A CRS-TYPE STACKING OPERATOR FOR CONVERTED WAVES

C. Vanelle, B. Kashtan, I. Abakumov, and D. Gajewski

email: *claudia.vanelle@zmaw.de*

keywords: *traveltimes, multiparameter stacking, converted waves*

ABSTRACT

Multiparameter stacking of monotypic reflections is an important tool in seismic data processing. An according formulation for converted waves exists, but it is cumbersome because more parameters are involved than for monotypic waves, making the optimisation process significantly more difficult and time-consuming. In this paper, we derive a new hyperbolic traveltime operator for the stacking of converted waves. It is formally identical with the existing formulation, but has the advantage that it can be directly expressed using the wavefield attributes describing monotypic reflections. Therefore, the parameter search for the converted waves can be significantly simplified because starting values known from a PP stack can be used.

INTRODUCTION

Shear waves play an important role in seismic imaging because they lead to knowledge of subsurface properties that cannot be obtained from PP-reflection surveys alone. However, corresponding SS-reflection experiments are rarely carried out, mainly due to the acquisition problems associated with SS-surveys.

Shear properties are key indicators for reservoir characterisation because parameters like porosity and permeability have strong influence on shear velocities (e.g. Nelson, 2001). Thus, the determination of shear velocities provides a direct means for the prediction of reservoir parameters. For example, it is possible to obtain information on the density and orientation of fractures from converted waves (e.g. Gaiser and Van Dok, 2003) since these fractures lead to seismic anisotropy.

Furthermore, the presence of gas clouds leads to high absorption for the P waves and makes imaging under such regions inadequate for PP surveys. Shear waves, on the other hand, do not suffer from the absorption (Stewart et al., 2003). Another example where converted waves are beneficial is imaging of targets with weak PP and strong PS impedance contrasts, e.g., for certain types of shale-sand boundaries (Stewart et al., 2003). Due to the smaller velocity of shear waves they can be used to enhance the seismic resolution. This is particularly interesting for the investigation of steeply-inclined near-surface structures (Stewart et al., 2003). Finally, shear waves are essential for the detection and quantification of seismic anisotropy (e.g. Tsvankin, 2001).

As an alternative to SS-surveys, PS-converted waves can be investigated. Here, the issues caused by difficulties with shear sources are avoided. The price we pay for the easier acquisition is that standard CMP-processing cannot be applied to converted waves in the same fashion as for monotypic (PP, SS) waves. The main reason is that the ray paths of converted waves are asymmetric with respect to interchanging sources and receivers. In particular in the presence of lateral inhomogeneities or anisotropy, the move-out of a converted wave becomes asymmetric because it contains a linear term, the so-called diodic move-out Thomsen (1999). This prevents the application of NMO correction in CMP gathers, which is based on the assumption of symmetric ray paths.

This problem is closely-related to that of conversion point dispersal. Although monotypic waves also encounter reflection point dispersal, the effect has a larger magnitude for converted waves. PS data are therefore sorted in common conversion point (CCP) gathers instead of CMP. However, the determination of the CCP itself can be rather complicated (e.g. Tessmer et al., 1990; Thomsen, 1999). Also, it is by no means trivial to obtain a velocity model from the subsequent processing. For example, neglecting the sign of the offset during the CCP binning can lead to a bimodal velocity spectrum due to the diodic move-out (Thomsen, 1999).

For monotypic waves, standard CMP stacking can be extended to multiparameter stacking. These methods, with one fundamental example being the Common Reflection Surface stack (CRS, Mueller, 1999), have gained a significant amount of recognition over the past decade. For 2D zero-offset CRS, the hyperbolic stacking surface is determined by three independent parameters or attributes: the incidence/emergence angle of the zero-offset ray and the curvatures of two fictitious wavefronts Hubral (1983). These can subsequently be exploited in applications like velocity model building and others (see, e.g., Baykulov et al., 2011, for details on a CRS-based processing workflow).

A corresponding multiparameter operator for converted waves was introduced by Bergler et al. (2002). It contains five parameters, two more than the monotypic version, which account for the asymmetry of the ray paths. In contrast to the attributes in the monotypic case, however, the five parameters for converted waves do not have a physically intuitive meaning in terms of wavefront curvatures.

In this work, we derive a CRS-type hyperbolic multiparameter stacking operator for converted waves. We use a model-based approach and obtain an expression that is formally identical to that of Bergler et al. (2002) but uses the same three parameters as the monotypic CRS operator. Our derivation begins with a constant v_p/v_s ratio, which leads to a physical interpretation of the attributes of the new operator. This assumption is not necessarily a restriction, as Abakumov et al. (2011) have shown that their operator, which was also derived for constant v_p/v_s, leads to good stack results even when the ratio is varied.

The assumption of constant v_p/v_s can even be used as an advantage, e.g. in formulating an efficient search strategy for converted waves. These advantages are discussed in detail after the derivation of the new operator.

DERIVATION OF THE CRS-TYPE OPERATOR FOR CONVERTED WAVES

Coordinates and ansatz

In order to derive the CRS-PS traveltime formula, we begin with defining our coordinates, parameters, and angles. They are depicted in Figure 1.

The circular reflector is defined by its radius R, the depth of its centre, H, and the lateral coordinate of its centre, x_c (see Figure 1a). The acquisition is described by x_1 and x_2, the coordinates of the source and receiver, which are assumed to lie on a flat datum at $z = 0$. The position at which the zero-offset ray emerges is denoted by x_0, see Figure 1b). The quantities $\epsilon_i = x_i - x_0$ are assumed to be small.

It is important to distinguish between the angles α, which describes the point on the circle $(R \sin\alpha, H - R\cos\alpha)$ where the zero-offset reflection takes place, and θ, which describes the point on the circle $(R\sin\theta, H - R\cos\theta)$ where the reflection occurs in the offset case.

Furthermore, we introduce the ray length of the one-way zero-offset ray,

$$D = \frac{H}{\cos\alpha} - R \quad . \tag{1}$$

The zero-offset coordinate is related to the angle α and the depth H by

$$x_0 = H\ \tan\alpha + x_c \quad . \tag{2}$$

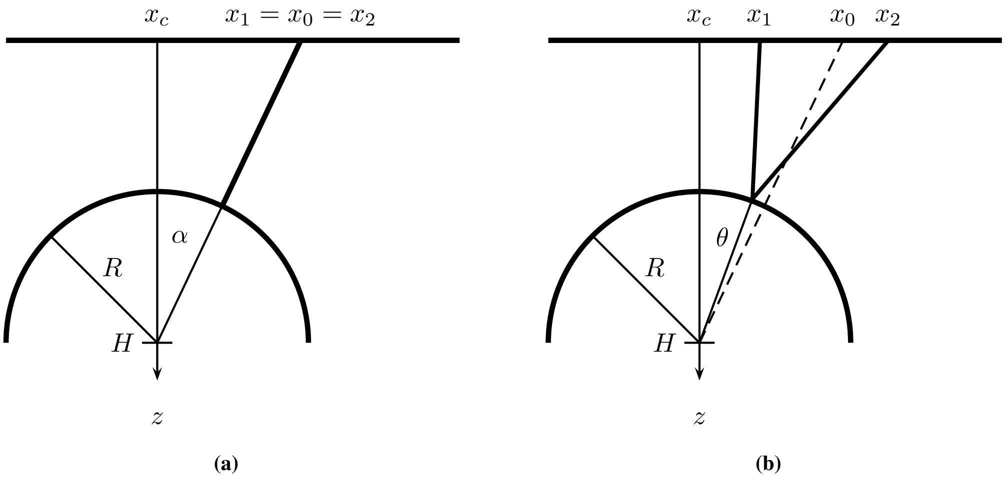

Figure 1: Reflection from a circle with radius R and centre (x_c, H). (a) The angle α describes the point on the circle where the zero-offset reflection takes place. (b) The angle θ describes the reflection point on the circle in the offset case.

For this geometry, the traveltime in terms of the reflection angle θ, $t(\theta)$ is given by

$$t(\theta) = t_1(\theta) + t_2(\theta) \quad , \tag{3}$$

where the traveltimes $t_1(\theta)$ and $t_2(\theta)$ are those of the down- and upgoing rays, i.e.,

$$t_i(\theta) = \frac{1}{V_i} \sqrt{(x_i - x_c - R\sin\theta)^2 + (H - R\cos\theta)^2} \quad , \tag{4}$$

or, rewritten in terms of ϵ_i,

$$t_i(\theta) = \frac{1}{V_i} \sqrt{(\epsilon_i + H\tan\alpha - R\sin\theta)^2 + (H - R\cos\theta)^2} \quad . \tag{5}$$

In the first step of the derivation of our new traveltime expression, we expand $t(\theta)$ in the vicinity of the zero-offset angle α, up to second order:

$$t(\theta) \approx t(\theta = \alpha) + \frac{\partial t(\theta = \alpha)}{\partial\theta} (\theta - \alpha) + \frac{1}{2} \frac{\partial^2 t(\theta = \alpha)}{\partial\theta^2} (\theta - \alpha)^2 \quad . \tag{6}$$

In order to describe the traveltime of a reflected wave, Snell's law must be fulfilled. This requires that $\partial t(\theta)/\partial\theta = 0$:

$$\frac{\partial t(\theta)}{\partial\theta} \approx \frac{\partial t(\theta = \alpha)}{\partial\theta} + \frac{\partial^2 t(\theta = \alpha)}{\partial\theta^2} (\theta - \alpha) = 0 \quad , \tag{7}$$

or:

$$\theta - \alpha = -\frac{\partial t(\theta = \alpha)}{\partial\theta} \Bigg/ \frac{\partial^2 t(\theta = \alpha)}{\partial\theta^2} \quad . \tag{8}$$

Substituting (8) into (6), we find that

$$t(\theta) \approx t(\theta = \alpha) - \left[\frac{\partial t(\theta = \alpha)}{\partial\theta}\right]^2 \Bigg/ 2\, \frac{\partial^2 t(\theta = \alpha)}{\partial\theta^2} \quad . \tag{9}$$

To evaluate (9), we need to find expressions for $t_i(\theta = \alpha)$, $\partial t_i(\theta = \alpha)/\partial\theta$, and $\partial^2 t_i(\theta = \alpha)/\partial\theta^2$. These will be derived in the following sections.

Derivation of the zero-order term

In this section, we derive an expression of second order in ϵ_i for the traveltime $t_i(\alpha) \equiv t_i(\theta = \alpha)$. We begin by setting $\theta = \alpha$ in (5) and rewriting it with the help of the expression for D, equation (1):

$$\begin{aligned} t_i(\alpha) &= \frac{1}{V_i}\sqrt{(\epsilon_i + H\tan\alpha - R\sin\alpha)^2 + (H - R\cos\alpha)^2} \\ &= \frac{1}{V_i}\sqrt{\left(\epsilon_i + \left[\frac{H}{\cos\alpha} - R\right]\sin\alpha\right)^2 + (H - R\cos\alpha)^2} \\ &= \frac{1}{V_i}\sqrt{(\epsilon_i + D\sin\alpha)^2 + D^2\cos^2\alpha} \\ &= \frac{1}{V_i}\sqrt{\epsilon_i^2 + 2\,D\epsilon_i\sin\alpha + D^2} \end{aligned} \tag{10}$$

In the next step, we expand equation (10) until second order in ϵ_i:

$$t_i(\alpha;\epsilon_i) \approx t_i(\alpha;\epsilon_i = 0) + \frac{\partial t_i(\alpha;\epsilon_i = 0)}{\partial\epsilon_i}\,\epsilon_i + \frac{1}{2}\,\frac{\partial^2 t_i(\alpha;\epsilon_i = 0)}{\partial\epsilon_i^2}\,\epsilon_i^2 \tag{11}$$

For the zero-order term we find

$$t_i(\alpha;\epsilon_i = 0) = \frac{D}{V_i} \quad . \tag{12}$$

Now we determine the first-order term:

$$\frac{\partial t_i(\alpha;\epsilon_i)}{\partial\epsilon_i} = \frac{\epsilon_i + D\sin\alpha}{V_i^2\,t_i} \quad , \tag{13}$$

which for $\epsilon_i = 0$ becomes

$$\frac{\partial t_i(\alpha;\epsilon_i = 0)}{\partial\epsilon_i} = \frac{\sin\alpha}{V_i} \quad , \tag{14}$$

where (12) was substituted.

For the second-order term, we obtain

$$\begin{aligned} \frac{\partial^2 t_i(\alpha;\epsilon_i)}{\partial\epsilon_i^2} &= \frac{1}{V_i^2}\,\frac{\partial^2}{\partial\epsilon_i^2}\left(\frac{\epsilon_i + D\sin\alpha}{t_i}\right) \\ &= \frac{1}{V_i^2\,t_i^2}\left(t_i - \frac{(\epsilon_i + D\sin\alpha)^2}{V_i^2\,t_i}\right). \end{aligned} \tag{15}$$

Setting $\epsilon_i = 0$ leads to

$$\frac{\partial^2 t_i(\alpha;\epsilon_i = 0)}{\partial\epsilon_i^2} = \frac{1}{D^2}\left(\frac{D^2 - D^2\sin^2\alpha}{V_i\,D}\right) = \frac{\cos^2\alpha}{V_i\,D} \quad . \tag{16}$$

Substituting these derivatives into equation (11) we arrive at a second-order expression in ϵ_i for the traveltime $t_i(\alpha)$:

$$t_i(\alpha) \approx \frac{D}{V_i}\left(1 + \frac{\sin\alpha}{D}\,\epsilon_i + \frac{\cos^2\alpha}{2\,D^2}\,\epsilon_i^2\right) \quad . \tag{17}$$

Derivation of the first-order term

In this section, we derive an expression for the first derivative of the traveltime, $\partial t_i(\theta = \alpha)/\partial\theta$. Using (5), we find that

$$\begin{aligned} \partial t_i(\theta)/\partial\theta &= \frac{1}{2\,V_i^2\,t_i}\,2\left[R\sin\theta(H - R\cos\theta) - R\cos\theta(\epsilon_i + H\tan\alpha - R\sin\theta)\right] \\ &= \frac{R}{V_i^2\,t_i}\left[H\sin\theta - (\epsilon_i + H\tan\alpha)\cos\theta\right] \quad , \end{aligned} \tag{18}$$

which, for $\theta = \alpha$ reduces to

$$
\begin{aligned}
\partial t_i(\theta = \alpha)/\partial\theta &= \frac{R}{V_i^2\, t_i}\left[H\sin\alpha - \epsilon_i\cos\alpha - H\sin\alpha\right] \\
&= -\frac{R\cos\alpha}{V_i^2\, t_i}\,\epsilon_i \\
&\approx -\frac{R\cos\alpha}{V_i\, D}\,\epsilon_i \quad . \qquad (19)
\end{aligned}
$$

The substitution of the last step in (19) is motivated by our search for a second-order expression and the fact that the first derivative appears in squared form in (9).

Derivation of the second-order term

In this section, we derive an expression for the second-order derivative of the traveltime, $\partial^2 t_i(\theta = \alpha)/\partial\theta^2$:

$$
\begin{aligned}
\frac{\partial^2 t_i(\theta)}{\partial\theta^2} &= \frac{R}{V_i^2}\frac{\partial}{\partial\theta}\frac{H\sin\theta - (\epsilon_i + H\tan\alpha)\cos\theta}{t_i} \\
&= \frac{R}{V_i^2\, t_i}\left[H\cos\theta + (\epsilon_i + H\tan\alpha)\sin\theta - \frac{R}{V_i^2\, t_i^2}\left(H\sin\theta - (\epsilon_i + H\tan\alpha)\cos\theta\right)^2\right] \quad (20)
\end{aligned}
$$

Since we are interested in an expansion of $t(\theta)$ up to second order in ϵ_i, we need to consider only constant terms in $\partial^2 t_i(\theta = \alpha)/\partial\theta^2$, as the first-order derivative is linear in ϵ_i and it enters the final traveltime equation in squared form (see (9)). Therefore, (20) can be reduced to

$$
\frac{\partial^2 t_i(\theta = \alpha)}{\partial\theta^2} \approx \frac{R(R+D)}{V_i\, D} \quad . \qquad (21)
$$

Final result in CMP coordinates

Substituting the results from the previous sections, equations (17), (19), and (21) into (9), we find that the traveltime expansion up to second order is

$$
\begin{aligned}
t(\theta) \approx\; & D\left(\frac{1}{v_1} + \frac{1}{v_2}\right) + \sin\alpha\left(\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2}\right) \\
& + \frac{\cos^2\alpha}{2\,D}\left(\frac{\epsilon_1^2}{v_1} + \frac{\epsilon_2^2}{v_2}\right) - \frac{R\,\cos^2\alpha}{2\,D(R+D)}\,\frac{\left(\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2}\right)^2}{\frac{1}{v_1} + \frac{1}{v_2}} \quad . \qquad (22)
\end{aligned}
$$

We will now rewrite this result in midpoint and half-offset coordinates, and then reformulate it in CRS parameters. With

$$
\begin{aligned}
\epsilon_1 &= x_m - h - x_0 \\
\epsilon_2 &= x_m + h - x_0
\end{aligned}
$$

we compute

$$\begin{aligned}
\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2} &= \frac{x_m - x_0 - h}{v_1} + \frac{x_m - x_0 + h}{v_2} \\
&= (x_m - x_0)\left(\frac{1}{v_1} + \frac{1}{v_2}\right) - h\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \quad ;
\end{aligned}$$

$$\begin{aligned}
\frac{\epsilon_1^2}{v_1} + \frac{\epsilon_2^2}{v_2} &= \frac{(x_m - x_0)^2 + h^2 - 2\,h\,(x_m - x_0)}{v_1} + \frac{(x_m - x_0)^2 + h^2 + 2\,h\,(x_m - x_0)}{v_2} \\
&= (x_m - x_0)^2\left(\frac{1}{v_1} + \frac{1}{v_2}\right) + h^2\left(\frac{1}{v_1} + \frac{1}{v_2}\right) - 2\,h\,(x_m - x_0)\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \quad ;
\end{aligned}$$

$$\left(\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2}\right)^2 = (x_m - x_0)^2\left(\frac{1}{v_1} + \frac{1}{v_2}\right)^2 + h^2\left(\frac{1}{v_1} - \frac{1}{v_2}\right)^2 - 2\,h\,(x_m - x_0)\left(\frac{1}{v_1} + \frac{1}{v_2}\right)\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \quad .$$

Now we introduce the abbreviations

$$\frac{2}{v^{\pm}} = \frac{1}{v_1} \pm \frac{1}{v_2}$$

and evaluate (22) in terms of the powers of $(x_m - x_0)$ and h:

$$\begin{aligned}
const. \quad &: \quad \frac{2\,D}{v^+} \\
(x_m - x_0) \quad &: \quad \frac{2\,\sin\alpha}{v^+} \\
h \quad &: \quad \frac{-2\,\sin\alpha}{v^-} \\
(x_m - x_0)^2 \quad &: \quad \frac{\cos^2\alpha}{v^+(R + D)} \\
h^2 \quad &: \quad \frac{\cos^2\alpha}{v^+\,D} - \frac{v^+\,R\,\cos^2\alpha}{(v^-)^2\,D\,(R + D)} \\
(x_m - x_0)\,h \quad &: \quad \frac{-2\,\cos^2\alpha}{v^-(R + D)}
\end{aligned}$$

In order to express these coefficients by the CRS parameters β_0, R_{NIP}, and R_N, we consider the monotypic case, where $v_1 = v_2 = v_0$, leading to $v^+ = v_0$, and $1/v^- = 0$. By comparison with the (parabolic) CRS formula we see immediately that

$$\beta_0 = \alpha \quad , \tag{23a}$$

$$R_{NIP} = D \quad , \tag{23b}$$

$$R_N = D + R \quad . \tag{23c}$$

Note that this result also follows from geometrical considerations (see Figure 1).

With (23), the coefficients for the (parabolic) CRS equation for converted waves become

$$\begin{aligned}
t_0 &: \quad \frac{2\,R_{NIP}}{v^+} \\
(x_m - x_0) &: \quad \frac{2\,\sin\beta_0}{v^+} \\
h &: \quad \frac{-2\,\sin\beta_0}{v^-} \\
(x_m - x_0)^2 &: \quad \frac{\cos^2\alpha}{v^+\,R_N} \\
h^2 &: \quad \frac{\cos^2\beta_0}{v^+\,R_{NIP}} - \frac{\cos^2\beta_0}{v^-}\left(\frac{R_N - R_{NIP}}{R_N\,R_{NIP}}\right)\frac{v^+}{v^-} \\
(x_m - x_0)\,h &: \quad \frac{-2\,\cos^2\beta_0}{v^-\,R_N}
\end{aligned}$$

In order to obtain a hyperbolic traveltime expression, we square the parabolic formula and neglect terms of higher order than two. This leads us to the final equation,

$$\begin{aligned}
t^2 \approx\; & \left(t_0 + \frac{2\,\sin\beta_0}{v^+}(x_m - x_0) - \frac{2\,\sin\beta_0}{v^-}\,h\right)^2 \\
& +2\,t_0\cos^2\beta_0\left(\frac{(x_m - x_0)^2}{v^+R_N} + \frac{h^2}{v^+R_{NIP}}\right) \\
& -2\,t_0\cos^2\beta_0\left(\frac{(R_N - R_{NIP})}{R_N R_{NIP}}\frac{v^+\,h^2}{(v^-)^2} + \frac{2\,(x_m - x_0)\,h}{v^-R_N}\right)
\end{aligned} \tag{24}$$

This equation includes the monotypic case as a subset with $v^+ = v_0$ and $1/v^- = 0$. Note that in addition to the velocities, only three parameters are required. The reason is that in our derivation, we have assumed a constant ratio of v_p/v_s. In this case, the zero-offset reflections stems from the same subsurface point for monotypic as the converted waves. Bergler et al.'s equation (2002) has five independent parameters because it is not restricted by such an assumption.

Result in γ-CMP coordinates: comparison with Abakumov et al.'s CRS-formula

The choice of an alternate coordinate system can lead to a considerable simplification of (24). Abakumov et al. (2011) have introduced γ-CMP coordinates, i.e.,

$$\tilde{x}_m = \frac{x_1 + \gamma x_2}{1+\gamma} \qquad \tilde{h} = \frac{x_2 - x_1}{1+\gamma} \quad , \tag{25}$$

where $\gamma = v_1/v_2$. With these coordinates, we can express ϵ_1 and ϵ_2 as

$$\begin{aligned}
\epsilon_1 &= \tilde{x}_m - x_0 - \gamma\tilde{h} \\
\epsilon_2 &= \tilde{x}_m - x_0 + \tilde{h} \quad .
\end{aligned} \tag{26}$$

As for the 'standard' CMP coordinates, we formulate

$$\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2} \quad , \qquad \frac{\epsilon_1^2}{v_1} + \frac{\epsilon_2^2}{v_2} \quad , \qquad \left(\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2}\right)^2$$

in terms of γ-CMP coordinates:

$$\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2} = (\tilde{x}_m - x_0)\left(\frac{1}{v_1} + \frac{1}{v_2}\right) \quad ;$$

$$\frac{\epsilon_1^2}{v_1} + \frac{\epsilon_2^2}{v_2} = \left((\tilde{x}_m - x_0)^2 + \gamma\tilde{h}^2\right)\left(\frac{1}{v_1} + \frac{1}{v_2}\right) \quad ;$$

$$\left(\frac{\epsilon_1}{v_1} + \frac{\epsilon_2}{v_2}\right)^2 = (\tilde{x}_m - x_0)^2\left(\frac{1}{v_1} + \frac{1}{v_2}\right)^2 \quad .$$

Substituting these expressions and the representation of the CRS parameters, (23), into (22), we find after some algebra that the linear term in $\tilde{h}$ vanishes, as well as the mixed quadratic term $(\tilde{x}_m - x_0)\tilde{h}$. The final (hyperbolic) result is

$$t^2 \approx \left(t_0 + \frac{2\,\sin\beta_0}{v^+}\,(\tilde{x}_m - x_0)\right)^2 + 2\,t_0\cos^2\beta_0\left(\frac{(\tilde{x}_m - x_0)^2}{v^+ R_N} + \frac{\gamma\tilde{h}^2}{v^+ R_{NIP}}\right) \quad . \tag{27}$$

This equation is identical to the one derived by Abakumov et al. (2011). It is also formally identical to the monotypic CRS expression in standard CMP coordinates: for $v_1 = v_2$ the γ-CMP and standard CMP coordinates coincide, and (27) reduces to the original, i.e., monotypic, CRS expression.

DISCUSSION

If γ-CMP coordinates are used, the pragmatic search strategy suggested by Abakumov et al. (2011) can be applied. Although this section focusses on the CRS-type operator for converted waves in standard CMP-coordinates as given by (24), some of our conclusions apply to Abakumov et al.'s operator in a similar fashion.

If the ratio of v_p/v_s (or v_1/v_2, accordingly) is constant even in heterogeneous media, both PP and PS reflections stem from the same subsurface point. In that case, the paths of the corresponding zero-offset rays coincide. If we knew that v_p/v_s is constant, we could therefore use the CRS parameters β_0, R_N, and R_{NIP} obtained from the PP stack directly to create the PS stack with (24) without carrying out an additional search.

If v_p/v_s varies, we could still use the PP parameters as starting values for the required five-parameter search using Bergler et al.'s 2002 equation with the starting parameters expressed by (24). This would considerably speed up the optimisation. Furthermore, the difference between the starting coefficients in (24) and the final ones resulting from Bergler et al.'s formula would depend on the variation of the v_p/v_s ratio. Although further investigations are required here, this difference could be evaluated for shear velocity determination, in particular in conjunction with the proposed strategy for NIP-Wave tomography for converted waves (Vanelle and Gajewski, 2009).

ACKNOWLEDGEMENTS

We thank the Applied Seismics group in Hamburg for continuous discussion, in particular Benjamin Schwarz. This work was kindly supported by the sponsors of the Wave Inversion Technology (WIT) Consortium.

REFERENCES

Abakumov, I., Schwarz, B., Vanelle, C., Kashtan, B., and Gajewski, D. (2011). Double square root traveltime approximation for converted waves. *15th Annual WIT report*.

Baykulov, M., Dümmong, S., and Gajewski, D. (2011). From time to depth with CRS attributes. *Geophysics*, 76:S151–S155.

Bergler, S., Duveneck, E., Höcht, G., Zhang, Y., and Hubral, P. (2002). Common-reflection-surface stack for converted waves. *Stud. geophys. geod.*, 46:165–175.

Gaiser, J. E. and Van Dok, R. R. (2003). Converted shear-wave anisotropy attributes for fractured-reservoir management. In *AAPG Annual Convention, Abstracts*.

Hubral, P. (1983). Computing true-amplitude reflections in a laterally inhomogeneous earth. *Geophysics*, 48:1051–1062.

Mueller, T. (1999). *The Common Reflection Surface stack method – seismic imaging without explicit knowledge of the velocity model*. PhD thesis, University of Karlsruhe.

Nelson, R. A. (2001). *Geologic analysis of naturally fractured reservoirs*. Gulf Professional Publishing, Houston.

Stewart, R. R., Gaiser, J. E., Brown, R. J., and Lawton, D. C. (2003). Converted-wave seismic exploration: Applications. *Geophysics*, 68:40–57.

Tessmer, G., Krajewski, P., Fertig, J., and Behle, A. (1990). Processing of PS-reflection data applying a common conversion-point stacking technique. *Geophysical Prospecting*, 38:267–286.

Thomsen, L. (1999). Converted-wave reflection seismology over inhomogeneous, anisotropic media. *Geophysics*, 64:678–690.

Tsvankin, I. (2001). *Seismic Signatures and Analysis of Reflection Data in Anisotropic Media*. Pergamon (Elsevier).

Vanelle, C. and Gajewski, D. (2009). NIP-wave tomography for converted waves. *13th Annual WIT report*.