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### SUMMARY

Recently, an iterative scheme has been introduced to retrieve the down- and upgoing Green's functions at an arbitrary level  $\Lambda_F$  inside an acoustic medium as if there were a source at the surface. This scheme requires as input the reflection response acquired at the surface and the direct arrival of the transmission response from the surface to level  $\Lambda_F$ . The source locations of these Green's functions can be effectively redatumed to level  $\Lambda_F$  by interferometric redatuming, which requires solving a multidimensional deconvolution problem, essentially being a Fredholm integral equation of the first kind. We show how this problem can be simplified by rewriting it as a Fredholm integral equation of the second kind that can be expanded as a Neumann series. Redatumed data can be used for multiplefree true-amplitude imaging at or in the vicinity of  $\Lambda_F$ . For imaging the closest reflector to  $\Lambda_F$  only, the Neumann series can be truncated at the first term without losing accuracy.

# INTRODUCTION

Broggini et al. (2012) introduced a data-driven scheme to obtain the Green's function at level  $\Lambda_F$  inside a layered acoustic medium, using reflection data at the surface only. Wapenaar et al. (2013a) extended this scheme to 3D media, but required as additional input the direct arrival of the transmission response from the surface to  $\Lambda_F$ . Output of this scheme are the down- and upgoing Green's functions as if there were sources at the surface and virtual receivers at  $\Lambda_F$ . By multidimensional deconvolution of the retrieved upgoing wavefield with the downgoing wavefield, these data can be transformed into data as if there were virtual sources at  $\Lambda_F$  that radiate downwards in a medium that is homogeneous above  $\Lambda_F$  but identical to the physical medium below this level and of which the reflection response is recorded by receivers at  $\Lambda_F$  (Wapenaar et al., 2011). An alternative multidimensional deconvolution problem can be formulated to generate upward radiating virtual sources in a medium that is homogeneous below  $\Lambda_F$  and identical to the physical medium above this level. Unfortunately, multidimensional deconvolution is computationally expensive and not always numerically stable (van der Neut and Herrmann, 2013). Therefore, we propose a more robust formulation that fits well within the developed framework, since it utilizes the same operators that are used to initialize the iterative scheme.

### AUTOFOCUSING

We start with a brief derivation of the iterative scheme that we use for autofocusing. We define a reference medium (indicated with a bar) which is identical to the physical medium above level  $\Lambda_F$  and homogeneous below this level. Both the physical medium (indicated without bar) and the reference medium do not have a free surface. Thus, we assume that surface-related multiples have been removed from the input data, which is recorded at  $\Lambda_0$ , the earth's surface. All expressions will be given in the frequency-space domain with superscripts + and - representing down- and upgoing fields, respectively. We define  $\bar{f}_1^+$  as the inverse of the downgoing field  $\bar{G}^+$  in the reference medium, according to

$$\int_{\Lambda_0} \bar{G}^+(\mathbf{x}, \mathbf{x}_A) \, \bar{f}_1^+(\mathbf{x}_A, \mathbf{x}_F) \, \mathrm{d}^2 \mathbf{x}_A = \delta\left(\mathbf{x}_H - \mathbf{x}_{H,F}\right), \quad (1)$$

where  $\delta (\mathbf{x}_H - \mathbf{x}_{H,F})$  is a 2D Dirac delta function with *H* denoting that only the horizontal coordinates are evaluated. In this expression,  $\mathbf{x}_A$  is located at  $\Lambda_0$ , whereas  $\mathbf{x}$  and  $\mathbf{x}_F$  are at  $\Lambda_F$ . We also define  $\bar{f}_1^-$  by a convolutional integral of  $\bar{f}_1^+$  with the reflection response  $\bar{R}^{\cup}$  of the reference medium:

$$\bar{f}_1^-(\mathbf{x}_B, \mathbf{x}_F) = \int_{\Lambda_0} \bar{R}^{\cup}(\mathbf{x}_B, \mathbf{x}) \,\bar{f}_1^+(\mathbf{x}, \mathbf{x}_F) \,\mathrm{d}^2 \mathbf{x}.$$
 (2)

Starting with reciprocity theorems for one-way wavefields, the following Green's function representations can be derived (Wapenaar et al., 2013b):

$$G^{-}(\mathbf{x}_{F}, \mathbf{x}_{B}) = \int_{\Lambda_{0}} R^{\cup}(\mathbf{x}_{B}, \mathbf{x}) \bar{f}_{1}^{+}(\mathbf{x}, \mathbf{x}_{F}) d^{2}\mathbf{x} - \bar{f}_{1}^{-}(\mathbf{x}_{B}, \mathbf{x}_{F}),$$
(3)

and

$$G^{+}(\mathbf{x}_{F},\mathbf{x}_{B}) = \bar{f}_{1}^{+*}(\mathbf{x}_{B},\mathbf{x}_{F}) - \int_{\Lambda_{0}} R^{\cup}(\mathbf{x}_{B},\mathbf{x}) \bar{f}_{1}^{-*}(\mathbf{x},\mathbf{x}_{F}) d^{2}\mathbf{x}.$$
(4)

Here  $R^{\cup}$  is the recorded data at the earth's surface and superscript \* denotes complex conjugation. According to this expression, the up- and downgoing fields can be expressed as functions of the known input data  $R^{\cup}$  and the two functions  $\bar{f}_1^+$  and  $\bar{f}_1^-$ . The goal of autofocusing is to find these functions, such that the Green's functions can be computed. To achieve this goal, we will make use of causality principles. We assume that the downgoing Green's function can be written as  $G^+ = G_d^+ + G_c^+$ , where subscript *d* refers to the direct field, arriving at  $t_d(\mathbf{x}_B, \mathbf{x}_F)$ . Subscript *c* refers to a coda, arriving after  $t_d(\mathbf{x}_B, \mathbf{x}_F)$ . As a consequence,  $\bar{f}_1^+$  can also be separated into a direct field and a coda, according to  $f_1^+ = f_{1,d}^+ + f_{1,c}^+$ , where the

direct field arrives at  $-t_d(\mathbf{x}_B, \mathbf{x}_F)$  and the coda arrives thereafter. Remember that  $\bar{f}_1^+$  and  $\bar{G}^+$  obey equation 1, being a convolutional integral. The first event of  $\bar{f}_1^+$  convolved with the first event of  $\bar{G}^+$  should produce the first event on the righthand side of equation 1, being the delta function. All other convolutions should arrive after this event and since there is only one event in the right-hand side, they should cancel each other. Therefore it can be concluded that

$$\int_{\Lambda_0} G_d^+(\mathbf{x}, \mathbf{x}_A) \, \bar{f}_{1,d}^+(\mathbf{x}_A, \mathbf{x}_F) \, \mathrm{d}^2 \mathbf{x}_A = \delta\left(\mathbf{x}_H - \mathbf{x}_{H,F}\right). \tag{5}$$

Assuming that  $G_d^+$  can be computed from a smooth velocity model or using Common Focus Point Technology (Thorbecke, 1997),  $\bar{f}_{1,d}^+$  can be constructed by inversion of equation 5.

Causality is imposed by a window function  $w_d(\mathbf{x}_B, \mathbf{x}_F)$ , which acts as a convolutional filter in the frequency domain (indicated by \*), being equivalent to multiplication in the time domain. The time-domain representation of the window function reads  $w_d(\mathbf{x}_B, \mathbf{x}_F) = 1$  for  $t < t_d(\mathbf{x}_B, \mathbf{x}_F)$  and  $w_d(\mathbf{x}_B, \mathbf{x}_F) = 0$ for  $t \ge t_d(\mathbf{x}_B, \mathbf{x}_F)$ . Since  $\bar{f}_{1,d}^+$  arrives at  $-t_d(\mathbf{x}_B, \mathbf{x}_F)$  and the coda arrives thereafter, it follows that

$$w_d(\mathbf{x}_B, \mathbf{x}_F) \underset{\omega}{*} \bar{f}_1^{+*}(\mathbf{x}_B, \mathbf{x}_F) = \bar{f}_{1,c}^{+*}(\mathbf{x}_B, \mathbf{x}_F).$$
(6)

With a similar (but slightly more involved) reasoning, we can show that  $\bar{f}_1^-$  'survives' the window function, that is

$$w_d(\mathbf{x}_B, \mathbf{x}_F) \underset{\boldsymbol{\omega}}{*} \bar{f}_1^-(\mathbf{x}_B, \mathbf{x}_F) = \bar{f}_1^-(\mathbf{x}_B, \mathbf{x}_F).$$
(7)

Due to causality,  $w_d(\mathbf{x}_B, \mathbf{x}_F) \underset{\omega}{*} G^+(\mathbf{x}_F, \mathbf{x}_B) = 0$  and  $w_d(\mathbf{x}_B, \mathbf{x}_F) \underset{\omega}{*} G^-(\mathbf{x}_F, \mathbf{x}_B) = 0$ . Substituting equations 3, 4, 6, 7 into these expressions leads to the coupled 3D Marchenko equations:

$$\bar{f}_{1}^{+*}(\mathbf{x}, \mathbf{x}_{F}) = \bar{f}_{1,d}^{+*}(\mathbf{x}, \mathbf{x}_{F}) + w_{d}(\mathbf{x}_{B}, \mathbf{x}_{F}) \underset{\omega}{*} \int_{\Lambda_{0}} \mathcal{R}^{\cup}(\mathbf{x}_{B}, \mathbf{x}) \bar{f}_{1}^{-*}(\mathbf{x}, \mathbf{x}_{F}) d^{2}\mathbf{x}, \quad (8)$$

and

$$\bar{f}_{1}^{-}(\mathbf{x}_{B},\mathbf{x}_{F}) = w_{d}(\mathbf{x}_{B},\mathbf{x}_{F}) \underset{\omega}{*} \int_{\Lambda_{0}} \mathcal{R}^{\cup}(\mathbf{x}_{B},\mathbf{x}) \bar{f}_{1}^{+}(\mathbf{x},\mathbf{x}_{F}) d^{2}\mathbf{x}.$$
(9)

Starting with  $\bar{f}_1^-(\mathbf{x}_B, \mathbf{x}_F) = 0$  or  $\bar{f}_1^+(\mathbf{x}_B, \mathbf{x}_F) = \bar{f}_{1,d}^+(\mathbf{x}_B, \mathbf{x}_F)$ , equations 8 and 9 can be solved iteratively, leading to the desired solutions  $\bar{f}_1^+$  and  $\bar{f}_1^-$ . Next, the Green's functions  $G^-$  and  $G^+$  can be computed with equations 3 and 4.

We demonstrate the autofocusing concept with an example. In Figure 1a, we show the velocity model of a simple layered medium. In Figure 1b, we show the reflection response of this medium at the surface without free-surface multiples. Together with the transmission response of the direct field to a focal point  $\mathbf{x}_F$  at 2000m depth (indicated by the red dot in Figure 1a), this response is input for the iterative scheme. In Figure 2, we show the output of the scheme (fields  $\bar{f}_1^+$ ,  $\bar{f}_1^-$ ,  $G^+$  and  $G^-$ ) (in red), overlaying the results of direct modeling (in black), exposing a perfect match.



Figure 1: a) Synthetic model without a free surface. The focal point  $\mathbf{x}_F$  is indicated by the red dot at 2000m depth. b) Reflection response at the surface.



Figure 2: Retrieved fields  $\bar{f}_1^+$ ,  $\bar{f}_1^-$ ,  $G^+$  and  $G^-$  (in red), overlaying the result of direct modeling (in black).

### ILLUMINATION FROM ABOVE

Once the up- and downgoing Green's functions at level  $\Lambda_F$  are known, the seismic wavefield can be redatumed by solving the following Fredholm integral equation of the first kind (Wapenaar et al., 2011):

$$G^{-}(\mathbf{x}_{G}, \mathbf{x}_{A}) = \int_{\Lambda_{F}} \underline{R}^{\cup}(\mathbf{x}_{G}, \mathbf{x}) G^{+}(\mathbf{x}, \mathbf{x}_{A}) d^{2}\mathbf{x}, \qquad (10)$$

with  $\mathbf{x}_G$  at  $\Lambda_F$ ,  $\mathbf{x}_A$  at  $\Lambda_0$  and  $\underline{R}^{\cup}$  being the reflection response as if there were sources and receivers at  $\Lambda_F$  in a new reference medium (indicated by the underbar) that is homogeneous above  $\Lambda_F$  and identical to the physical medium below this level. One way to go would be to solve equation 10 by leastsquares inversion. However, this problem is ill-posed and additional regularization is required (van der Neut and Herrmann, 2013). Instead, we can substitute  $G^+ = G_d^+ + G_c^+$ , convolve

with  $\bar{f}_{1,d}^+(\mathbf{x}_A, \mathbf{x}_F)$ , and integrate over  $\mathbf{x}_A$ , yielding (with help of equation 5),

$$\int_{\Lambda_0} G^-(\mathbf{x}_G, \mathbf{x}_A) \bar{f}^+_{1,d}(\mathbf{x}_A, \mathbf{x}_F) d^2 \mathbf{x}_A = \int_{\Lambda_F} \underline{R}^{\cup}(\mathbf{x}_G, \mathbf{x}) \times \int_{\Lambda_F} [\delta(\mathbf{x}_H - \mathbf{x}_{H,F}) + \int_{\Lambda_0} G^+_c(\mathbf{x}, \mathbf{x}_A) \bar{f}^+_{1,d}(\mathbf{x}_A, \mathbf{x}_F) d^2 \mathbf{x}_A] d^2 \mathbf{x},$$
(11)

being a Fredholm integral equation of the second kind. Three important observations can be made at this point:

1. The delta function in equation 11 is a bandlimited delta function (or sinc function) in practice. However, we can replace this bandlimited delta function with a synthetic delta function of infinite spatial and temporal bandwidth. By doing this, we apply natural regularization to the inverse problem such that additional regularization is no longer required.

2. Alternatively, equation 11 can be expanded with a Neumann series, yielding a robust solution, as we have seen before in free-surface multiple elimination (van Borselen et al., 1996).

3. Finally, if we care only about the first reflector of  $\underline{R}^{\cup}$ , the Neumann series can be truncated at the first term, since this is the only term that contributes. This observation can be crucial for efficient imaging schemes with image points at or just below the focusing level.



Figure 3:  $\underline{R}^{\cup}$  at the focusing level, retrieved by a) regularized least-squares inversion of equation 10 and b) unregularized inversion of equation 11 (in red) overlaying the result of direct modeling (in black).



Figure 4: Contributions of a) the first term and b) higher-order terms to the Neumann series expansion of equation 11.

We illustrate these concepts with the synthetic example that was introduced in the previous section. In Figure 3, we show the result of regularized least-squares inversion of equation 10 and direct inversion of equation 11 with a synthetic delta function of infinite bandwidth (in red), overlaying the response of direct modeling (in black). Both methods retrieve the desired reflection response within the spatial bandwidth that has propagated through the overburden. However, we emphasize that regularization was not required in Figure 3b, thus theoretically preserving the bandwidth in an optimal way and practically simplifying the processing flow.

Solving this problem with a Neumann series expansion leads to a similar result. In Figure 4a, we show the first term of the series. In Figure 4b, we show the contribution of the higherorder terms. Note that the higher-order terms cancel the spurious events that are present in the first-order term for this simple example with just a single reflector below the focusing level. Note also that the higher-order terms do not contribute to the first event and therefore truncating the series after one term is sufficient to correctly retrieve the first reflector below the focusing level.

# **ILLUMINATION FROM BELOW**

Alternatively, we can retrieve a reflection response as if there were sources and receivers at  $\Lambda_F$ , radiating upwards in the original reference medium that is homogeneous below  $\Lambda_F$  and identical to the physical medium above this level. This can be highly beneficial for subsalt imaging, where it is sometimes more effective to image target reflectors from below rather than from above (Vasconcelos et al., 2008). We start with a relation from Wapenaar et al. (2004) to relate the reflection response from above  $\overline{R}^{\bigcirc}$  at the surface to the reflection response from below  $\overline{R}^{\cap}$  at the focusing level:

$$\int_{\Lambda_0} \bar{G}^+(\mathbf{x}, \mathbf{x}_B) \bar{R}^{\cap *}(\mathbf{x}_B, \mathbf{x}_A) \, \mathrm{d}^2 \mathbf{x}_B = -\int_{\Lambda_F} \bar{R}^{\cap}(\mathbf{x}, \mathbf{x}_G) \, \bar{G}^{+*}(\mathbf{x}_G, \mathbf{x}_A) \, \mathrm{d}^2 \mathbf{x}_G.$$
(12)

We apply  $\bar{f}_1^{+*}(\mathbf{x}_A, \mathbf{x}_F)$  to this equation and integrate  $\mathbf{x}_A$  over  $\Lambda_0$ . Next, we use equations 1 and 2. Multiplying the result with  $\bar{f}_1^+(\mathbf{x}_A, \mathbf{x})$  and integrating over  $\mathbf{x}$ , we find

$$\bar{f}_{1}^{-*}(\mathbf{x}_{A},\mathbf{x}_{F}) = -\int_{\Lambda_{F}} \bar{f}_{1}^{+}(\mathbf{x}_{A},\mathbf{x})\bar{R}^{\cap}(\mathbf{x},\mathbf{x}_{F})\,\mathrm{d}^{2}\mathbf{x}.$$
 (13)

Here, we have used the fact that

$$\int_{\Lambda_m} \bar{f}_1^+ \left( \mathbf{x}_A, \mathbf{x} \right) \bar{G}^+ \left( \mathbf{x}, \mathbf{x}_B \right) \mathrm{d}^2 \mathbf{x} = \delta \left( \mathbf{x}_{H,A} - \mathbf{x}_{H,B} \right), \qquad (14)$$

as can be verified with equation 1. Similar to what we did in the previous section, we can separate  $\bar{f}_1^+$  into a direct field and a coda. Substituting  $\bar{f}_1^+ = \bar{f}_{1,d}^+ + \bar{f}_{1,c}^+$  into equation 13, multiplying with  $G_d^+(\mathbf{x}_G, \mathbf{x}_A)$  and integrating  $\mathbf{x}_A$  over  $\Lambda_0$ , it follows that

$$\int_{\Lambda_0} G_d^+(\mathbf{x}_G, \mathbf{x}_A) \, \bar{f}_1^{-*}(\mathbf{x}_A, \mathbf{x}_F) \, \mathrm{d}^2 \mathbf{x}_A = \int_{\Lambda_F} [\delta\left(\mathbf{x}_H - \mathbf{x}_{H,G}\right) + \int_{\Lambda_0} G_d^+(\mathbf{x}_G, \mathbf{x}_A) \, \bar{f}_{1,c}^+(\mathbf{x}_A, \mathbf{x}) \, \mathrm{d}^2 \mathbf{x}_A] \bar{R}^{\cap}(\mathbf{x}, \mathbf{x}_F) \, \mathrm{d}^2 \mathbf{x},$$
(15)

where we used equation 5. The same three observations that were made in the previous section also hold for this section. This is illustrated in Figure 5, showing the result of regularized least-squares inversion of equation 13 and direct inversion of equation 15. The results are of similar quality. However, regularization is not required for figure 5b, which can be illustrated well if we consider the kernels of the inverse problems in the frequency-wavenumber domain, see Figure 6. Because we have replaced the bandlimited delta function by a delta function of infinite bandwidth (corresponding to a flat spectrum), the use of regularization has been effectively avoided.



Figure 5:  $\overline{R}^{\cap}$  at the focusing level, retrieved by a) regularized least-squares inversion of equation 13 and b) unregularized inversion of equation 15.



Figure 6: Kernels of a) the normal equation of inverse problem 13 and b) the unregularized inverse problem 15.

# UTILIZING MULTIPLE REFLECTIONS

Neither equation 13 nor equation 15 uses information from below the focusing level. This can be easily seen, since the focusing operators  $\bar{f}_1^+$  and  $\bar{f}_1^-$  depend only on the reference medium which is homogeneous below  $\Lambda_F$ . A different approach was suggested by van der Neut et al. (2013), by estimating the upward radiating reflection response from multiple reflections. We evaluate the equations of van der Neut et al. (2013) for the arrays  $\Lambda_0$  and  $\Lambda_F$ , yielding

$$G^{+}(\mathbf{x}_{G}, \mathbf{x}_{A}) - \bar{G}^{+}(\mathbf{x}_{G}, \mathbf{x}_{A}) = \int_{\Lambda_{F}} \bar{R}^{\cap}(\mathbf{x}_{G}, \mathbf{x}) G^{-}(\mathbf{x}, \mathbf{x}_{A}) d^{2}\mathbf{x},$$
(16)

and

$$G^{-*}(\mathbf{x}_{G}, \mathbf{x}_{A}) - \int_{\Lambda_{0}} \bar{G}^{+}(\mathbf{x}_{G}, \mathbf{x}) R^{\cup *}(\mathbf{x}, \mathbf{x}_{A}) d^{2}\mathbf{x} =$$

$$\int_{\Lambda_{F}} \bar{R}^{\cap}(\mathbf{x}_{G}, \mathbf{x}) G^{+*}(\mathbf{x}, \mathbf{x}_{A}) d^{2}\mathbf{x}.$$
(17)

On the left-hand sides of these equations, we find internal multiples in the down- and upgoing wavefield, respectively, that have contributions from below the focusing level. All fields except for the unknown reflection response  $\bar{R}^{\cap}$  can be computed from the 3D coupled Marchenko equations, where  $G^+$  can be estimated by inversion of  $\bar{f}_1^+$  (see equation 1). Equations 15, 16 and 17 can be inverted jointly, where each subproblem can be assigned a weight. By varying these weights, we can choose to boost the importance of the multiples in the inverse problem. In the following example, we have normalized each problem and gave weight 1 to equation 15, and weights 0.5 to equations 16 and 17. In Figure 7a, we show the result of the inversion, being not much different from figure 5b. However, if we consider the kernel of the joint inverse problem, we see that the multiples fill in additional parts of the spectrum, compare Figure 7b with 6b. This indicates that multiples could provide additional information. However, we must be careful, since these signals are weaker and therefore boosting them is likely to bring additional noise into the problem. Future research on more complex models should show if adding the multiples to the inverse problem is providing us useful additional illumination. However, with the current set-up, we have created flexibility in 'raising or lowering the voice of the multiples'.



Figure 7: a)  $\overline{R}^{\cap}$  at the focusing level, retrieved by solving the joint inverse problem. b) Kernel of this joint inverse problem.

### CONCLUSION

Interferometric redatuming of autofocused data requires solving a Fredholm integral equation of the first kind. We have shown how this problem can be rewritten as a Fredholm integral equation of the second kind, using the fields that were used to initiate the autofocusing scheme. This adapted problem is computationally more attractive to solve, since it requires no additional regularization and it can be expanded effectively as a Neumann series. If it is our aim to image at, just below or just above the focusing level only, the Neumann series can be truncated after the first term, being computationally attractive.

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