REPRESENTATIONS OF SEISMIC REFLECTION DATA

Part II: NEW DEVELOPMENTS

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ABSTRACT

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We present reciprocity and representation theorems for one-way wave fields. The latter theorem is the basis for the derivation of the one-way volume integral representation of seismic reflection data. Its properties are compared with the representations discussed in Part I of this paper.

KEY WORDS: reciprocity, representation, one-way, inversion.

INTRODUCTION

In Part I of this paper (Wapenaar and Berkhout, 1993) we discussed two-way boundary and volume integral representations as well as a one-way boundary integral representation of seismic reflection data. Here we show step by step how to arrive at a *one-way volume* integral representation, which fully accounts for internal multiple reflections. The applications in seismic inversion will be briefly indicated. For detailed derivations we refer to two papers on reciprocity and representation theorems for one-way wave fields (Wapenaar, 1993a, 1993b; hereafter referred to as paper A and paper B, respectively).

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ONE-WAY WAVE EQUATION

We denote the Cartesian coordinate vector by $\boldsymbol{x}$ = (x,y,z) and the angular frequency by ω. In the $\boldsymbol{x},\omega$-domain the one-way wave equation reads

$$\partial \boldsymbol{P}(\boldsymbol{x})/\partial z = \hat{\mathbf{B}}(\boldsymbol{x})\boldsymbol{P}(\boldsymbol{x}) + \boldsymbol{S}(\boldsymbol{x}) \ , \tag{1}$$

(the parameter ω is omitted for notational convenience). Here the one-way wave vector $\boldsymbol{P}$ contains the downgoing and upgoing wave fields $\boldsymbol{P}^+$ and $\boldsymbol{P}^-$, respectively, according to

$$\boldsymbol{P}(\boldsymbol{x}) = \begin{pmatrix} \boldsymbol{P}^+ \\ \boldsymbol{P}^- \end{pmatrix}(\boldsymbol{x}) \ . \tag{2}$$

In the acoustic situation $\boldsymbol{P}^\pm$ is a scaled version of the downgoing / upgoing acoustic pressure; in the full elastic situation $\boldsymbol{P}^\pm$ contains the three wave-types $qP^\pm$, $qS_1^\pm$ and $qS_2^\pm$. The one-way source vector $\boldsymbol{S}$ is defined in a similar way as $\boldsymbol{P}$ in equation (2). $\hat{\mathbf{B}}$ is a 2 × 2 (acoustic) or 6 × 6 (elastic) *pseudo-differential operator* matrix (it contains the operators $\partial/\partial x$ and $\partial/\partial y$, see paper A; for a discussion about its existence in the acoustic situation, see de Hoop, 1992). It is expressed in terms of the (block-) diagonal operator matrix $\hat{\Lambda}$ and a non-diagonal coupling operator matrix $\hat{\Delta}_0$, according to

$$\hat{\mathbf{B}}(\boldsymbol{x}) = -j\omega\hat{\Lambda}(\boldsymbol{x}) + \hat{\Delta}_0(\boldsymbol{x}) \ , \tag{3}$$

where

$$\hat{\Lambda} = \begin{pmatrix} \hat{\Lambda}^+ & \mathrm{O} \\ \mathrm{O} & \hat{\Lambda}^- \end{pmatrix} \text{ and } \hat{\Delta}_0 = \begin{pmatrix} \hat{\mathbf{T}}^+ & \hat{\mathbf{R}}^- \\ -\hat{\mathbf{R}}^+ & -\hat{\mathbf{T}}^- \end{pmatrix} . \tag{4a,b}$$

The generalized vertical slowness operators $\hat{\Lambda}^+$ and $\hat{\Lambda}^-$ essentially govern the *propagation* of the downgoing and upgoing waves, respectively. The transmission operators $\hat{\mathbf{T}}^+$ and $\hat{\mathbf{T}}^-$ as well as the reflection operators $\hat{\mathbf{R}}^+$ and $\hat{\mathbf{R}}^-$ govern the *scattering* of the various wave types. These operators are proportional to the vertical derivative $\partial/\partial z$ of the medium parameters. They vanish in any region where the medium parameters do not vary with depth.

RECIPROCITY OF ONE-WAY WAVE FIELDS

In general, a reciprocity theorem interrelates the quantities that characterize two admissible physical states that could occur in one and the same domain in space-time (de Hoop, 1988; Fokkema and van den Berg, 1993). Here we introduce the reciprocity relations for one-way wave fields. The two different states (i.e., wave fields, sources and medium parameters) will be distinguished by the subscripts A and B. We consider the interaction between downgoing waves in one state and upgoing waves in the other and vice versa (Fig. 1). To be more specific, we consider the interaction quantity

$$(\boldsymbol{P}_A^+)^T\boldsymbol{P}_B^- - (\boldsymbol{P}_A^-)^T\boldsymbol{P}_B^+ \ , \tag{5}$$

where T denotes transposition (modified after Berkhout and Wapenaar, 1989). To simplify the notation we rewrite the interaction quantity as

$$\boldsymbol{P}_A^T \mathbf{N} \boldsymbol{P}_B \quad , \quad \text{with } \mathbf{N} = \begin{pmatrix} \mathbf{O} & \mathbf{I} \\ -\mathbf{I} & \mathbf{O} \end{pmatrix} \quad . \tag{5}$$

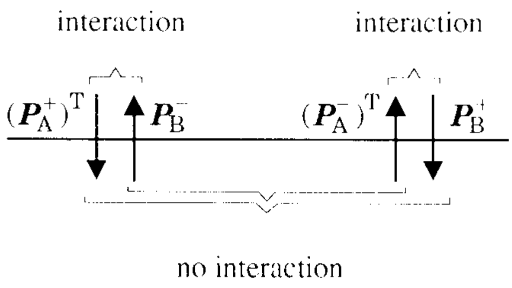

Fig. 1. Both terms of the interaction quantity (5) contain waves that propagate in opposite directions.

Applying the operator $\partial/\partial z$ to this quantity and using the one-way wave equation (1) yields the *local* reciprocity relation, according to

$$(\partial/\partial z)(\boldsymbol{P}_A^T\mathbf{N}\boldsymbol{P}_B) = \boldsymbol{P}_A^T\mathbf{N}\hat{\mathbf{B}}_B\boldsymbol{P}_B + (\hat{\mathbf{B}}_A\boldsymbol{P}_A)^T\mathbf{N}\boldsymbol{P}_B + \boldsymbol{P}_A^T\mathbf{N}\boldsymbol{S}_B + \boldsymbol{S}_A^T\mathbf{N}\boldsymbol{P}_B \ . \tag{7}$$

It would be useful if the right-hand side could be reorganized such that it contains a term proportional to $\hat{\mathbf{B}}_B - \hat{\mathbf{B}}_A$, which vanishes when the medium parameters in both states are identical. This reorganization appears to be possible by integrating both sides of equation (7) over a volume V, 'enclosed' by two infinite horizontal surfaces, denoted by ∂V, with outward pointing normal vector $\boldsymbol{n} = (0,0,n_z)$, see Fig. 2. The result of this integration is the *global* reciprocity relation, given by

$$\int_{\partial V} (\boldsymbol{P}_A^T\mathbf{N}\boldsymbol{P}_B)n_z d^2\boldsymbol{x} =$$

$$\int_V \boldsymbol{P}_A^T\mathbf{N}(\hat{\mathbf{B}}_B - \hat{\mathbf{B}}_A)\boldsymbol{P}_B d^3\boldsymbol{x} + \int_V (\boldsymbol{P}_A^T\mathbf{N}\boldsymbol{S}_B + \boldsymbol{S}_A^T\mathbf{N}\boldsymbol{P}_B) d^3\boldsymbol{x} \ . \tag{8}$$

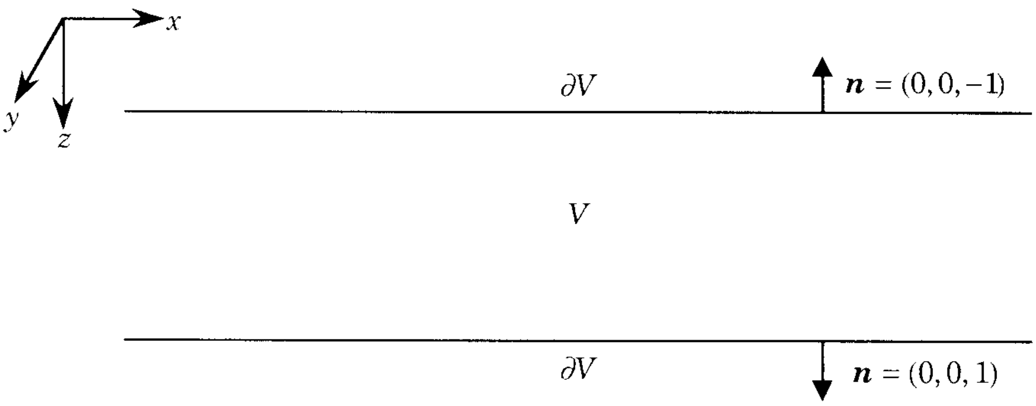

Fig. 2. The configuration for the global reciprocity theorem.

For details of the derivation see paper A. As an illustration we consider a special situation. We choose identical medium parameters in both states so that the first volume integral vanishes. Moreover, we choose the medium outside ∂V scatter-free (i.e., $\hat{\mathbf{\Delta}}_0 = \mathbf{O}$) and source-free. Now it is easily seen that the interaction quantity (5) vanishes at ∂V and so does the left-hand side of equation (8). We consider the acoustic (i.e., scalar) situation and we choose point sources for the downgoing waves at $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$ in V, according to $\boldsymbol{S}_A^+ \rightarrow \delta(\boldsymbol{x} - \boldsymbol{x}_A)$ and $\boldsymbol{S}_B^+ \rightarrow \delta(\boldsymbol{x} - \boldsymbol{x}_B)$ and we set the sources for the upgoing waves equal to zero. Now equation (8) yields

$$\boldsymbol{P}_B^-(\boldsymbol{x}_A) = \boldsymbol{P}_A^-(\boldsymbol{x}_B) \ . \tag{9}$$

This equation formulates the property that sources for downgoing waves and receivers for upgoing waves are interchangeable, see Fig. 3. Hence, when seismic data are decomposed into one-way responses, their reciprocity properties are fully preserved. A more general formulation of equation (9) will be given in the next section.

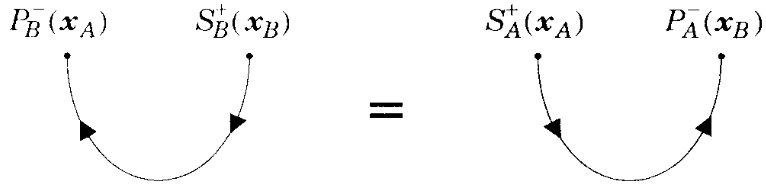

Fig. 3. Reciprocity of decomposed seismic data.

GREEN'S ONE-WAY WAVE FIELD MATRIX

We introduce a (2×2 or 6×6) Green's matrix **G** which satisfies the following one-way wave equation

$$\partial \mathbf{G}/\partial z = \check{\mathbf{B}}\mathbf{G} + \mathbf{I}\delta(\boldsymbol{x} - \boldsymbol{x}_A) \quad , \tag{10}$$

where $\check{\mathbf{B}}$ is the pseudo-differential operator matrix defined in some reference medium. The (2 or 6) columns of $\mathbf{G} = \mathbf{G}(\boldsymbol{x},\boldsymbol{x}_A)$ represent (2 or 6) independent Green's one-way wave fields at observation point $\boldsymbol{x}$, related to (2 or 6) independent one-way sources at source point $\boldsymbol{x}_A$. **G** may be partitioned as follows

$$\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_A) = \begin{pmatrix} \mathbf{G}^{+,+} & \mathbf{G}^{+,-} \\ \mathbf{G}^{-,+} & \mathbf{G}^{-,-} \end{pmatrix} (\boldsymbol{x},\boldsymbol{x}_A) \quad , \tag{11}$$

where the superscripts refer to the propagation direction at $\boldsymbol{x}$ and $\boldsymbol{x}_A$, respectively. Let $\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_A)$ play the role of state A in equation (8) and let a similar matrix $\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_B)$ play the role of state B. Then a similar exercise as in the previous section yields the following reciprocity relation

$$\mathbf{G}(\boldsymbol{x}_A,\boldsymbol{x}_B) = -\mathbf{N}^{-1}\mathbf{G}^T(\boldsymbol{x}_B,\boldsymbol{x}_A)\mathbf{N} \quad , \tag{12}$$

which is a generalization of equation (9).

REPRESENTATION OF ONE-WAY WAVE FIELDS

Consider a one-way wave vector $\boldsymbol{P}(\boldsymbol{x})$ related to a one-way point source $\boldsymbol{S}_0(\boldsymbol{x})\delta(\boldsymbol{x} - \boldsymbol{x}_S)$, with $\boldsymbol{x}_S$ in V. Our aim is to find a representation for $\boldsymbol{P}(\boldsymbol{x}_D)$, with detector point $\boldsymbol{x}_D$ in V. To this end we let a Green's matrix $\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_D)$ play the role of state A in equation (8) and we let $\boldsymbol{P}(\boldsymbol{x})$ play the role of state B. Using relation (12) as well, we obtain

$$\boldsymbol{P}(\boldsymbol{x}_D) = \mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x}_S)\boldsymbol{S}_0(\boldsymbol{x}_S) - \int_{\partial V} \mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x})\boldsymbol{P}(\boldsymbol{x})n_z d^2\boldsymbol{x}$$
$$+ \int_V \mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x})\{\hat{\mathbf{B}}(\boldsymbol{x}) - \check{\mathbf{B}}(\boldsymbol{x})\}\boldsymbol{P}(\boldsymbol{x})d^3\boldsymbol{x} \quad , \tag{13}$$

where $\hat{\mathbf{B}}$ and $\check{\mathbf{B}}$ are the operator matrices for $\boldsymbol{P}$ in the true medium and for **G** in the reference medium, respectively (see also paper B). Note the analogy with equation (3) in Part I. In the remainder of this paper we let V span the entire space so that the boundary integral vanishes.

PRIMARY REPRESENTATION

For the reference operator we choose $\check{\mathbf{B}} = -j\omega\hat{\mathbf{\Lambda}}$, hence $\hat{\mathbf{B}} - \check{\mathbf{B}} = \hat{\mathbf{\Delta}}_0$. Since $\hat{\mathbf{\Lambda}}$ is a (block-) diagonal operator matrix (in the true medium), $\mathbf{G}$ will also get a (block-) diagonal structure, according to

$$\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S) = \begin{pmatrix} \mathbf{W}_p^+ & \mathbf{O} \\ \mathbf{O} & -\mathbf{W}_p^- \end{pmatrix} (\boldsymbol{x},\boldsymbol{x}_S) \quad . \tag{14}$$

We refer to $\mathbf{W}_p^+$ and $\mathbf{W}_p^-$ as the extrapolation operators for the *primary* downgoing and upgoing waves in the true medium. Note that $\mathbf{W}_p^+(\boldsymbol{x},\boldsymbol{x}_S) = [\mathbf{W}_p^-(\boldsymbol{x}_S,\boldsymbol{x})]^T$, on account of equation (12). Also note that $\mathbf{W}_p^+(\boldsymbol{x},\boldsymbol{x}_S) = \mathbf{O}$ for $z < z_S$. We replace $\boldsymbol{P}(\boldsymbol{x})$ in the right-hand side of equation (13) by the 'incident' one-way wave vector, defined as $\boldsymbol{P}^i(\boldsymbol{x}) = \mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S)\boldsymbol{S}_0(\boldsymbol{x}_S)$. Hence

$$\boldsymbol{P}(\boldsymbol{x}_D) = \boldsymbol{P}^i(\boldsymbol{x}_D) + \boldsymbol{P}^s(\boldsymbol{x}_D) \quad , \tag{15}$$

with

$$\boldsymbol{P}^s(\boldsymbol{x}_D) = \int_V \mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x})\hat{\mathbf{\Delta}}_0(\boldsymbol{x})\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S)\boldsymbol{S}_0(\boldsymbol{x}_S)\mathrm{d}^3\boldsymbol{x} \quad . \tag{16}$$

Note the similarity with the two-way volume integral representation, given by equation (11a) in Part I. However, the difference becomes clear if we compare the contrast function Δ in the two-way representation (equation 11b in Part I) with the contrast operator $\hat{\mathbf{\Delta}}_0$ in the one-way representation, see Fig. 4. Remember that $\hat{\mathbf{\Delta}}_0$ is proportional to the vertical derivative of the medium parameters. Hence, for the special situation of a single interface between two homogeneous half-spaces, the one-way representation reduces to a boundary integral (unlike the two-way representation). Next consider another special situation for which $\boldsymbol{S}_0^- = \mathbf{O}$. We now easily find from equations (2), (4b), (14) and (16)

$$P^-(\boldsymbol{x}_D) = \int_V \mathbf{W}_p^-(\boldsymbol{x}_D,\boldsymbol{x})\hat{\mathbf{R}}^+(\boldsymbol{x})\mathbf{W}_p^+(\boldsymbol{x},\boldsymbol{x}_S)\boldsymbol{S}_0^+(\boldsymbol{x}_S)\mathrm{d}^3\boldsymbol{x} \quad , \tag{17}$$

or, upon introducing the kernel $\mathbf{R}^+(\boldsymbol{x},\boldsymbol{x}')$ of $\hat{\mathbf{R}}^+(\boldsymbol{x})$,

$$P^-(\boldsymbol{x}_D) = \int_V \int_\Sigma \mathbf{W}_p^-(\boldsymbol{x}_D,\boldsymbol{x})\mathbf{R}^+(\boldsymbol{x},\boldsymbol{x}')\mathbf{W}_p^+(\boldsymbol{x}',\boldsymbol{x}_S)\boldsymbol{S}_0^+(\boldsymbol{x}_S)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}^3\boldsymbol{x} \quad , \tag{18}$$

where Σ is a horizontal surface defined by $z' = z$. Note the similarity with the one-way boundary integral representation, given by equation (16) in Part I. In the next section we generalize this primary representation so that internal multiple reflections are taken into account.

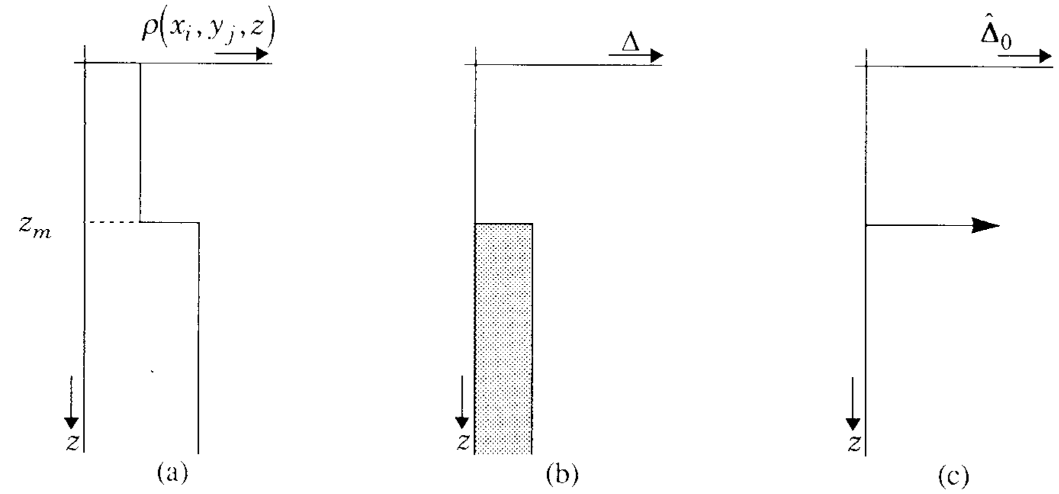

Fig. 4. (a) Vertical cross-section of one medium parameter (mass density) for the situation of a single interface at z_m. (b) Contrast function for the two-way volume integral representation (equation 11, Part I of this paper). (c) Contrast operator for the one-way volume integral representation (equation 16).

GENERALIZED PRIMARY REPRESENTATION

For the reference operator we write (see paper B)

$$\check{\mathbf{B}}(\boldsymbol{x}|z') = -j\omega\hat{\Lambda}(\boldsymbol{x}) + H(z'-z)\hat{\Delta}_0(\boldsymbol{x}) \quad , \tag{19}$$

where H(z) is the Heaviside step function. Hence, $\check{\mathbf{B}}(\boldsymbol{x}|z')$ applies to a configuration that is identical to the true medium for the upper half-space $z < z'$ and that is scatter-free for the lower half-space $z > z'$. We let $\check{\mathbf{B}}(\boldsymbol{x}|z')$ govern a Green's matrix $\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S|z')$ and we let a similar operator $\check{\mathbf{B}}(\boldsymbol{x}|z'')$ govern a reference wave vector $\bar{\boldsymbol{P}}(\boldsymbol{x}|z'')$. Note that $\bar{\boldsymbol{P}}(\boldsymbol{x}|-\infty) = \boldsymbol{P}^i(\boldsymbol{x})$ and $\bar{\boldsymbol{P}}(\boldsymbol{x}|\infty) = \boldsymbol{P}(\boldsymbol{x})$. Now instead of equation (13) we may write

$$\bar{\boldsymbol{P}}(\boldsymbol{x}_D|z'') - \bar{\boldsymbol{P}}(\boldsymbol{x}_D|z') = \int_V \mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x}|z')\{\check{\mathbf{B}}(\boldsymbol{x}|z'') - \check{\mathbf{B}}(\boldsymbol{x}|z')\}\bar{\boldsymbol{P}}(\boldsymbol{x}|z'')\mathrm{d}^3\boldsymbol{x} \ . \tag{20}$$

Next we choose $z'' = z' + dz'$ and we take the limit for $dz' \rightarrow 0$. We thus obtain

$$\{\partial\bar{\boldsymbol{P}}(\boldsymbol{x}_D|z')\}/\partial z' = \int_V \mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x}|z')\{\partial\check{\mathbf{B}}(\boldsymbol{x}|z')/\partial z'\}\bar{\boldsymbol{P}}(\boldsymbol{x}|z')\mathrm{d}^3\boldsymbol{x} \quad . \tag{21}$$

Using equation (19) the right-hand side of eq. (21) reduces to a surface integral. Integrating both sides with respect to z′ from $-\infty$ to ∞ and omitting the primes in the result again yields equations (15) and (16), with $\mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x})$ and $\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S)$ replaced by $\mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x}|z)$ and $\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S|z)$, respectively. However, unlike in the previous section, no approximations have been made in this section.

We now consider the configuration of Fig. 5, in which the upper half-space $z \leq z_0$ is homogeneous. We choose $\boldsymbol{x}_S$ and $\boldsymbol{x}_D$ in this upper half-space, so that for $z > z_0$ we may write

$$\mathbf{G}(\boldsymbol{x},\boldsymbol{x}_S|z) = \begin{pmatrix} \mathbf{W}_g^+ & \mathbf{O} \\ \mathbf{O} & \mathbf{O} \end{pmatrix}(\boldsymbol{x},\boldsymbol{x}_S) \quad , \tag{22a}$$

and

$$\mathbf{G}(\boldsymbol{x}_D,\boldsymbol{x}|z) = \begin{pmatrix} \mathbf{O} & \mathbf{O} \\ \mathbf{O} & -\mathbf{W}_g^- \end{pmatrix}(\boldsymbol{x}_D,\boldsymbol{x}) \quad , \tag{22b}$$

see Fig. 5. We refer to $\mathbf{W}_g^+$ and $\mathbf{W}_g^-$ as the extrapolation operators for the *generalized primary* downgoing and upgoing waves, respectively (conform with Hubral et al. (1980) and Resnick et al. (1986), who used this term for 1-D waves through finely layered 1-D media). Note that these operators account for internal multiple scattering occurring in the region between z_0 and z, whereas reflections from the region below z are excluded. Finally, if we consider again the special situation that $\boldsymbol{S}_0^- = \mathbf{O}$, we obtain, in a similar way as in the previous section:

$$\boldsymbol{P}^-(\boldsymbol{x}_D) = \int_V \int_\Sigma \mathbf{W}_g^-(\boldsymbol{x}_D,\boldsymbol{x})\mathbf{R}^+(\boldsymbol{x},\boldsymbol{x}')\mathbf{W}_g^+(\boldsymbol{x}',\boldsymbol{x}_S)\boldsymbol{S}_0^+(\boldsymbol{x}_S)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}^3\boldsymbol{x} \quad , \tag{23}$$

see again Fig. 5.

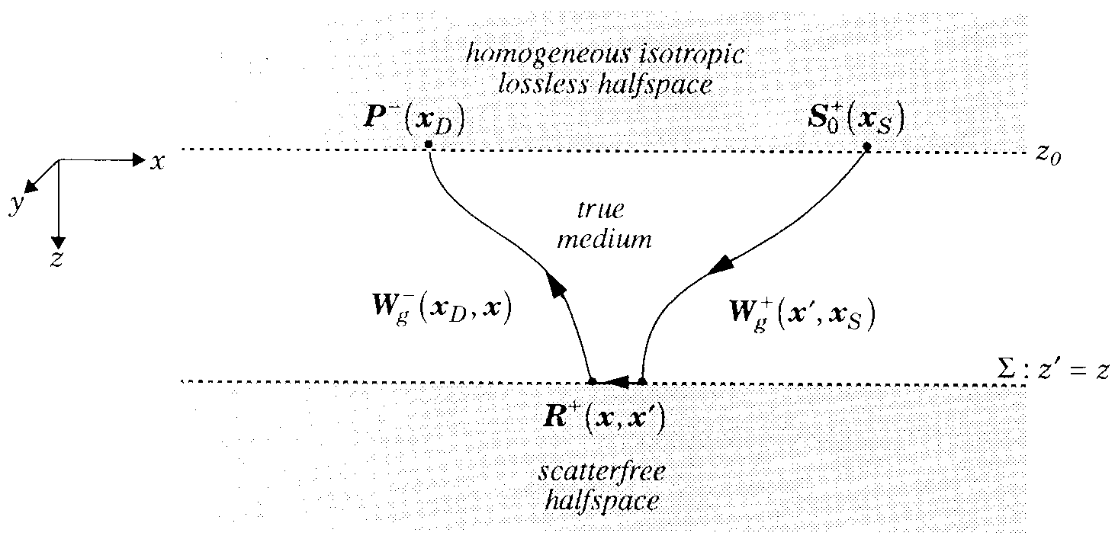

Fig. 5. Generalized primary representation.

CONCLUSIONS

In Part I of this paper we noted that in seismic reflection experiments the *boundaries* between the different layers are the main cause for scattering; as a consequence, the two-way *volume* integral representation is not very well suited as a starting point for seismic inversion (see Fig. 2b in Part I as well as Fig. 4b in Part II). The one-way volume integral representations, derived in this paper, have the attractive property that the contrast function vanishes in regions where the medium parameters do not vary with depth (see Fig. 4c). As a consequence, these representations relate the registered upgoing wave field directly to the reflection properties of the boundaries between the different layers. Therefore, these representations provide an excellent starting point for seismic inversion [after decomposition (Wapenaar et al., 1990) and surface-related multiple elimination (Verschuur et al., 1992)]. This is particularly true for the generalized primary representation (23) since it fully accounts for internal multiples and wave conversions, whereas its format is just as simple as the primary representation (18). Hence, by properly inverting the generalized primary operators $\mathbf{W}_g^+$ and $\mathbf{W}_g^-$, one may even account for the complicated anisotropic dispersion effects due to fine layering (see paper B and Wapenaar and Herrmann, 1993).

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