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Interactive comment on “Regional wave propagation using the discontinuous Galerkin method” by S. Wenk et al.

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Page 1130, lines 18-19 (definition): "...on regional seismic wave propagation...". Since this is the main concern of your article, please define at the beginning what you mean by "regional". For instance, you can give some indications on the model dimensions, in terms of kms, degrees, etc...

Corrected

Old: on regional seismic wave propagation

New: on regional seismic wave propagation (continental scale)

Added

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...up to periods of 20s...

Page 1131, line 5 (terminology): "Besides semi-analytical algorithms, numerical direct solvers evolved such as the Finite-Difference...". The term "direct solvers" is somehow misleading since in the applied mathematical community, this term is related to an algorithm that are solving linear system with numerical techniques such as LU factorization. Therefore, I would mention instead "explicit time marching schemes".

Corrected

Old: Besides semi-analytical algorithms, numerical direct solvers evolved such as the Finite-Difference

New: Besides semi-analytical algorithms, full numerical schemes evolved such as the Finite-Difference

Page 1131, line 23 (explain): "...and explicit symplectic time extrapolation schemes". You are referring to the time integration used in SE methods. Concerning the standard SE method (Komatitsch 1997), I believe that the time integration is performed via a second-order operator based on a predictor corrector scheme. Maybe, other modelers using SE are using different schemes. Hence, I do not understand your point. Please clarify why you specify that SE is linked to a symplectic time interpolation? Is it really specific to SE methods?

Corrected

Old: and explicit symplectic time extrapolation schemes

New: and explicit time extrapolation schemes

Page 1132, line 3 (be more precise): "...the elements can locally be adapted (h-adaptivity) without overhead". Please explain why there is no overhead?

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Here, with overhead we mean that no further techniques like e.g. filtering or other mechanisms preventing spurious oscillations at interfaces between elements of different sizes are necessary while using the ADER-DG method. However, this discussion is not in the scope of the paper and, thus, we decide to avoid mentioning possible overhead.

Corrected

Old: ...the elements can locally be adapted (h-adaptivity) without overhead

New: ...the elements can locally be adapted (h-adaptivity)

Page 1132, line 18 (sounds awkward): "...technical properties of the implementation..." Are you referring to "computing strategies for the implementation of the DG method" or "numerical properties of the DG scheme"?

Corrected

Old: technical properties of the implementation

New: numerical properties of the ADER-DG implementation

Page 1133, line 9 (correct english): "Like every Finite-Element method" instead of "As every Finite-Element method"?

Corrected

Old: As every Finite-Element method

New: Like every Finite-Element method

Page 1133, lines 11-12 (sounds awkward): "In the scheme (add a comma) the complete 3-D computational domain..." Do you mean: "In our implementation of the DG scheme, the complete 3-D computational domain..."?

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Corrected

Old: In the scheme the complete 3-D computational domain

New: In our implementation of the DG scheme, the complete 3-D computational domain

Page 1133, lines 17-18 (add information): "We use an orthogonal basis suggested by Dubiner (1991)". I would recommend indicating that you are using modal basis functions. This is an important characteristic of your approach.

Corrected

Old: We use an orthogonal basis suggested by Dubiner (1991).

New: We use an orthogonal, modal basis suggested by Dubiner (1991).

Page 1133, lines 24-25 (wrong statement): "Note that differently from FV only adjacent elements communicate, and a reconstruction process is not required". First: in FV methods, the communication do actually concerns only adjacent elements. At least, this is the case for the P0 FV method where the solution is approximated as piece-wise constant per element. Second: what do you mean with a reconstruction process? Do you refer to the assembling usually encountered in standard FE methods? Please clarify.

That is correct. Low order FV schemes communicate (via fluxes) only between adjacent elements. However, high-order FV schemes incorporate also information from non-direct neighbour elements depending on the desired order of accuracy. The process of building the so-called stencil to gather all necessary information for the flux computation is referred as "reconstruction". This is a well known process within typical FV schemes that are used in practise, but to clarify our statement and respect low-order formulations we will be more precise.

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Corrected

Old: differently from FV only adjacent

New: differently from high-order FV schemes only adjacent

Page 1134, line 3 (add information and explain): "many occurring integrals can be pre-computed in the reference space". You should give more information concerning the integrals. For the reader not familiar with the DG method, it is useful to mention the name of whose matrices: mass, stiffness and flux matrices. Then, when you are saying that many matrices can be pre-computed, is it related to the fact that you are using homogeneous properties within the elements? I think this is a really important assumption in your formalism and since you mentioned in the introduction that you will focus on the model discretization, I am surprised that this assumption is not even mentioned here. Please, add a sentence concerning the approximation of the physical properties within the elements (it is piece-wise constant?) and explain why you have chosen this specific approximation.

Corrected

Old: many occurring integrals can be pre-computed in the reference space

New: in the discrete form of the scheme, the occurring mass, stiffness and flux matrices can be pre-computed.

Added

The elastic material properties vary in the subsurface, depending on the physical model applied. In our approach, elastic parameters are averaged over each vertex of an element and only a single value is assigned to the entire element. The piece-wise constant approximation simplifies the implementation, but it is not an intrinsic limitation of the scheme, as shown by Castro et al. (2010)

Page 1134, line 26 (english): "Until now, this is handled by zoning...". Replace

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"Until now" with a less abrupt expression (like "This issue can be handled by zoning...") or remove these words which are not really informative.

Corrected

Old: Until now, this is handled by zoning

New: This issue can be handled by zoning

Page 1135, line 10 (english): "...which have tremendous influence on the propagation...". Here, "tremendous" seems too excessive, use instead a more neutral adjective.

Corrected

Old: which have tremendous influence on the propagation of seismic waves

New: that governs the propagation of seismic waves.

Page 1135, lines 24-26 (move statement or explain): "In contrast, Komatitsch (1997) assign the material properties directly to single integration nodes in the SE scheme, at least, if interfaces cannot be respected within the computational mesh." Actually, this corresponds to the simplest strategy you mentioned at the beginning of section 2.3.1. (line 15 "material properties are simply assigned to nodes...") Please explain why you mention here the SE as a contrast of the approach of Kristek et al.? This statement should be moved around the line 15.

Changed Section 2.3

Geoscientific models include geometrically complex 3-D structures such as rough surface topography, as well as complicated undulating interfaces at subsurface velocity contrasts, which have considerable influence on the propagation of seismic waves.

The generation of a computational mesh, incorporating such features, can be the most time-consuming part of the whole forward modeling process. Therefore, we

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want to review different meshing concepts, with respect to the model complexity, using structured and unstructured meshing schemes. Structured meshing denotes the subdivision of the computational domain in a regular-spaced mesh. Unlike structured meshes, unstructured meshes are composed by an irregular pattern of elements, which are not arranged in a logical sequence.

Furthermore, we want to define the explicit and implicit meshing paradigms, which can be applied in structured as well as unstructured meshing schemes. Explicit meshing denotes the concept to adjust element boundaries exactly along known material interfaces of the physical model. In contrast, implicit meshing schemes do not respect internal material discontinuities in the mesh.

The meshing approach with respect to the approximation of the material values, can significantly influence runtime and simulation accuracy in consideration of the numerical method. Recent studies investigated whether internal material discontinuities of complex 3-D structural models should be geometrically respected by the mesh or not (Komatitsch 2004, Lee 2008, Casarotti2008a, Stupazzini2009, Pelties2010, Cupillard2012). In general, the explicit meshing of complex boundaries leads to the most accurate results. However, using an implicit representation, comparable results can be obtained at a lower meshing effort, but at much higher computational costs.

Page 1136, lines 25-26 (english): “Furthermore, assembling a scheme that is...”
The term “assembling” may be associated to finite-element methods and therefore I would recommend replacing it with another word.

Corrected

Old: Furthermore, assembling a scheme that is as accurate and efficient as a method

New: Furthermore, deriving a scheme that is as accurate and efficient as a method

Page 1137, lines 9-10 (english): “...but are usually only in low-order formulations efficiently implementable that are very dispersive.” Please reformulate this sentence

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which sounds awkward.

Corrected

Old: but are usually only in low-order formulations efficiently implementable that are very dispersive.

New: but can usually be implemented efficiently only in low-order formulations that are very dispersive.

Page 1137, line 14 (english): "...tetrahedral grids are much more flexible to align". The term "align" is misleading. Please replace this word with another.

Corrected

Old: tetrahedral grids are much more flexible to align

New: tetrahedral grids are much more flexible to adapt

Page 1137, line 14-15 (explain): "This tremendously reduces the meshing effort potentially at the expense of longer simulation time". Please explain your point concerning the simulation time. If the mesh allows for a better discretization of the model, one may expect a more precise solution with a reduced numerical cost. Here, you should explain how and why the simulation time can be affected.

At this point, we mean with 'expense of longer simulation time' the overhead generated by the book keeping of the element nodes and its connectivity. Furthermore, methods implemented on unstructured meshes tend to have problems with efficient cache use and how to make use of standard libraries for computational linear algebra (e.g. MKL). So, in general they are less efficient compared to methods using structured grids, unless strong mesh coarsening allows to save more computational time than it is needed by the mentioned drawbacks. However, even if we do not gain a speed up with a unstructured tetrahedral mesh, the meshing process itself can be

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reduced compared to using unstructured hexahedral meshes. This could mean less manual interaction of a scientist at the expense of a longer computation time.

Added

This tremendously reduce the meshing effort potentially at the expense of longer simulation time, due to the overhead generated by the book keeping of the element nodes and its connectivity. On the other hand, the extensive use of mesh coarsening capabilities using DG on unstructured tetrahedral meshes, as it is shown for an exploration scale study in Käser et al. (2010), also will save numerical costs. If a net reduction of the computational time is achieved or not, depends highly on the given problem setup.

Page 1138, line 1 (punctuation): “Recent studies investigated, whether internal material...”. Remove the comma after “investigated”.

Corrected

Old: Recent studies investigated, whether internal material

New: Recent studies investigated whether internal material

Page 1138, lines 1-4 (add information): you are referring to studies (Komatitsch, Lee, Casarotti, Stupazzini and Cupillard) but you are not saying anything about the conclusions of these studies. Please add some information. What are the conclusions of the authors? Do we need absolutely to respect the interfaces within the mesh?

See answer to comment of reviewer 1 page 1135, lines 24-26

Page 1138, lines 5-6 (explain): “Not respecting material interfaces of strong contrasts requires a high resolution for ADER-DG schemes”. Do you mean here that you need a very fine discretization? I guess that this is linked to the constant properties per

element. If so, you should indicate it clearly since at the beginning of the section 2.4.1 you refer to the SE method which is not based on this assumption.

Corrected

Old: Not respecting material interfaces of strong contrasts requires a high resolution for ADER-DG schemes, similar as seen for structured discretizations. Consequently, the computational costs are unnecessary expensive, since the dispersion properties would allow for larger elements. In order to reduce the runtime...

New: Implicit meshing of strong material contrasts requires a high resolution of the mesh in our ADER-DG implementation, because a constant material approximation is used. Consequently, the computational costs could be unnecessary expensive, although the dispersion properties would allow for larger elements. In order to reduce the runtime...

Page 1138, lines 17-18 (useless statement): “A Matlab parser can read the file to a Matlab structure which contains the material information and locations of the 3 D interfaces”. The fact that you are using a Matlab program is not informative for the reader. Remove this statement.

Corrected

Old: A Matlab parser can read the file to a Matlab structure which contains the material information and locations of the 3 D interfaces

New: The file contains material information and locations of the 3-D interfaces.

Page 1138, lines 18-20 (explain): “The upper-mantle discontinuities of the ak135 model are manually projected on spherical shells using the same lateral sampling points”. What do you mean by “manually projected”? Does this task can be done automatically which some kind of interpolation?

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Corrected

Old: The upper-mantle discontinuities of the ak135 model are manually projected on spherical shells using the same lateral sampling points

New: The upper-mantle discontinuities of the ak135 model are represented in the model as smooth spherical shells. The surfaces are reconstructed in Cubit using the radius of the respective discontinuity, and the same lateral sampling points of the crustal interfaces.

Page 1138, lines 24-25 (explain): “In Cubit a surface reconstruction directly from these pointsets failed”. Include a comma after “Cubit”. If you want to enter into such details when using Cubit, you should indicate why the process failed. Does Cubit give information about the failure?

Misleading statement, reformulated

To reconstruct the surface a set of parallel spline curves along a row or column of a pointset has to be created using the vertices as a spatial support.

Page 1138, lines 25-26 (explain): “Therefore, parallel spline curves along a row or column of the structured pointsets had to be created using the vertices as spatial support”. Does it that after this procedure, the surface has been smoothed?

Added

NURBS surfaces not necessarily coincide with their local control points. However, in case of the reconstruction of the 3-D Moho discontinuity, the distance in normal direction of the parametric surface, to points given by the EPcrust model, is less than 0.01% relative to their absolute location. Furthermore, the spacing of the pointsets is smaller than the element size, whereby mesh spacing determines the accuracy of the surface reconstruction.

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Page 1138, lines 26-27 (punctuation): Add a comma after “From the generated lineset”.

Corrected

Old: From the generated lineset an accurate

New: From the generated lineset, an accurate

Page 1139, lines 4-6 (explain): “Furthermore, so-called imprinting surfaces have to be defined to generate conforming meshes at each layer boundary”. What are the imprinting surfaces? Does the mesh built in several pieces? Why the need to define surface in order to generate conforming mesh. Please explain better.

Imprinting of surfaces is necessary if interfaces occur twice. Actually, this step was not necessary to create the mesh. It was mentioned for the sake of completeness.

Misleading statement, reformulated

For each layer of the model, corners of upper and lower surfaces are connected by line segments to generate the boundary faces of the domain. Therefore, interfaces and boundaries are connected at common edges and a closed volume can be obtained.

Page 1139, line 20 (add information): “Cubit provides geometry adaptive sizing functions to control the element size...”. What is the parameter for measuring the element size? Edge length, insphere radius, volume? Be more precise.

Corrected

Old: Cubit provides geometry adaptive sizing functions to control the element size and its growth rate in a volume during meshing.

New: Cubit also provides sizing functions to control the element size and its growth rate in a volume during meshing, where the element size is defined by its edge length.

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This allows for a local mesh refinement or coarsening, considering a well balanced aspect ratio ($AR = r_c/3r_i$, with r_c circumsphere radius and r_i insphere radius) of the tetrahedral elements.

Page 1140, line 6 (add information): “In case of distorted elements in the mesh...” Again, indicate how you detect a distorted element? What is the criterion you adopt with Cubit? Also can you provide more information about the algorithm implemented in Cubit? How the mesh is actually built? Does the process rely on a Delaunay triangulation?

Corrected

Old: In case, of distorted elements in the mesh, re-meshing with a different element size or manual changes of the mesh nodeset improved mesh quality.

New: In case, the aspect ratio of elements has been large ($r_c \gg 3r_i$), re-meshing with a different element size or manual changes of the mesh nodeset improved mesh quality.

Page 1140, line 13 (punctuation): Add a comma after “despite the mentioned difficulties”.

Corrected

Old: despite the mentioned difficulties the generation

New: despite the mentioned difficulties, the generation

Page 1140, lines 13-14 “...the generation of a high-quality tetrahedral mesh took one day...”. An important part of your article is devoted to the construction of tetrahedral meshes. Here, you should give some statistics about the mesh you built for the European model. I would suggest to add a table with at least the total nb of elements, min/max quality factors, min/max edge lengths and some other useful

information. This table will help the reader to understand the complexity of the mesh while illustrating the flexibility offered by tetrahedral elements.

Added table

Page 1140, line 24 (punctuation): Add a comma after “In the first experiment”.

Corrected

Old: In the first experiments we investigate

New: In the first experiments, we investigate

Page 1141, line 5 (punctuation): Add a comma after “With respect to the results of the SE method”.

Corrected

Old: With respect to the results of the SE method, a seismogram difference can be quantified by

New: With respect to the results of the SE method, a seismogram difference can be quantified by

Page 1141, line 12 (punctuation): Add a comma after “In this test”.

Corrected

Old: In this test we analyze

New: In this test, we analyze

Page 1141, line 18 (be more precise): “with a main period of $T_{\text{peak}} = 20\text{s}$ ”. Here, I guess you refer to the dominant period of the Ricker wavelet? In this case, you

may indicate that the minimum period of the source function is 8 s (i.e. $20 / 2.5$).

Corrected

Old: with a main period of $T = 20\text{s}$.

New: with a dominant period of $T = 20\text{s}$ which we want to accurately recover in our simulations.

Added

Note that the signal contains a considerable amount of energy within the range of approximately half the dominant period. Since, these low periods can be distorted by the simulation, the synthetics are lowpass filtered.

Page 1141, lines 19-20 (add figure and explain): “The physical domain of the SeisSol simulation, is a cuboid of $\Omega = [-1000 \text{ km}, 1000\text{km}] \times [-500 \text{ km}, 3500\text{km}] \times [2400 \text{ km}, 6400\text{km}]$...”. I would suggest to add a figure that shows the geometry of the mesh and possibly a view of its interior. It is particularly illustrative to show how the mesh honors the Earth discontinuities and how you adapt the size of the element with depth.

Added figure

Page 1141, lines 25-26 (explain): “This keeps a constant number of $n_{\min} = 3$ tetrahedral elements per shortest wavelength in each subdomain to model a shortest wave period of $T_{\min} = 20\text{s}$ ”. First point : Please justify why you adopt an average spatial discretization of 3 elements per shortest wavelength. I guess that with $O=5$, the recommended discretization with the SE method is only one element per shortest wavelength. Explain, why your discretization rules with DG-ADER are more severe than with SE. This is an important point, taken into account that for the same discretization length, the nb of tetrahedra is more important than with hexahedra. Second point: here you mention a shortest period of 20 s. This is not consistent with my precedent

comment (see above).

Corrected

Old: This keeps a constant number of $n_{min} = 3$ tetrahedral elements per shortest wavelength in each subdomain to model a shortest wave period of $T = 20s$. The high spatial discretization of the mesh is also suited to model wavefields over long propagation distances.

New: This keeps a constant number of 3 tetrahedral elements per shortest wavelength in each subdomain, to model a dominant wave period of $T = 20s$. We applied a severe spatial discretization of the mesh, to ensure a very high accuracy of the simulation.

Page 1142, lines 1-2 (add more information): “This high spatial discretization of the mesh is also suited to model wavefields over long propagation distances”. Can you be more precise and indicate a typical range of propagation distances in terms of nb of wavelength?

Misleading statement, reformulated

We applied a severe spatial discretization of the mesh, to ensure a very high accuracy of the simulation.

Page 1142, lines 3-8 (add a table): to conclude the descriptions of the meshes used by the SeisSol and SpecFEM codes, I would suggest to add a comparison table with some basic information: the volume of the modelling domain, the total nb of elements, min/max quality factors, min/max edge lengths and some other useful information for both SeisSol and SpecFEM.

The scope of the paper is to show the feasibility of DG simulations on a regional scale. In our opinion a quantitative comparison unfortunately cannot be derived in this study, as already explained in the text.

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Page 1142, lines 9-10 (add information): Can you indicate the range of propagation instances in terms on nb wavelength between the source and the receivers?

Added

The propagation distance in terms of the number of wavelengths between source and receivers $\# \lambda = 16$.

Page 1142, line 14 (punctuation): Add a comma after “For each station”.

Corrected

Old: For each station the traces

New: For each station, the traces

Page 1143, lines 12 (explain): “For the SeisSol simulation (add a comma) we reduced the block model of...”. Please explain why the model has been reduced in this case. At the end of this paragraph, you should indicate the position of the receivers since they probably are not located at the same positions than in the precedent test. Again, specify the range of propagation distances in terms of nb of wavelength.

The model has been reduced to reduce computational costs.

Corrected

Old: For the SeisSol simulation, we reduced the block model of Sec. 3.1 to a spherical

New: For the SeisSol simulation, we adapted the size of the block model of Sec 3.1 around the source region to a spherical

Added

The propagation distance in terms of the number of wavelengths between source and receivers $\# \lambda = 8$. At four stations, which are located at latitudes from 78° to 73° N and

longitude 0° W

Page 1143, line 20 (punctuation): Add a comma after “As expected”.

Corrected

Old: As expected the signals

New: As expected, the signals

Page 1144, lines 8-9 (add information): “In SeisCol (add a comma) a constant value for each parameter is interpolated in one single tetrahedral element...” I believe that this assumption should have been introduced in section 2.1 (see my precedent comment). Can you also indicate how the properties are interpolated per element? Do you perform a kind of averaging? Is it based on the barycenter of the element?

Added, see answer to comment of reviewer 1 page 1134 line 3

Page 1144, lines 13-15 (english and explain): “But, (remove the comma) tests have shown that the spatial discretization already is determined by an accurate approximation of the wavelength due to the CFL-condition”. I do not understand your point, please reformulate this sentence.

Corrected

Old: But, tests have shown that the spatial discretization already is determined by an accurate approximation of the wavelength due to the CFL-condition. Therefore, the sampling of the relatively low material gradient in PREM is sufficient.

New: In case of the PREM model, the relatively low material gradient (max. 1.5 % velocity variation in one element) is already accurately sampled, if the spatial discretization is adapted to the smallest wavelength. The smallest wavelength has to be resolved by the simulation in consideration of the propagation distance of the

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signal. That means, the sampling of the material distribution does not require a smaller mesh spacing even a constant material approximation is used.

Page 1144, lines 15-16 (shortcoming): “Therefore, the sampling of the relatively low material gradient in PREM is sufficient”. Can you justify your statement? For instance you can rely on the theoretical variation of properties within the elements, i.e. what is the typical percentage of velocity variation at the scale of the elements?

Corrected, see answer to comment of reviewer 1 page 1144, lines 13-15

Page 1144, line 18 (punctuation): Add a comma after “At near offset stations”.

Corrected

Old: At near offset stations larger envelope misfits occurred

New: At near offset stations, larger envelope misfits occurred

Page 1144, lines 21-22 (punctuation): Add comma after “Käser and Igel (2001) claimed that” and after “an isotropic elastic medium”.

Corrected

Old: Käser and Igel (2001) claimed that for an explosive source excited in an isotropic elastic medium the application

New: Käser and Igel (2001) claimed that, for an explosive source excited in an isotropic elastic medium, the application

Page 1144, lines 26-27 (comment): “the effect is purely numerical and can be diminished by refining the mesh around the source”. I guess you implement the source on a single element. What happens if the source coincides with one corner of the

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element? Also, have you tried to spread the source over several elements? You may discuss a little bit about the implementation of the source since it seems that it is mesh-dependent.

In the code of [L.C. Wilcox, G. Stadler, C. Burstedde and O. Ghattas: A high-order discontinuous Galerkin method for wave propagation through coupled elastic-acoustic media, Journal of Computational Physics, 229, Nr. 24, pp. 9373-9396, (2010).] the (Dirac) source is normalized (Gaussian) and spread over several elements. Simulation results of the Ghattas nodal DG code showed almost no artificial S-wave excitation, but in the far-field, amplitude differences occurred compared to analytical solutions. Therefore, we decided not to spread the source.

Added to Section 3

In SeisSol as well as in SpecFEM, the source can be located at an arbitrary position inside the element, and does not necessarily have to coincide with a mesh point or Gaussian integration node. But, since different polynomial basis functions are used, the discrete representation of the source term is different. In SeisSol, the basis functions are evaluated directly at the source position, whereas in SpecFEM the point source gets spread over the entire source element. If the source point coincides with an element boundary or vertex, only one element is allowed to contain the source.

Page 1145, lines 8-10 (add information): “Since the simulations of this study provides a different level of accuracy on different meshes and physical domains (add a comma) a quantitative comparison is not possible (, remove the comma) in fair terms”. I believe you have valuable information to provide here. It is true that the modeling with DGADER and SE have been performed on completely different meshes but there are some interesting parameters to look at. Therefore and again, I would suggest adding a comparison table. In this table you should indicate, for both SE and DG-ADER: the nb of unknowns, the dimension of the modelling domain, the nb of time steps and also the

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measured computation time with the nb of MPI process. Then, from these values, you can estimate the average computation time per unknown, per MPI process and per time step. In Etienne et al. 2010, we found out at this computation time is comparable between SE and DG. Is it also the case with your specific DG-ADER formulation? Let me say that this is just an interesting parameter and the objective is not to indicate that a code is better than another and vice-versa. But since you decided to include a paragraph entitled “Comparison of code performance”, I think you should give some statistics for the reader.

Indeed, the title of the section is misleading. Therefore, we merged the section to the discussion of the benchmark results. As already described in the text, the comparison between the methods is not quantitative enough if such different models are compared. We agree that a study comparing the code performances might be of interest, but would require experts of both methods in order to get a reliable result. Principle differences have been mentioned where it was possible, e.g. ODG 2.8OSE.

Page 1145, line 11 (punctuation): Add a comma after “...efficiency of numerical codes”.

Corrected

Old: the efficiency of numerical codes a conceptual

New: the efficiency of numerical codes, a conceptual

Page 1145, line 20 (punctuation): Add a comma after “In the previous test”. Remove comma after “...it could be demonstrated”.

Corrected

Old: In the previous tests it could be demonstrated, that

New: In the previous tests, it could be demonstrated that

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Page 1145, line 21 (punctuation): Add a comma after “In this section”.

Corrected

Old: In this section we qualitatively

New: In this section, we qualitatively

Page 1146, line 11 (punctuation): Add a comma after “of the Earth (and remove 's) crust”

Corrected

Old: To consider a realistic representation of the Earth's crust we introduce

New: To consider a realistic representation of the Earths crust, we introduce

Page 1147, line 14 (punctuation): Add a comma after “To generate a mesh inside the volume”

Corrected

Old: To generate a mesh inside the volume an appropriate

New: To generate a mesh inside the volume, an appropriate

Page 1147, lines 19-20 (justify): “a spatial sampling of 2 tetrahedral elements per smallest wavelength, if an $O = 5$ scheme is applied”. Here you adopt a different discretization from the validation test of section 3 where you decided to use 3 elements per smallest wavelength (with also $O = 5$). Please, explain why you are changing your discretization criteria. Actually, one would have expected that the validation tests allow estimating the required discretization to be used later in the real application.

In the benchmark studies we focused on highly accurate results, also in consid-

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eration of very low envelope misfits. Here we put a less conservative rule to reach an error level lower than 1% of phase misfit at an acceptable computational effort.

Corrected

Old: Due to Käser et al. (2008), who carried out an a ADER-DG convergence study on a simple block model, we expect high simulation accuracies over regional propagation distances at a spatial sampling of 2 tetrahedral elements per smallest wavelength, if an $O = 5$ scheme is applied.

New: According to an average minimum crustal velocity (PREM model) of $v_S = 3200\text{m/s}$ the number of propagated wavelengths is assumed to be $\#\lambda \approx 20$. Due to Käser et al. (2008), we expect high simulation accuracies over regional propagation distances at a spatial sampling of 2 tetrahedral elements per smallest wavelength, if an $O = 5$ scheme is applied.

Page 1147, line 21 (punctuation and shortcoming): “As already mentioned, in SeisSol (add comma) the materials values of tetrahedral elements are averaged over all vertex values”. Well, it has not been “already mentioned”. Please refer to my precedent comments.

Added, see answer to comment of reviewer 1 page 1134, line 3

Page 1147, line 23 (punctuation): Add a comma after “...mesh generation”.

Corrected

Old: for mesh generation the interpolation of the material values

New: for mesh generation, the interpolation of the material values

Page 1147, line 24-26 (shortcoming): “Assuming a seismic source signal at a peak frequency of 0.03 Hz (add a comma ,) the smallest wavelength of 36 km can be

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sampled correctly”. If I understand well, the average size of the element is 18 km (line 22). Then you have indicated that in the EPcrust model the S-wave velocity varies from 0.4 to 4.1 km/s. Then this leads to a wavelength of $0.4 / 0.03 = 13.3$ km. You can see here that the elements are larger than the wavelength and therefore the near subsurface (where the surface waves propagate) is not well sampled. But due to the interpolation of the physical properties, the minimum Vs is 1.1 km and this changes a lot the physical model. Please, comment the effect of the interpolation that produced higher Vs at the surface than in the real Earth.

Added

The significant change in the velocity model cannot be avoided, unless the sedimentary layer is respected explicitly in the mesh, or an inhomogeneous material distribution inside elements is applied in case of implicit meshing. However, this would lead to such a high number of additional elements that the simulation would not be feasible anymore on available HPC resources.

Page 1148, line 1 (punctuation): Add a comma after “In the mantle”.

Corrected

Old: In the mantle the mesh size

New: In the mantle, the mesh size

Page 1148, line 3 (typo): “3.7Melements” should be written “3.7 million elements”. Do not use the point for the thousand separator in “1.164 M degrees” since it has been used before as the decimal separator. This makes around 315 degrees of freedom per element. Is is correct?

315 degrees of freedom per element is correct. Polynomials of 5th order lead to 35 degrees of freedom per variable in one element. 9 variables (6 stress, 3 velocity

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components) were calculated.

Corrected

Old: For the whole mesh, this results in a total number of 3.7M elements leading to 1.164M degrees of freedom for an O5 ADER-DG simulation.

New: For the whole mesh, this results in a total number of 3.7 million elements leading to 1164 million degrees of freedom for an O5 ADER-DG simulation.

Page 1148, line 8 (punctuation): Add a comma after “For the l’Aquila earthquake”.

Corrected

Old: For the L’Aquila earthquake broadband data

New: For the L’Aquila earthquake, broadband data

Page 1148, line 10 (punctuation): Add a comma after “From these networks”.

Corrected

Old: From these networks we chose

New: From these networks, we chose

Page 1148, line 15 (punctuation): Add a comma after “For the simulation”.

Corrected

Old: For the simulation a source mechanism

New: For the simulation, a source mechanism

Page 1148, line 17 (punctuation and acronym): Define “STF”. Add a comma after “To obtain the STF”.

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Corrected

Old: To obtain the STF an inversion scheme

New: To obtain the STF, an inversion scheme

Page 1148, line 19 (punctuation): Add a comma after “Subsequently”.

Corrected

Old: Subsequently the real and synthetic data

New: Subsequently, the real and synthetic data

Page 1148, line 22 (punctuation): Add a comma after “For real and synthetic data”.

Corrected

Old: For real and synthetic data the amplitude

New: For real and synthetic data, the amplitude

Page 1148, line 23 (punctuation): Add a comma after “Here”.

Corrected

Old: Here, we want to emphasize

New: Here, we want to emphasize

Page 1149, lines 1-2 (explain): “The misfit between data and synthetics can be attributed mainly to the approximation of the material values inside the Earth by the applied velocity models”. You could probably improve your analysis. It seems that the S and the surface waves arrive earlier in the numerical simulation with SeisSol than in the observed data. This can be due to higher velocities in the near sub-surface

of the modelling mesh. Is it related to the approximation that changes for instances S-wave velocity from 0.4 to 1.1 km / s at the surface? Also, you did not indicate if an attenuation law was applied in your modelling. Please clarify.

Added

As already mentioned, also the fact that not every small feature can be modeled exactly with the given resolution (e.g. shallow low velocity zones) can have an influence on the simulation results. Since the surface waves tend to arrive earlier in the simulations, what suggests an overestimation of the velocities, an influence of the model discretization cannot be excepted.

Page 1149, line 3 (punctuation): Add a comma after “Concluding”.

Corrected

Old: Concluding we want to mention

New: Concluding, we want to mention

Page 1149, line 4 (english): Use “For instance” instead of “Exemplary”

Corrected

Old: Exemplary this can be seen

New: For instance this can be seen

Page 1149, lines 4-6 (be more precise): “...this can be seen, at the near offset station MATE where boundary reflections only occur after the surface wave has passed”. To help the reader, indicate at what time these reflections can be observed in the seismograms.

Misleading statement, reformulated

Concluding, we want to mention, that an interference of the synthetics by artificial boundary reflections cannot be excepted. However, clear signal onsets could not be identified.

Page 1149, line 17 (punctuation): Add a comma after “Due to the use of unstructured tetrahedral meshes”.

Corrected

Old: Due to the use of unstructured tetrahedral meshes numerical artifacts

New: Due to the use of unstructured tetrahedral meshes, numerical artefacts

Page 1149, line 19 (punctuation): Add a comma after “In the second part”.

Corrected

Old: In the second part the simulation

New: In the second part, the simulation

Page 1149, line 25 (punctuation): Add a comma after “As described in Sec 2.2”.

Corrected

Old: As described in Sec 2.2 ...

New: As decribed in Sec 2.2, ...

Page 1149, line 27 (english): “...this study can focus the computational effort using the ADER-DG method”. Instead of “focus” do you mean “justify”?

Corrected

Old: this study can focus the computational effort using the ADER-DG method

New: As described in Sec. 2.2, the design of unstructured tetrahedral meshes is fast and flexible. In addition, features like p-adaptivity and local time stepping can focus the computational effort using the ADER-DG method.

Page 1150, line 3 (punctuation): Add a comma after “In a future study”.

Corrected

Old: In a future study we want to

New: In a future study, we want to

Figure 2: Could you explain why the seismograms are not complete for each receiver?

Added

Artificial boundary reflections are cropped.

Figure 3: Same comment than above.

Added, see answer to comment of reviewer 1 Figure 2

Figure 4: This is an interesting figure but it is really too small. I suggest to enlarge it (over two columns). Indicate the scale for the dimension of the mesh (left). In the zoom (bottom right), we have the impression that the properties are represented with gradient within the elements while it should be piece-wise constant per element. Please clarify.

Changed figure

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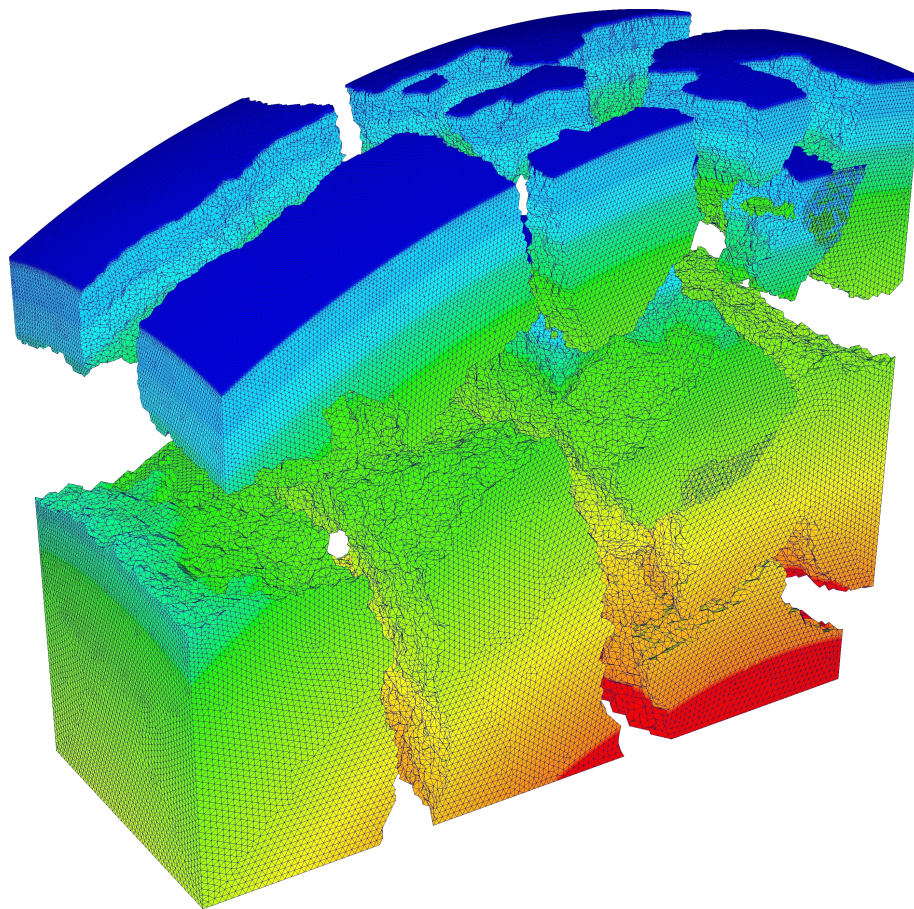


Fig. 1.

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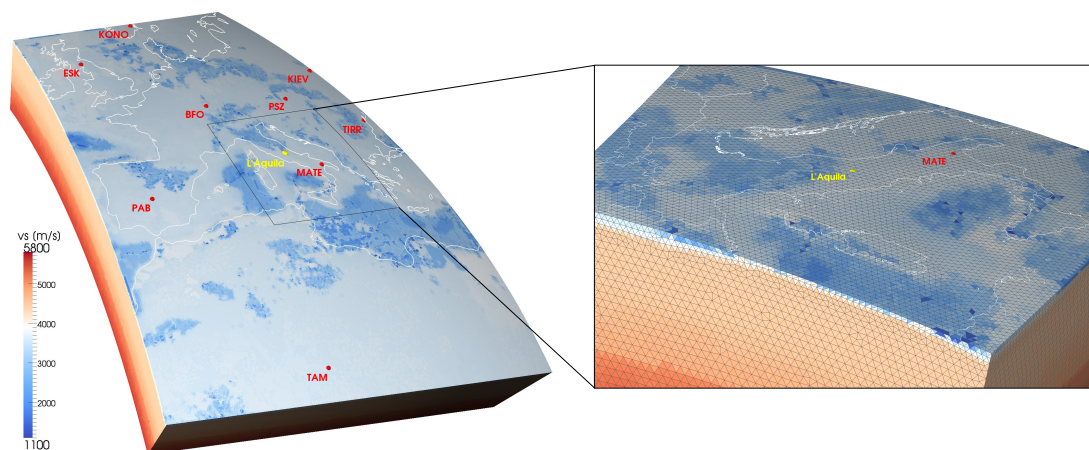


Fig. 2.

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