shot at x_2, giving us a shot record $V_2(x, t)$. Now let us take a subset of V_1: $V_1(x_2+n\Delta x, t)$, with $n = -N,...,-1,0,1,...,N$ (Δx is the distance between adjacent receivers). Typical values for N are 4, 5, or 6. Notice carefully what we are doing. For a shot located at position x_1, we are examining the records clustered around a receiver at x_2. Proceeding in a reciprocal manner, let us also examine $V_2(x_1+n\Delta x, t)$, with n and Δx defined as before.

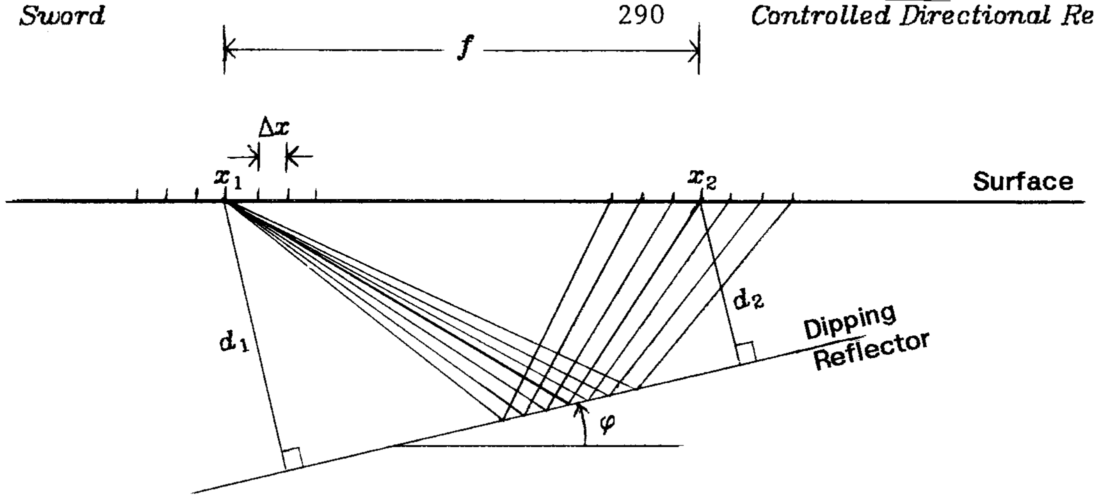

FIG. 1. Shooting geometry. This shows a typical split-spread seismic survey. A shot at x_1 is picked up by receivers clustered around x_2 producing shot record V_1. Record V_2 is produced similarly, using a shot at x_2 and receivers clustered around x_1.

Figure 1 shows what we are doing. Both shot records are imaging the same general area of a dipping reflector. Now we can perform the operation of "directional stacking", which is actually a simple slant stack. Defining $U_i(p, \tau)$ as the slant stack of $V_i(p, \tau)$, we come up with the equations

$$U_1 = \sum_{n=-N}^{N} V_1(x_2+n\Delta x, \tau+pn\Delta x)$$

$$U_2 = \sum_{n=-N}^{N} V_2(x_1+n\Delta x, \tau+pn\Delta x)$$

where Δx and n have the same definitions as before. In Russian geophysical terminology, U_1 and U_2 are known as "summolentas", which translates literally as "sum-ribbons". The origin of this term is fairly obvious -- usually not many values of p are used, so a plot of $U(p, \tau)$ ends up looking fairly ribbon-like.

For the reflector shown in Figure 1, we should get a shot record $V_1(x, t)$ that looks something like that shown in Figure 2a. Notice that we are defining t_1 to be the the arrival time of the reflected wave for a receiver at x_2. If we slant-stack $V_1(x, t)$ in order to generate $U_1(p, \tau)$, we will get something similar to Figure 2c. In this Figure the most prominent feature is a "burst" at $p = p_1$, with $\tau = t_1$. We can consider this burst to have an amplitude of A_1. In the same way, Figures 2b and 2d show $V_2(x, t)$ and $U_2(p, \tau)$ respectively. In the

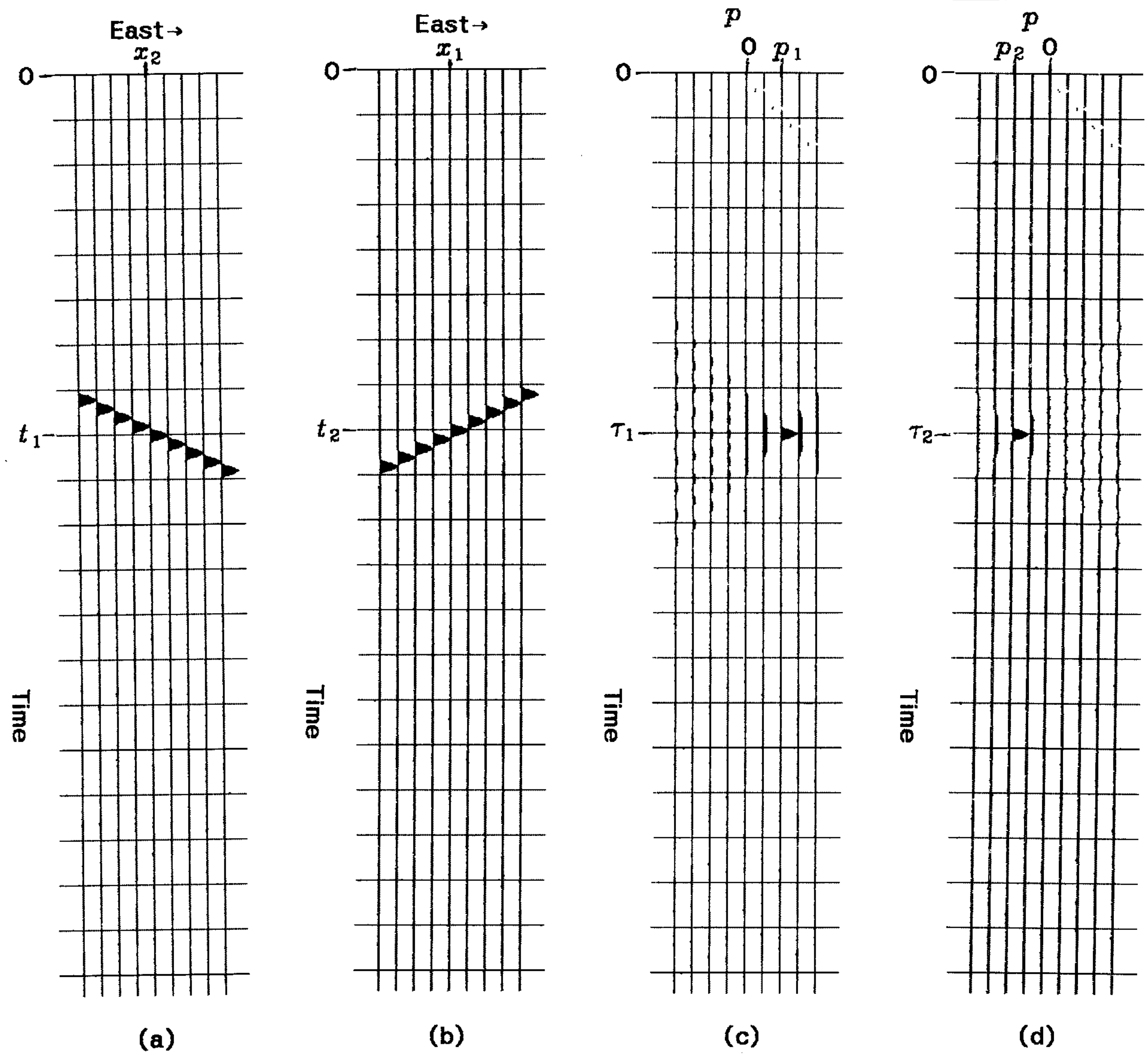

FIG. 2. a) Shot record V_1 for shot at x_1, receivers clustered around x_2. b) Slant stack U_1 of shot record V_1. c) Shot record V_2 for shot at x_2, receivers clustered around x_1. d) Slant stack U_2 of shot record V_2.

case of $U_2(p, \tau)$ we have a burst on trace $p = p_2$ at $\tau = t_2$, with amplitude A_2.

Now for a few definitions. Let $t_0 \equiv \frac{t_1+t_2}{2}$, $A \equiv \frac{A_1+A_2}{2}$, $\Delta p^+ \equiv p_1+p_2$, and $\Delta p^- \equiv p_1-p_2$. Notice that t_1 should in theory always equal t_2, so our definition of t_0 may seem superfluous. However, in real life there may be fluctuations in t_1 and t_2 due to noise. It should only take a few moments to convince yourself that when φ (the angle of dip) equals zero, Δp^+ will equal zero. Thus φ is to some extent a function of Δp^+ and perhaps velocity V_{const}. It should also be fairly reasonable to think that Δp^- could depend only on offset (x_2-x_1), velocity, dip angle φ, and travel time (t_0). Assume that we already know V_{const}, the constant velocity. Then we could perhaps determine φ using Δp^+ and velocity V_{const}, and from there determine an apparent velocity V_{app} using Δp^- and the angle φ that we just calculated. Notice that although we have assumed constant velocity V_{const}, we are determining a new apparent velocity V_{app}. We do this because the deviation of V_{app} from V_{const} will give us an idea of how "believable" our apparent reflector is, and thus how much credence to give to our resulting dip-bar.

V_{app}, φ, and t_0 are enough to give us the spatial (x-z) coordinates of the portion of the reflector that we have been imaging. Now we could plot a dip bar with dip φ on our depth section. However, before doing this, there some refinements to this algorithm.

The first refinement is quite obvious. Instead of plotting all dip-bars with the same intensity, we should plot each dip-bar at an intensity that corresponds to A, the average amplitude of the bursts on our $p-\tau$ plots U_1 and U_2. But in doing this we can add one more level of sophistication. Previously we noted that the deviation of V_{app} from V_{const} should give us some estimate of how much we could trust any resulting dip bar. This can be done quantitatively. Let us define κ to be the deviation of the apparent velocity from the assumed constant velocity: $\kappa = \dfrac{V_{const} - V_{app}}{V_{const}}$. Then we can define a new quantity Q as a function of κ and a parameter α: $Q = e^{-\alpha\kappa^2}$. This quantity is clearly a Gaussian function that equals 1 when V_{app} equals V_{const}, and that diminishes as V_{app} deviates from V_{const}. Thus Q is in some way a measure of how reliable our dip-bar will be. Then the easiest way to show that our dip-bar is not too reliable is to lower its amplitude by plotting it with an amplitude A_{new}, where $A_{new} = QA$.

Next we can consider the length of the dip-bar. Just by looking at Figure 1 we can see that we are imaging not just one point, but a line segment. In addition, the wave equation tells us that what we have drawn as rays actually have a sort of width to them. In theory, then, we should draw the dip bar not as a point or as a bar of constant amplitude, but as a line with the highest intensity in the middle, tapering off at both ends.

The last improvement in the method is to automate the picking of the p's and τ's from the slant stacks U_1 and U_2. This is not, in principle, too difficult. Simply find the p and τ of an amplitude peak on U_1, and see if that peak correlates in τ with an amplitude peak on U_2. In theory, both peaks should come in with exactly the same value of τ, but for practical purposes it works better to use a window of about 5 milliseconds.

Now we are ready to plot our dip-bar. Given t_0, φ, and V_{app}, we can determine x, z, and φ_{real}. We can plot the bar with an intensity A_{new}, and give it a length corresponding to the uncertainty in position due to beam-spreading. Doing this for all possible values of x_1 and

x_2, we will have constructed a migrated depth section without using conventional NMO stacking.

Quantitative Discussion

In this section I will attempt to deal with the quantitative aspects of CDR, drawing as much as possible on Russian journals and inventing the rest. Suppose we have the situation as shown in Figure 1, with a couple of new quantities defined: f is the distance between x_1 and x_2, and d_2 is the minimum distance from x_2 to the reflector (Similarly, d_1 is the minimum distance from x_1 to the reflector). Having these, we are prepared to develop some formulas.

In order to find formulas for p_1 and p_2, we can assume that p_1 is the derivative with respect to f of the travel time curve for a shot at x_1. Then

$$\tau_1 = t_1 = \frac{1}{V_{const}}(f^2+4d_1^2-4d_1 f \sin\varphi)^{1/2}$$

giving

$$p_1 = \frac{dt}{df} = \frac{1}{2V_{const}^2\tau_1}(2f-4d_1\sin\varphi)$$

We can perform a similar operation for p_2. Noting that $d_1 = d_2+f\sin\varphi$, we find that

$$\Delta p^+ = p_1+p_2 = \frac{1}{V_{app}^2\tau_0}4f\cos^2\varphi \tag{1}$$

and

$$\Delta p^- = p_1-p_2 = \frac{1}{V_{const}^2\tau_0}(8d_2\sin\varphi+4f\sin^2\varphi). \tag{2}$$

Notice that in Equation 1 we have V_{app} rather than V_{const}. the reason for this will be explained soon.

Now Equation 2 is not too useful in its present form. We are not able to solve for φ given a known V_{const}, because of the d_2 term that is present. In order to get around this problem, the Russians use what they call a "parabolic approximation". This approximation was not given in any of the literature available to me, so I have had to make some guesses. However, making the approximation

$$t \approx t_0+\frac{x^2}{2V^2t_0}+\frac{f\sin\varphi}{V},$$

with $t_0 \equiv \frac{2d}{V}$, I eventually came up with

$$\Delta p^- = p_1 - p_2 \approx \frac{2\sin\varphi}{V_{const}}. \tag{3}$$

Using Equation 3, then, and given a known V_{const}, it is possible to find φ. Now that we are armed with a value for φ, we can go back to solve Equation 1 for V_{app}. We call this velocity V_{app} (apparent velocity) because we want to emphasize that it most likely will differ from our original constant velocity, V_{const}. The apparent velocity can be used, as shown in the first section of this paper, to find a weight Q which can be applied to the amplitude A to give $A_{new} = QA$.

Once we have φ, τ_0, and V_{app}, we are in a position to locate the corresponding dip-bar on the $x-z$ plot, giving it an amplitude A_{new}. The formulas for x and z as a function of φ, τ_0, and V_{app} can be derived in a fairly straight-forward but messy fashion. I will not give them here.

Conclusions

We have seen how it is possible to construct a migrated depth section using unstacked traces. It remains to be seen whether this method works in practice. Unfortunately, I am unable to provide any examples of how the method works in practice. Dr. Zavalishin showed me some, but I of course was not able to take them with me. It was my impression, however, from looking at the data that Dr. Zavalishin showed me, that the CDR method is at its best when imaging unconformities and small faults. In any case, the sections that I saw would not be very useful for comparative purposes unless we could compare them with sections produced from the same data using conventional American methods. Dr. Zavalishin realized this, and so he made an offer. If we send him a tape of seismic data, he will process it on his computer in Moscow using the CDR method. At the same time we can process it here using our own pre- or post-stack migration methods. Then we can compare results and get an idea of the advantages and disadvantages of both methods. Of course, before we can take him up on his offer, we have to determine what sort of data would be most useful, what sort of format it should be sent in, and that sort of thing. The process of nailing down all these details could easily take a long time. In addition, of course, such exchanges of raw data and processed results are always subject to the whims of US and Soviet foreign-policy makers. Thus, for the time being we can only keep our fingers crossed.

Bibliography and Acknowledgements

Here some general references for the further study of CDR. The first of the two Russian references is the abstract of Dr. Zavalishin's dissertation (I don't have the dissertation itself). It contains the general outline of the method that I have described in this paper, as well as an interesting sketch of the history of seismological data processing in the Soviet Union. As far as I know, I have the only copy on this side of the Iron Curtain. The other Russian reference is a recent journal article by Dr. Rjabinkin, Dr. Zavalishin's mentor and the man who developed CDR to its present point in the Soviet Union. The first American reference is an article by Hermont, who describes what he learned of CDR while visiting the Soviet Union. The second is an article by Prof. Phinney of Princeton, who has independently invented many aspects of the CDR method. (Dr. Zavalishin cited this particular article as an example of the wasted effort caused by the lack of communication between American and Russian seismologists). Of course my main reference cannot be cited easily in a Bibliography -- the discussion that took place between Dr. Zavalishin and me during the course of an evening in Suzdal. In this paper I have attempted to explain what he explained to me that night. Any mistakes are, of course, my own.

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Perfect day for scrubbing the floor and other exciting things.

As the trials of life continue to take their toll, remember that there is always a future in Computer Maintenance.

Excellent day to have a rotten day.

You can't judge a book by the way it wears its hair.

Enzymes are things invented by biologists that explain things which otherwise require harder thinking.
---Jerome Lettvin

"I don't know what you mean by 'glory,'" Alice said

Humpty Dumpty smiled contemptuously. "Of course you don't -- till I tell you. I meant 'there's a nice knock-down argument for you!'"

"But glory doesn't mean 'a nice knock-down argument,'" Alice objected.

"When I use a word," Humpty Dumpty said, in a rather scornful tone, "it means just what I choose it to mean -- neither more nor less."

"The question is," said Alice, "whether you can make words mean so many different things."

"The question is," said Humpty Dumpty, "which is to be master -- that's all."

Interpreter: One who enables two persons of different languages to understand each other by repeating to each what it would have been to the interpreter's advantage for the other to have said.

If God is perfect, why did He create discontinuous functions?

Who needs companionship when you can sit alone in your room and drink?

"Contrariwise," continued Tweedledee, "if it was so, it might be, and if it were so, it would be; but as it isn't, it ain't. That's logic!"
-- Lewis Carroll