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Dear Reviewer,

Thank you for the constructive comments on our paper "Element-by-element parallel spectral-element methods for 3-D acoustic-wave-equation-based teleseismic wave modeling" (Manuscript se-2017-38). We have carefully revised the paper following your comments and suggestions. Our replies are highlighted in blue color.

We believe that we have answered all your questions and hope that the revised manuscript is now to your satisfaction.

We look forward to hearing from you.

Best regards,

Prof. Dinghui Yang

Main revisions

(1) The title of the origin manuscript was changed to "Element-by-element parallel spectral-element methods for 3-D teleseismic wave modeling".

(2) The acoustic wave equation was changed to elastic wave equation in the whole manuscript.

(3) The gray figures was changed to color figures.

(4) The element stiffness matrix was written as the tensor product of submatrices.

Response to reviewer comments

The authors derived and presented a new hybrid numerical method which combines the spectral-element method and the frequency-wavenumber (FK) method for simulating teleseismic waves. Mainly constrained by the computational ability and resources of nowadays, the hybrid methods are highly demanded for modeling relatively high frequency teleseismic waves and for the purpose of generating high-resolution subsurface images. This paper is well organized and well written. It is suitable for publishing in Solid Earth if the authors can address the following concerns.

Response: We greatly thank the reviewer for the carefully review of our manuscript. The suggestions are very important and greatly improve the quality of the paper. The point-by-point responses are listed below.

1. The authors called the discussing numerical method as the element-by-element parallel spectral-element method. What is the mathematical difference between your EBE-SEM and the so-called traditional SEM (your probably mean the one proposed in Komatitsch et al. 1998 as you cited this paper)? Why do you call it element-by-element? Do you also mean that the Komatitsch one cannot

be paralleled in an element-by-element way?

Response: Thanks for your comments. The traditional SEM (Komatitsch et al. 1998) needs to store the global stiffness matrix. One of the most efficient method that store the spare global stiffness matrix is the CSR method (Greathouse and Daga, 2014). We compared the traditional SEM with our method in the Section 4. We call our method element-by-element because the element stiffness matrices do not be assembled to generate the global stiffness matrix, which lead to great parallel efficiency (Figure 5). Furthermore, the element matrix can be written as the tensor product of submatrices, which leads to a great reduction of computer memory (Table 1).

Reference

Greathouse, J., and Daga, M.: Efficient sparse matrix-vector multiplication on GPUs using the CSR storage format, International Conference for High Performance Computing, Netwroking, Storage and Analysis, 769-780, 2014.

2. It is better to move the first two sentences in Abstract to the Introduction section.

Response: Done. The revision can be found from lines 28 to 29 in the revised manuscript.

3. Line 31. In the past fourth years -> In the past forty years

Response: Corrected. Please see line 31 in the revised version.

4. Lines 35-38. It is hard to understand "For the requirements of …"

Response: We are sorry for the unclear statement. "For the requirements of high-resolution teleseismic wave imaging" was changed to "To achieve the high-resolution imaging of lithosphere structure". Please find the revision in lines 35and 36.

5. Lines 39-41. by two times of numerical solving full seismic wave equations -> To reduce the storage requirement, Tromp et al. actually need to solve three wave equations to compute a wanted kernel.

Response: We thank the reviewer for this very important comment. In our code, we store the forward wavefields on computer disk, and read back the wavefields to computer memory during the constriction of sensitivity kernel. To save the computer memory, we does not using an interpolation procession to construct the forward wavefield (Sun and Fu, 2013), and we just shorten the time interval of saving the forward wavefield.

In our inversion examples (100 km * 100 km * 60 km), we set the cutoff frequency to be 1 Hz. The maximum time interval for saving the foward wavefields is 1/(2*1)=0.5 s, and choose the time interval to be 0.1 s. Using the formula to estimate the time interval (Fichtner, 2011), we also obtain the time interval is about 0.1 s. The storage requirement is only 23.3 GB, and the total time for writing and reading procedures is less than 10% of the time for one forward simulation. Our inversion results demonstrate this treatment works well. This treatment may be analogy to the code SES3D, which is designed by Andreas Fichtner (http://www.cos.ethz.ch/software.html).

In the revised manuscript, we add "if the forward wavefields are stored on computer disk at every given time interval" in lines 40 and 41, we also added the reference Fichtner (2011).

Reference

Sun W., and Fu L., 2013. Two effective approaches to reduce data storage in reverse time migration. Computers & Geosciences, 56, 69-75.

Fichtner A., 2011. Full seismic waveform modelling and inversion. Springer-Verlag Berlin Heidelberg.

6. Line 43. the seismic wave-equation-based adjoint waveform tomography. You have a long but seldom used name for adjoint tomography. Just use adjoint tomography.

Response: Corrected. Thank you for this good advice.

7. Line 48. Related to the earthquake events -> related to the number of earthquakes

Response: Done.

8. Line 53. In local region seismic tomography -> In local seismic tomography.

Response: Done.

9. Line 106. Misfit kernel -> Please use sensitivity kernel instead.

Response: We are sorry for the wrong use of terminology misfit kernel, which is defined by Tape et al., (2007). The sensitivity kernel does not contain volume integration (Tong et al., 2014, Eq. 11). The kernel obtained in the manuscript contains volume integration (please see Eq. (43)-(45), and Appendix C), which is the gradient of misfit function for a single event. In the revised manuscript, the misfit kernel is changed to the gradient of misfit function (called misfit gradients for short) in line 13 and the rest of the manuscript.

Reference

Tape C., Liu Q., and Tromp J., 2007. Finite-frequency tomography using adjoint methods-methodology and examples using membrane surface waves. Geophysical Journal International, 168, 1105-1129.

Tong P., Zhao D., Yang D., Yang X., Chen J., and Liu Q., 2014. Wave-equation-based travel-time seismic tomography-Part 1: Method. Solid Earth, 5, 1151-1168.

10. Line 175. Are -> is.

Response: Done.

11. Line 201. A discussion of - > Discussion of.

Response: Done.

12. Line 225. For storage -> for the storage.

Response: Done.

13. Line 401. Waveform misfit kernel -> waveform kernel.

Response: “misfit kernel” was changed to “misfit gradient”.

14. Lines 562-565. How do you estimate the storage of the stiffness matrix for the traditional SEM? Have you used the SPECFEM2D or SPECFEM3D package?

Response: We thank the reviewer for this good advice. We have read the SPECFEM2D package. In the package, element stiffness matrices are collected to assemble the global stiffness matrix. The classical compressed sparse row (CSR) storage format (Greathouse and Daga, 2014), which is the one of the most economic method to store the spare stiffness matrix. The estimate the storage of the stiffness matrix for the traditional SEM based CSR, which is discussed from lines 374 to 382.

15. Line 591. By subtraction of -> by subtracting

Response: Done.

16. Figures 3, 6, and 8 are not very clear to the readers, especially the annotations of the scales. You may want to use color figures instead.

Response: Thank you for this useful advice. The gray figures are changed to color figures according to suggestion.

17. This hybrid method is based on the acoustic wave equation. If it is possible, the discussion based on the elastic wave equation is more interesting.

Response: The major revision has been made to the manuscript. In the revised version, the acoustic equation has been changed to elastic equation.