Improvements in Constructing Seismic Images Using CDR*

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Translated by Chuck Sword

Translator's note: In this paper, Dr. Zavalishin develops the ideas that were previously discussed in a paper in SEP-26: CDR – A Russian Form of Pre-Stack Migration. Since Soviet reflection seismology has developed in isolation from its Western counterpart, it should not be surprising that the same vocabulary is not used, nor that there are Soviet terms that have no direct English equivalent. Chief among these terms is CDR (Controlled Directional Reception). (Be sure to watch for the occasional appearance of old familiar CDP!) For the purposes of this paper, a CDR gather can be considered to be the same as a transposed *slant-stack section, except that the vertical axis is Δt rather than p $(\Delta t / \Delta x)$. I will attempt to explain some of the other terms as they crop up in the article.*

The construction of dynamic depth sections (migration) is accomplished by means of a continuation of the recorded wave field, from the surface of observation to internal points of the medium being studied [7, 12, 13]. Algorithms for the approximate continuation of seismic wave fields are constructed using methods for solving the scalar wave equation that are borrowed from mathematical physics. Two of these methods have received wide currency in the field of exploration seismology: the method based on Kirchoff's integral [12, 16], and the method of finite differences [13]. The differences in solving the problem by these various computational schemes are almost unnoticeable in terms of results [14,16]. Therefore, if we wish to discuss the future, then the prospects for the application of any of these migration algorithms depends on which one of them can be effective in the struggle against regular noise, can more accurately determine the velocity characteristics of the medium, as well as which one can reduce the amount of migration noise [14] that is characteristic of the migration algorithm itself.

Because integration methods of migration are closer to the traditional ways of interpreting exploration seismic data, it is likely that the goal of solving the problems pointed out above is more easily aimed at in the framework of this approach. Here one is able to make

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use of the rich experience in interpreting data by the method of controlled directional reception (CDR) [11], as well as the method of effective parameters [8].

The approximate integral continuation of the wave field, resulting in the construction of a dynamic depth section*, is accomplished using the diffraction transformation** [12, 16] -- that is, the stacking of traces or time sections along diffraction hyperbolas. It is well known [5] that one of the practical approaches to diffraction transformation is to cross-sum CDR gathers in the depth regime. Therefore, CDR stacking can be looked at as a way of building a seismic image; and taking into account the fact that the wave parameters determined from the CDR gathers can be used to calculate effective velocities, CDR is a type of velocity analysis as well.

The complete equivalence between the direct summation of the wavefield along diffraction hyperbolas and the cross-summation of CDR gathers is illustrated in Fig. 1. The integral transformation of the observations along profile l of the wave field $F(l,t)$ can be described at the image Φ_A of point A (on reflecting boundary Γ) by the formulas

$$\Phi_A = \int_{l_1}^{l_n} F(l,t-d(l))dl = \tag{1a}$$

$$= \int_{l_1}^{l_2} F(l,t-d(l))dl + \cdots + = \int_{l_{n-1}}^{l_n} F(l,t-d(l))dl \tag{1b}$$

The first of these (1a) represents the diffraction transformation, while the second represents the CDR transformation[1]. If the base of observations $\delta l = l_2 - l_1 = \cdots = l_n - l_{n-1}$ is so small that the hyperbolic element $d(l)$ within its bounds can be replaced by a straight line segment, then we obtain the full integral over the base $l_1 - l_n$ by summing the corresponding excerpts with all the [unknown word] of the CDR gathers that lay on it. By means of cross-summing of the gathers in the depth regime (see Fig. 1), the necessary excerpts reinforce each other, since the rays (from all CDR gathers) that intersect at any point in the depth section correspond to a given diffraction hyperbola [11]. In Fig. 1 are shown the results of cross-summing (in the depth regime) fragments of one CDR gathers, computed on the base $l_5 - l_6$, as well as the rays from other CDR gathers that intersect at point A. The diffraction hyperbola $d(l)$ corresponds to these rays.

* Depth-migrated section.

** Kirchoff migration.

1. Author's note: It is convenient thus to term the interferential summation of the vibration fields of CDR gathers in the depth regime. The introduction of this term is appropriate not only for the sake of compactness, but also in order to distinguish this approach towards constructing a section using CDR gathers, from the construction of a section using wave parameters that have been picked from CDR gathers, as well as from the entire CDR method, which has, in contrast to constructing sections, a wider setting. Note that the method of constructing sections, here called CDR transformation, was proposed by L.A. Riabinkin as long ago as 1953, and patented in 1958 [10].

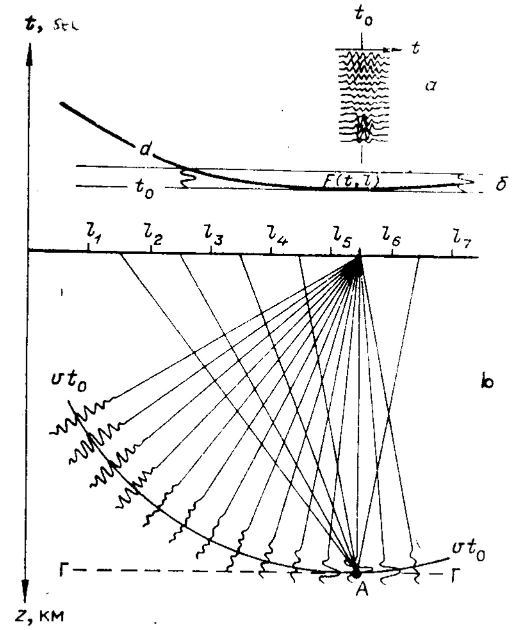

FIG. 1. Constructing the image of point A on the reflector Γ, using the CDR transform. Here, a is the fragment of the CDR gather for the base l_5-l_6, δ is the wavefield $F(t, l)$ reflected from Γ, d is the travel-time curve of the wave diffracted from the point A, b is the image space, and vt_0 is an isochron.

Besides the preceding, Fig. 1 also illustrates one of the deficiencies in algorithms for transforming the wave field into an image of the Earth. It shows the inherent transformation noise which forms due to the out-of-phase summation of regular vibrations of the useful waves. From Fig. 1 it is apparent that in the case of CDR-transformation the transform noise arises from those waves on CDR gathers which are associated with the intermediate and secondary maximums of the directional characteristic of summation* [11]. In correspondence with (1a,1b), it is identical for both CDR and diffraction transformation. It is clear that a sharpening of the main lobe of the directional characteristic, and a weakening of all intermediate and secondary lobes, would be conducive to a decrease in the transformation noise.

A decrease in CDR-transformation noise can also be accomplished by supplementing the procedure of CDR summation with any of the forms of amplitude or energy analysis [11, 15]. This allows one, in an automated mode, to extract from a CDR gather only those waves which correspond to an in-phase [un-aliased] summation of the regular waves. But for an increase in the reliability of the selection of regular waves and in the accuracy of the determination

* A concept similar to the dependence of a geophone array on the angle of incidence.

of their parameters, it is important to increase the resistance to irregular noise of that same procedure of CDR summation on a small base.

The usual way to accomplish such an increase involves stacking multifold* CDP data, preceded by another form of processing, in particular, CDR [5]. Its deficiency is that in areas of intersecting interference of waves, distortions and even losses of potential information are inevitable. Below, I present a method of overcoming these obstacles -- coordinated-summation CDR (CDRC). It is possible to look on it as a type of time-field analysis which has as its goal the determination of the effective parameters of the reflected wave [8], and as a particular case of the method of multifold stacking [3], in the sense that the CDRC gather represents a sort of selection from multifold stacking. It is, however, necessary to emphasize that CDRC summation is based on the previously developed approaches to constructing an image by the CDR method, and aids their improvement by taking into account new technology for recording and processing data.

CDRC summation is offered as an approach which helps one solve the following problems: to eliminate the loss of wave information about reflections from boundaries of varying dip, by means of stacking the data of multifold observations; to increase the noise resistance and quality of CDR summation over short bases by previously stacking the data; to sharpen the main directional characteristic lobe, thus increasing the resolution and accuracy of the calculated wave parameters; and to weaken the intermediate and secondary lobes of the directional characteristic and thus decrease the inherent noise of CDR transformation when constructing sections.

Using data obtained from multifold observation systems, we group the CDP traces which correspond to a small portion of the profile, and this will serve as the base of CDP summation. So that the effectivity of the CDR summation of the traces In order for the efficacy of CDR stacking to be identical for all waves, no matter what the dip of the reflecting boundary, each wave must have an individual NMO correction curve, depending on the angle of dip of the corresponding boundary. Indeed, in order to shift the times t_{ij} of the reflected wave to the perpendicular summation time t_0 at the center of the base of summation, it is necessary to satisfy the equation [4]

$$t_0 = \frac{2h_0}{v} = \left[t_{ij}^2 - \frac{x^2 \cos^2 \varphi}{v^2} \right]^{1/2}, \qquad (2)$$

where i is the position of the source, j is the position of the receiver, h_0 is the perpendicular-reflection depth of the boundary, measured from the base of summation,

* As contrasted with single-fold CDP data.

$x = j - i$, v is the velocity, which is assumed here to be known *a priori*, and φ is the dip angle of the reflecting boundary. In the general case φ is an unknown quantity, but in CDR stacking it turns out to be the stacking time shift (Δt). This is so, since stacking using a suite of time shifts is carried out in CDR, because in the medium there are boundaries with dip angles corresponding to these shifts. Therefore, before each successive trace of the CDR gather is obtained, the original CDP traces can be stacked using the NMO correction which corresponds to the dip angle of the reflecting boundary, where the dip angle is given by the value of the CDR gather time shift. The time shift of the CDR summation Δt corresponds to reflecting boundary's dip angle φ, obtained from the simple relation

$$\sin\varphi = \frac{v\,\Delta t}{\Delta x}, \tag{3}$$

where Δx is the distance between geophones. The substitution of (3) in (2) results in the equation

$$t_0 = \left[t_{ij}^2 - \frac{x^2}{v^2} + \frac{x^2}{\Delta x^2} \right]^{\frac{1}{2}}, \tag{4}$$

in accordance with which it is necessary to alter the time t_{ij} on the CDP traces. Since the time shift Δt is a function of trace position in the CDR gather, all values on the right side of (4) are known. Thanks to the fact that the right part of equation (4) does not depend on the sign of Δt, use of either NMO correction curve allows one to obtain two traces of the CDR gather -- for the positive and for the negative time shift Δt.

We will illustrate the sequence of computing CDR gathers in an example. Let us examine a wavefield reflected from a dipping boundary ($\varphi = 30^o$), recorded using a multifold system of observation (Fig. 2). On a segment of the profile we will place a 200-meter base of CDR summation having its center at midpoint 7. In this base are five CDP midpoints. The perpendicular-reflection depth of the reflecting boundary h_0 at the center is 2 km, and the velocity v in the overlying medium is 2.5 km/sec. CDRC summation consists of the following: we introduce the NMO correction in formula (4) to the CDP traces, assuming a horizontal reflecting boundary ($\Delta t = 0$), and carry out CDP stacking; the five traces thus obtained are summed by the CDR method, using parameter $\Delta t = 0$. Now we introduce to the CDP traces an NMO correction which corresponds to $\Delta t = \pm 2$ ms, and after stacking we compute the two traces of the CDR gather corresponding to $\Delta t = -2$ ms and $\Delta t = 2$ ms. All the remaining CDRC gather traces are calculated in an analogous way (see Fig. 3a). The efficacy of this method is shown in an example of a comparison with normal (uncoordinated) CDR stacking (see Fig. 3b). It is from a time section that was obtained using a constant NMO correction, calculated for a dip angle of $\varphi = 30^o$ ($\Delta t = 20$ ms). The comparison shows that coordinated

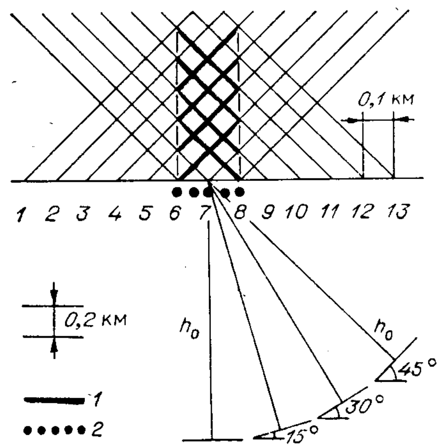

FIG. 2. The observation scheme in the model of the experiment. Here, the line labeled 1 represents the symbol for the base of CDR summation, and the line labeled 2 represents the CDP midpoint stations. The diagonal gridwork can be used for calculating midpoints. For instance, the line heading to the right and up from point 5 represents a shot at point 5, while a line heading to the left and up from point 9 represents a geophone at 12. In this case, the two lines intersect above point 7, indicating that the midpoint belongs there.

CDR stacking (CDRC) has two advantages: a strong weakening of vibrations in the area of suppression, including the first secondary maximum; and an increase in the sharpness of the main maximum of the directional characteristic, thus improving the resolving ability of the stack. The reason for these advantages is easily explained, and consists of the fact that the directional characteristic of coordinated stacking represents the product of spectral directional characteristics of two methods of summation: CDR, and CDP cross-summation [4, 11].

Thanks to the decrease of the wave background in the area of suppression, coordinated summation is capable of reducing the noise of CDR-transformation in the construction of dynamic depth sections. But more important is the fact that coordinated summation proves equally effective in the summation of the useful signals which have been reflected from boundaries of various dips. As an illustration of this, let us look at the interfering wave field which consists of reflections from four boundaries, inclined at angles of 0, 15, 30, and 45 degrees (see Fig. 2). The calculated time shifts of the corresponding reflected waves are 0, 10.3, 20.0, and 28.3 ms for a Δx of 0.1 km. The segments of the boundaries are tangent to a circle which has its center at the center of the CDR summation base, and which has a radius $h_0 = 2$ km. This model geometry was used in order to produce intersecting

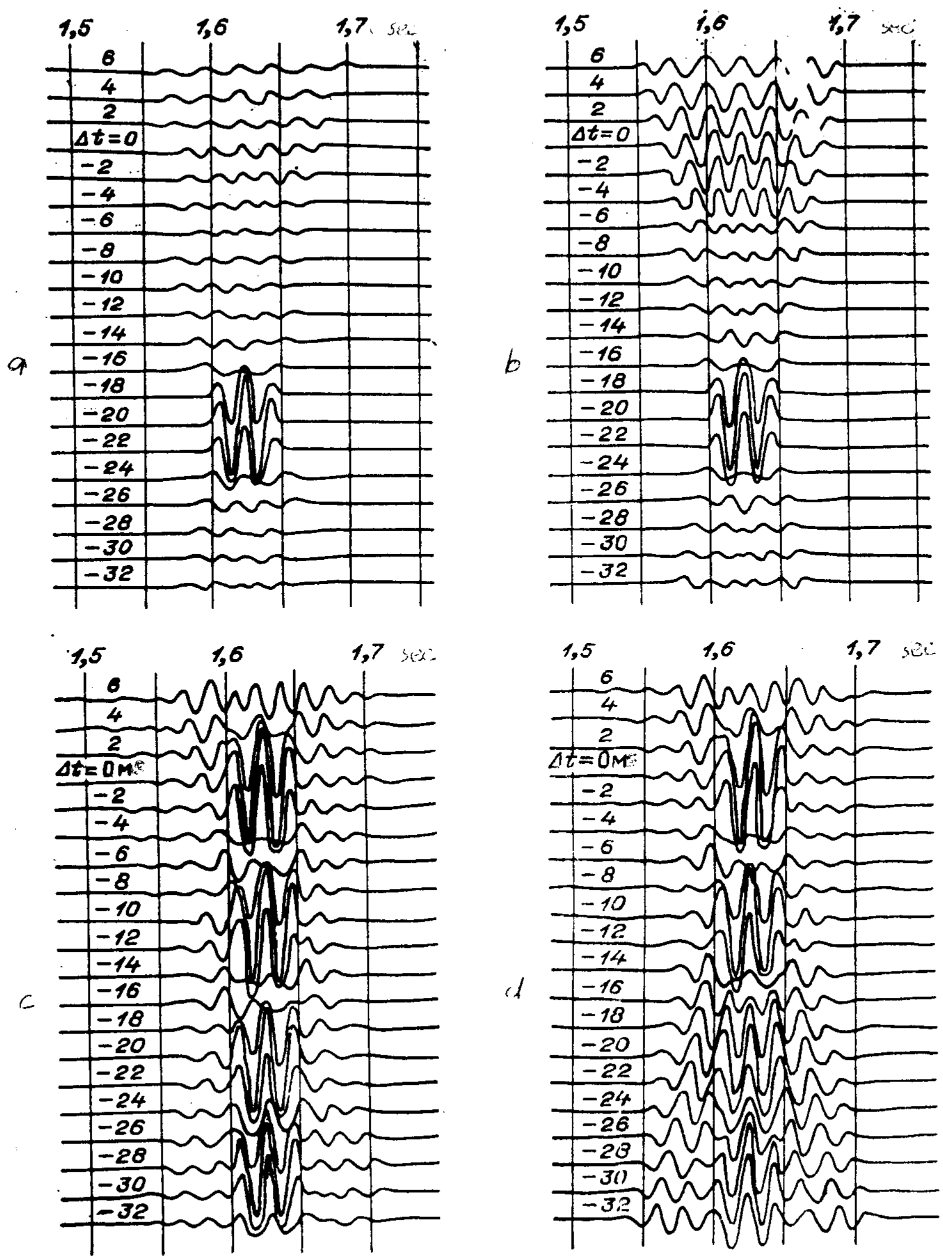

FIG. 3. CDR gathers from coordinated (a, c) and uncoordinated (ordinary) (b, d) stacking of multifold seismic data.

interference; for all for waves t_0 = 1.6 sec. For greater specificity, we note that the maximum shot-geophone offset x_{max} = 1.1 km, while the maximum time shift on the CDP traveltime curve at midpoint 7 for the four waves is respectively 49, 46, 37,and 25 ms.

Coordinated summation leads to the CDR gather shown in Fig. 3c, in which each of the four waves is fully resolved. In Fig. 3d is shown the result of uncoordinated CDR summing of a CDP section which had been stacked with a single NMO correction corresponding to a horizontal reflecting boundary. Noticeable here are the lack of resolution of the increased amplitude of waves that have time shifts of 20.0 and 28.3 ms, reflected from the boundaries having dip angles of 30 and 45 degrees, and the increased wave background over time intervals as great as 0.15 sec, despite a useful signal length of 0.05 sec. The unsatisfactory trace resolution is the result of two causes: the addition of secondary growth from waves with shifts of 0 and 10.3 ms, and an unsuitable velocity v_{CDP}. It is possible to judge the intensity of secondary growth in Fig. 3b. The question of the effect of an erroneous velocity v_{CDP} on the curvature of stacked time fields is analogous to the question of permissible error in the given *a priori* velocity. The effect of curvilinear summation on amplitude is determined by the corresponding directional characteristic [4, 6]. Thanks to the slope of the characteristic, a 10 percent error in the given *a priori* velocity, when stacking over a 1 km base, doesn't lower the amplitude effect to a value lower than 0.7 and doesn't make selection of the wave more difficult. Several concrete examples [1] and a test of scanning real materials by velocity persuades one, that even a 20 percent error in the given *a priori* velocity will not lead to a loss of wave information.

CDRC summation can be accomplished in two modifications. The first of these is based on the construction only of an image of the medium by means of CDR transformation, or on the basis of the parameters t, Δt, and a (amplitude). As input data for this modification, we use CDP traces recorded using an arbitrary multifold system of observation. The second modification of CDRC, besides constructing an image of the medium as before, pursues the goal of velocity analysis and selection of useful waves according to velocity characteristics. For its realization it is necessary to have a symmetrical system of observations and a fulfillment of certain conditions for the selection of traces from CDP data [1]. Before shifting to a discussion of the question of velocity analysis using CDRC gathers, we will clarify why multipart summation [3, 6], which resembles CDRC, is not used for this, even though it allows one in principle to determine the important velocity parameter v_{CDP}. The reasons follow. The acquisition of a multipart gather and the calculation from it of the wave parameters is more complicated and expensive than in CDRC. The proposed approaches toward this goal lie along the same course that processing data by the CDP method lies along, and their use in constructing images by the CDR method is difficult both from a technological and from logical point of view. At the heart of the logical plane is the question of the resolving ability of velocity analysis, when done by means of curvilinear summation. It is well known that in order to resolve interfering waves by velocity using such summation, it is necessary that the difference in the increases of their travel time curves on the base of analysis exceed the apparent period of the vibrations being analyzed. In order to exceed the limit of resolution, in the CDP method one strives for an increased offsets. Besides the other difficulties that arise (refraction, a broader class of recording noise, and so on), we note an important conclusion of reference [17]: accurate values for of depth and velocity can only be computed if the distance of offset does not exceed the approximate sizes of the planar elements of the boundaries. Consequently, an increase in offset limits the possibility of studying media with complex structures. In the CDR method one uses approaches to studying velocities whose resolution is dependent, to the least possible extent, on the length of recording offset, and therefore it lacks a striving for increase in offset.

Multipart analysis [6], where CDR summation precedes curvilinear summation, allows one under certain circumstances to hope for an increase in the resolving ability of velocity analysis without an unjustified increase in the length of offsets. In method [6], in distinction to CDRC (see Fig. 3), there is no weakening in the intermediate and secondary maxima of the CDR directional characteristic. This can lead to the formation of false waves and to difficulties in analysis in interference zones.

The calculation of velocity [2] using the parameters t and Δt in CDR gathers and the selection of useful waves by means of their velocity characteristics [1, 9] are based on the method of reciprocal points (N. N. Puzyrev, V. N. Rudnev, 1945). We will now examine the specifics of the acquisition and use of CDRC gathers for this purpose.

In Fig. 2 is shown a multifold symmetrical system of observations, which will acquire four pairs (on a base of .4 km) of the usual reciprocal CDR gathers. We will calculate, using the wave parameters of each pair of reciprocal CDR gathers, the effective wave velocities. This is possible even in the case where CDR summation is performed with NMO corrections that depend on the dip angle of the reflecting boundaries, as is provided for in CDRC. We will start from the fact that in the general case, the *a priori* velocity v, which is used for the introduction of the NMO correction, differs from the true mean wave velocity $\bar{v}$. Then the arrival time of the wave in the CDR gather, in accordance with equation (2), is

$$t_1 = \left\{ t_0^2 + x^2 \cos^2\varphi \left(\frac{1}{\bar{v}^2} - \frac{1}{v^2} \right) \right\}^{1/2} \approx t_0 \tag{5}$$

where x is the distance from the source to the center of the summation base. The time shift Δt_1 of the wave, obtained as the derivative of (5) with respect to x, (and letting $t_0 = 2h_0/\bar{v} = 2(h_i \mp x/2\sin\varphi)/\bar{v}$ (with h_i the perpendicular-reflection depth from the source)), equals

$$\Delta t_1 = \Delta x \left[\frac{x \cos^2\varphi}{t_1} \left(\frac{1}{\bar{v}^2} - \frac{1}{v^2} \right) \mp \frac{2h_0 \sin\varphi}{\bar{v}^2 t_1} \right] \tag{6}$$

In the general case ($\bar{v} \neq v$), the time shifts of the wave in individual reciprocal CDR gathers are not equal, in accordance with (6), since for the right gather, $x>0$, while for the left gather $x<0$. This allows someone who has already determined the difference r in observed time shifts of the wave in reciprocal CDR gathers to determine the value of the effective velocity:

$$r = \frac{2x\Delta x \cos^2\varphi}{t_1}\left(\frac{1}{\bar{v}^2} - \frac{1}{v^2}\right). \tag{7}$$

If $r = 0$, then the effective velocity of the wave coincides with the *a priori* given velocity, and for $r \neq 0$ these velocities do not coincide. For the calculation of true effective velocity in the previous case, it is necessary to have an estimate of the angle φ, which is obtained from the average, s, of the time shifts (6) of the wave in the reciprocal CDR gathers:

$$s = \mp\frac{t_0}{t_1}\frac{\Delta x \sin\varphi}{\bar{v}} \approx \mp\frac{\Delta x \sin\varphi}{\bar{v}}; \ \sin\varphi = \mp\frac{\bar{v}s}{\Delta x}. \tag{8}$$

Substituting (8) in (7), we have the equation

$$r = \frac{2x\Delta x}{t_1}\left(\frac{1}{\bar{v}^2} - \frac{1}{v^2}\right)\left(1 - \frac{\bar{v}^2 s^2}{\Delta x^2}\right) \tag{9}$$

with one unknown, $\bar{v}$.

In order to transform CDRC gathers, we put together four individual CDR gathers from the right flank of the system of observation (see Fig. 2), and separately, four CDR gathers from the left flank of the system. The two are stacked in such a way that the CDR gathers satisfy the principle of reciprocity to the same extent as do the pairs of individual gathers that comprise them. By virtue of the linearity of the summation procedure, the composition of the prepared CDR gathers is equivalent to stacking the original traces according to CDP and a subsequent summation by CDR, that is, the CDRC summation scheme described above. Economically, it is more profitable. Therefore, the specific character of CDRC summation with the goal of velocity analysis consists of the fact that a symmetrical multifold system of observations is broken up into two flanks, and from the CDP traces are chosen only those traces which belong to complete individual bases of CDR summation [1]. For instance (see Fig. 2), in order to obtain the right-flank CDR gather from midpoint location 6, the two most distant traces are included, while from CDP midpoint location 8, the two nearest-offset traces are used. To obtain the opposite CDRC gathers, the two nearest traces from midpoint location 6 are included, while the most distant are included from midpoint location 8. Thanks to such a selection of original traces, an inequality in the time shifts of waves on opposite (reciprocal) CDRC gathers is obtained, if $\bar{v} \neq v$.

CDRC gathers represent the result of stacking several individual CDR gathers with various x. Therefore an appropriate question is: with which concrete offset x is it necessary to associate the parameter r, which was calculated from the pair of CDRC gathers? By virtue of the linear dependence of r on x in formula (9), the concrete offset is chosen as the arithmetic mean of the offsets of the individual CDR gathers which make up the CDRC gather. For instance, the system of observations in Fig. 2 makes it possible to obtain the CDRC gather composed of four individual CDR gathers whose centers of bases have offsets from the source of $x = 0.2$, 0.4, 0.6, and 0.8 km. Consequently, the average offset is about 0.5 km.

Without going into the fine details, we note that thanks to the parameters s and r, determined from the CDRC gather, it is possible to determine more precisely the velocity characteristics of the medium and select the useful waves according to their velocity characteristics to the same extent as is done in ordinary CDR gathers [1, 9]. The parameter r plays an important role. The fact that it is zero for a correct choice of the *a priori* velocity tells us to what extent a wave belongs to the class of non-multiple useful waves. A variation of the parameter r from zero, for a correctly chosen *a priori* velocity, tells us about the difference between the true effective velocity of the wave and the given velocity, or about the amount of error in the calculated time shifts. In both cases it is desirable to weaken the wave's amplitude proportionately to the value of r, since this wave is either regular noise, or else a distortion of a useful wave, the use of which would lead to a distortion in the image. In practice, useful waves are selected with the help of a weighted amplitude multiplier in the form of a bell-shaped function with argument r^2. If in the course of processing there appears a statistical shift in the observed values r of the basic useful waves in either the positive or negative direction, then this can indicate a error in the *a priori* velocity information. Formula (9) is suitable for correcting this.

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29. The International Checkers Tournament finals involved three players, each from a different country. A five game series was played, and each loser was replaced in the next game by the player who watched. Can you deduce the identity of each player from the following information?

(1) In the first game, Carl played against Mr. Gainor while the man in the white shirt watched.

(2) In the second game, Mr. Farley played against the Englishman while the man in the blue shirt watched.

(3) In the third game, the Frenchman played against Bob while the man in the yellow shirt watched.

(4) In the fourth game, Al played against the American while Mr. Harkness watched.

(5) The loser of the fifth game wore a blue shirt. The winner of the fifth game won the tournament wearing a yellow shirt.

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30. "Startling" can be changed into eight other words by successive deletions, from a different place, of one letter at a time. What are the words?

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31. What is curious about this sentence: "Show this bold Prussian that praises slaughter, slaughter brings rout."

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32. The shortest word with all five vowels has seven letters. It starts with "s"; the other consonant is in the third position. What is the word?

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33. Figure out the rule that is used to determine the prices below and find the price of the last item.

Watch	$46
Bracelet	$ 4
Earrings	$10
Chain	$ 6
Ring	$?