Minimization effect of sedimentary layer on synthetic receiver function

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Abstract. We calculated the radial synthetic model of receiver function consisting of the sedimentary layer, crust, and mantle (SCM). The models were computed using the program hftn96 implemented in computer program in seismology (CPS). Synthetic receiver functions are generated using the following parameters: for sedimentary layers, \( V_p \), \( V_s \), and density are 1.8, 0.41 and 1.83 g/cm\(^3\) respectively; for the crustal layer, the values are 6.10, 3.52 and 2.73 g/cm\(^3\) with the depth of the Moho layer at 40 km; and for the mantle, the values are 8.15, 4.7 and 3.36 g/cm\(^3\). We varied sedimentary layer with the thickness of 0.0, 0.4, 0.5 and 1.0 km. We applied the Gaussian width parameter of 1.5 removing frequency content above 0.75 Hz. We designed the filter for the synthetic receiver function model in order to minimize reverberation effect due to the presence of sedimentary layer near the surface. To test the effectiveness of this filter, we adopted H-\( k \) stacking method for this model to calculate the moho thickness before and after sediment removal.

1. Introduction

Receiver function is one of the seismological approaches for characterizing the subsurface structure beneath a seismic station. The method is applied for a single seismic station and computed by deconvolution of the source waveform obtained from the teleseismic events. The method utilizes the fact that the teleseismic P wave impinging the discontinuity layer will result in P-to-S conversion wave and its multiple. On the receiver function, this phase arrives after the direct P phase. Thus, the time difference between the direct P and the converted wave arrivals will show the location of the discontinuity layer.

However, identification of P-to-S converted wave is sometimes difficult when the sedimentary layer is present beneath a seismic station [1]. The presence of this sediment layer may reduce the seismic velocity significantly which will cause a problem to the implementation of receiver function. The velocity contrast between the low-sediment layer and the crust may result in the strong amplitude of reverberations on the receiver function, obscuring the conversion wave related to the Moho discontinuity layer [2, 3]. Consequently, the analysis of receiver function for estimating crustal thickness beneath a seismic station may lead to the ambiguous results. The effect of sediment thickness to the receiver function has been investigated through several studies. For example, Anggono et al. [2] used forward modeling to examine the effect of sediment thickness to the synthetic receiver functions. They found that reverberation in receiver function due to the presence of
sedimentary layer effect to the crustal estimation. Thus, better results may be obtained by minimizing this reverberation from the signal of receiver function. A previous study, conducted by Yu et al. [3], has been tried to minimize reverberation on receiver function using filter resonance. The filter successfully reduced the effect of sediment layer to the receiver function.

In this study, we examine how to minimize the effect of sediment thickness on the receiver functions by applying a predictive filter. To test the robustness of the filter, we use H-κ stacking method to the filtered and unfiltered synthetic receiver functions. The H-κ stacking method is used to estimate the crustal thickness and the Vp/Vs. The effective filter should provide the closest result of the crustal thickness estimation without the effect of sediment layer.

2. Data Observation and Methods
To calculate synthetic receiver functions, we applied forward modeling. We calculated synthetic receiver functions using hrftn96 program implemented in Computer Program in Seismology (CPS) [4]. Receiver function computation in the code hrftn96 is based on the Thomson-Haskell matrix method. To generate synthetic receiver function model (figure 1), we used the following parameters from R.B Hermann [4], as showed in table 1.

We generated synthetic receiver function model with the variation of sediment thickness from 0.0 (synthetic receiver function model without sedimentary layer effect), 0.4 and 0.5 km, and 1.0 km. Synthetic receiver function model with sedimentary layer effects was then prepared for the filtering process. We implemented a predictive filter to minimize the effect of sedimentary layer thickness. This filter has been widely applied in petroleum exploration to quantify and remove multiples associated with a surface water layer [5]. This filter uses autocorrelation process for the signal of receiver function in time domain to obtain the parameters of the filter. Parameters of the filter are two-way time reverberations (Δt) and strong reverberations (τo). The filter is then designed at the time domain after IFFT (Inverse Fast Fourier Transform) process. Finally, we convolved the input signal and the design filter at time domain to reduce the effect of sediment layer in the receiver functions.

We applied H-κ stacking method developed by Zhu and Kanamori [6] to estimate the depth of the Moho layer and Vp/Vs ratio. We estimated the depth of Moho and Vp/Vs ratio on the synthetic receiver function before and after applying the filter. Then, we compared both results for every sediment thickness on the synthetic receiver function before and after applying the filter.

Table 1. Parameters of synthetic receiver function model.

|               | Vp (km/s) | Vs (km/s) | Density (g/cm³) | Moho depth (km) |
|---------------|-----------|-----------|-----------------|-----------------|
| Sediment      | 1.80      | 0.41      | 1.830           | 40              |
| Crust         | 6.10      | 3.52      | 2.730           | 40              |
| Mantle        | 8.15      | 4.70      | 3.364           | 40              |

![Figure 1. Synthetic receiver function model with sedimentary layer 1-D.](image)
3. Results and Discussion

3.1 Synthetic receiver function model without sedimentary layer effect

Figure 2 (a) shows the synthetic receiver function model without the sedimentary layer effect. We observe that the Ps phase related to the Moho discontinuity layer on the model is very visible. The direct P, Ps, PpPs, and PsPs+PpPs phases are observed at 0, 4.9, 17.5 and 22.5 s, respectively. Figure 2 (b) shows the result of H-κ stacking method for the synthetic receiver function model with the sediment thickness of 0.0 km. The result shows that the depth of the Moho layer and Vp/Vs ratio are estimated around 39.5 km and 1.75, respectively.

3.2 Synthetic receiver function model with the sediment thickness of 0.4, 0.5 and 1.0 km

Figure 3 (a) shows the model synthetic receiver function containing the effect of sedimentary layer before applying the filter. The effect of sedimentary layer can result in high amplitude and low-frequency reverberations on the receiver function [3]. The Ps phase of the Moho at this figure is covered by the delayed first peak corresponding to the arrival Ps phase of the sedimentary layer [3, 7]. This condition is caused by the reverberations on the shallow depth due to the density contrast between the sediment and the crust [2, 3]. Consequently, the Ps phase of synthetic receiver function is not clearly visible. In this condition, the application of H-κ may fail to provide good results. The reverberation does not occur if the sediment thickness is less than one-fourth of the wavelength of the Ps phase, also when the thickness of the sediment is very thick (e.g., thicker than 5-8 km, depending on the attenuation factor) [3, 4]. In the case of the sediment layer is very thick, the impedance contrast between the crust and the sediment layer is too small to generate significant reverberations due to gravitational compaction [3].

Figure 4 (a) shows the model synthetic receiver function with the effect of sedimentary layer after applying the filter. Figure 4 (a) shows the results of the first peak, Ps, PpPs, and PsPs+PpPs phases are about 1.0, 6.0, 18 and about 22.5 s, respectively. By comparing figure 4 (a) to figure 2 (a), we observe that this filtering process provides almost similar waveform with the receiver function without the effect of sedimentary layer.

Figures 3 (b) and 4 (b) show the estimation of the Moho depth and Vp/Vs ratio produced by applying H-κ stacking method for the filtered and unfiltered synthetic receiver function model with sediment thickness of 0.4 km. The result shows that the analysis provides the different values of the Moho depth and Vp/Vs ratio for these models. The H-κ stacking result for the unfiltered synthetic receiver function model with sediment thickness of 0.4 km provides 42 km and 1.69 km for the depth of the Moho layer and Vp/Vs ratio, respectively, as shown in figure 3 (b). For the filtered synthetic receiver function model, the H-κ stacking result gives similar value with the result of H-κ stacking analysis for the synthetic receiver function model sediment thickness 0.0 km. The depth of the Moho layer and Vp/Vs ratio are around 40 km and 1.87, respectively, as presented in figure 4 (b).

**Figure 2.** (a) Synthetic receiver function model without sedimentary layer effect and (b) H-κ stacking result on synthetic receiver function.
Figure 5 (a) shows the synthetic receiver function model with sediment thickness of 0.5 km before the filtering process. After applying the filter, the result of the receiver function presents that the direct P, Ps, PsPs, and PsPs+PpSs phases are about 1.2, 6.3, 18.3 and 23.3 s, respectively, as shown in figure 6 (a). The H-κ stacking results for the filtered synthetic receiver function model with the sediment thickness of 0.5 km are 34.2 km and 2 km/s for the depth of the Moho layer and Vp/Vs ratio, respectively, as presented in figure 5 (b). Furthermore, the stacking H-κ results for the corrected receiver function with the sediment effect show that the depth of the Moho layer and Vp/Vs ratio are 40.5 km and 1.9, respectively.
Figure 6. (a) The synthetic receiver function model with sediment thickness of 0.5 km and (b) stacking H-κ results after applying the filter.

Figure 7 (a) shows the model of synthetic receiver function for sediment thickness of 1.0 km before the filtering process. After applying the filter, the direct P, Ps, PsPs, and PsPs+PpSs phases are identified at around 2.9 s, 7 s, 19.9 s, and 25.0 s, respectively, as shown in figure 8 (a). The stacking H-κ results of the synthetic receiver function model with the sediment thickness of 1.0 km before filtering process show that the depth of the Moho layer and $V_p/V_s$ ratio are about 45.0 km and 1.71, respectively, as presented in figure 7 (b). After applying the filter on the receiver function, the result of the stacking H-κ analysis shows that the depth of the Moho layer and $V_p/V_s$ at around 38.5 and 2 km/s, respectively.

The results of the filtered and unfiltered receiver function show the significant difference in every phase arrivals on the receiver function and the H-κ stacking results (the $V_p/V_s$ and the Moho depth). As described earlier, the unfiltered receiver functions still contain the random noise generated the density contrast between the crust and sediment layer masking the PS Moho conversion wave and providing incorrect results for the crustal thickness measurement. Thus, the filtering process for reducing the effect of sediment layer on the receiver function gives similar results with the H-κ analysis as receiver function without the effect of sedimentary layer.

Figure 7. (a) The synthetic receiver function model with sediment thickness of 1.0 km and (b) stacking H-κ results before applying the filter
Figure 8. (a) The synthetic receiver function model with the sediment thickness of 1.0 km and (b) stacking H-κ results after applying the filter.

4. Conclusions
We calculated the synthetic receiver function model with the sediment thickness varying from 0.0 to 1.0 km. We applied the predictive filter to reduce the reverberation on the receiver function. The stacking H-κ method was applied to test the robustness of the filter. The results show that the filtered receiver function provide the same results of the H-κ analysis and the receiver function without the presence of the sedimentary layer.

Acknowledgments
This study is supported by LIPI and Indonesian Ministry of Research Technology and Higher Education through INSINAS Grant 060/P/RPL-LIPI/INSINAS-1/III/2018. We thank Puji Arianto for fruitful discussion. We also thank for R.B. Herrmann for providing software used in this study.

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