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Comparison of Numerical Methods for Seismic Wave Propagation and Source Dynamics - the SPICE Code Validation

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ABSTRACT - The Southern California Earthquake Center (SCEC) organized the 3D Numerical Simulation Code Validation Project for wave propagation in the past years. Recently, SCEC organizes an earthquake source physics code validation/comparison exercise. The goal of both efforts is to validate 3D earthquake simulation methods and foster their application by engineering community. Development of the earthquake motion numerical simulation methods is one of the primary goals of the Seismic Wave Propagation and Imaging in Complex Media: a European Network (SPICE), the EU FP6 project. SPICE provides a reasonable platform for a code validation effort in Europe. We present here the SPICE Code Validation. The intention is to create a long-term basis for possible tests/comparisons/validation of numerical methods and codes for the earthquake motion simulation. The basis should serve even after the SPICE project is completed. Technically, the code validation process will be facilitated using the web-based interface (http://www.nuquake.eu/SPICECVal/). The submitted solutions will be evaluated and compared using quantitative misfit criteria based on the time-frequency representation of the signals.

1. Introduction

The intention of the SCEC 3D Numerical Simulation Code Validation Project for wave propagation and the earthquake source physics code validation/comparison exercise efforts was to validate 3D earthquake simulation methods and foster their application by engineering community. The SCEC code validation project (Day et al., 2003) compared 3D wave propagation codes for a hierarchy of test problems, ranging from simple point-source problems in canonical earth structures (e.g., a layer over halfspace) to propagating ruptures in complex 3D representations of Los Angeles Basin geology. A review table of the SCEC wave propagation test models is given in Table 1. Given the time available for the SCEC code validation, the set of models had to be relatively limited. Therefore, it was not possible to detail as many models as it would be necessary to enable tests for individual structural/methodological aspects of the computational methods. The earthquake source validation set will similarly cover models starting from relatively simple ones up to complex real events.

Development of the earthquake motion numerical simulation methods is one of the primary goals of the Seismic Wave Propagation and Imaging in Complex Media: a European Network (SPICE), the EU FP6 project that involves fourteen European institutions. This is why the SPICE project provides a reasonable platform for a code validation effort in Europe.

The main intention of the SPICE Code Validation effort is to create a long-term basis for possible tests/comparisons/validation of numerical methods and codes for the seismic wave propagation and earthquake motion simulation. The basis should serve even after the SPICE project is completed. The possibility to test methods/codes should be open and user-friendly for anybody interested in the use of the SPICE Code Validation models.

Table 1. Review table of the SCEC wave propagation test models

Model Name	Geometry	VS	VP	VP/VS	QS	QP	Source	Freq. Range	ABC	Purpose / Note	SPICE Code Validation Subset
UHS1	halfspace	3 464	6 000	1.73	inf.	inf.	DCP 0.58 λs (1 Hz)	0 - 5	distant	reference solution	WP 1
UHS2	halfspace	3 464	6 000	1.73	inf.	inf.	DCP 0.58 λs (1 Hz)	0 - 5	close	accuracy of ABC	WP 1
LOH1	1000 m layer / halfspace	2 000 3 464	4 000 6 000	2 / 1.73	inf.	inf.	DCP 0.58 λs (1 Hz)	0 - 5	distant	presence of a layer ; interface on a grid plane	WP 2
LOH2	1000 m layer / halfspace	2 000 3 464	4 000 6 000	2 / 1.73	inf.	inf.	Fin. Kin. on a grid plane	0 - 5	distant	LOH1 + FinKinSource on a grid plane	SD 1
LOH3	1000 m layer / halfspace	2 000 3 464	4 000 6 000	2 / 1.73	40 69.3 const	120 155.9 const	DCP 0.58 λs (1 Hz)	0 - 5	distant	LOH1 + Attenuation	WP 2
LOH4	1000 m layer / halfspace	2 000 3 464	4 000 6 000	2 / 1.73	inf.	inf.	Fin. Kin. general pos.	0 - 5	distant	LOH1 + FinKinSource in a general position	SD 1
SC2.1	realistic model SFv/LAb									complex structure	WP 3
SC2.2	realistic model SFv/LAb									simplified complex structure	WP 3

2. Model Sets

The test-model sets should be designed such that new models could be added in correspondence with progress in the numerical modeling methods. The long-term plan may include models for which we do not know reference solutions at present but it is very likely that the models/problems will be addressed in near future.

The elaboration of the SPICE test models started with the evaluation of the models used in the SCEC Code Validation. Based on the evaluation of the SCEC Code Validation and capabilities of recent numerical-modeling methods, two model sets were elaborated: Wave Propagation (WP) model set and Source Dynamics (SD) model set. Both model sets are then divided into three subsets. The first subset includes the simplest canonical models that should enable testing of methods for their abilities to account for individual structural/methodological aspects. The second subset includes simple canonical models that combine two or more structural/methodological aspects. The third subset includes realistic (structurally complex) models.

A concise outline of the WP and SD test model sets is given in the following sub-sections.

2.1. Wave Propagation (WP) Model Set

SPICE Subset WP I

Simplest canonical models designed to test accuracy of the methods/codes with respect to individual factors/features of the models including absorbing boundary conditions:
(*includes SCEC_UHS1 and SCEC_UHS2*)

- homogeneous elastic space : dispersion, local error
- homogeneous viscoelastic space : incorporation of attenuation
- 2 homogeneous halfspaces : planar interface
  - coinciding with a grid plane
  - parallel with a grid plane
  - non-parallel with a grid plane
  - elastic interface
  - viscoelastic/pure_Q interface
- homogeneous halfspace : planar free surface
- homogeneous anisotropic elastic space : anisotropy

SPICE Subset WP II

Canonical models combining two or more basic individual factors/features:
(*includes SCEC_LOH1 and SCEC_LOH3*)

- layer over halfspace : planar interface + free surface
  - coinciding with a grid plane
  - parallel with a grid plane
  - non-parallel with a grid plane
  - elastic and viscoelastic
  - source inside layer, source in the halfspace
- layer over halfspace : gradient in velocity / Q
- layer over halfspace : random velocity distribution
- soft inclusion in a halfspace : lateral heterogeneity
  - interfaces coinciding with a grid plane
  - parallel with a grid plane
  - non-parallel with a grid plane
- vertical layer in a halfspace : interface at the free surface
- 2 homogeneous halfspaces : non-planar interface
- free-surface topography : traction-free condition on non-planar surface
  - Gaussian hill
  - cliff
  - slope

SPICE Subset WP III

Realistic models (*includes SC_2.1 and SC_2.2*):

- Colfiorito, Central Italy : laterally bounded sedimentary basin
  (in cooperation with the INGV Rome, Italy)

- Grenoble, France : deep Alpine valley
  (in cooperation with the ESG-2006 Grenoble benchmark organizers)

2.2. Source Dynamics (SD) Model Set

Source dynamics models will be characterized by (visco)elastic parameters, friction laws, initial stress, nucleation, and fault geometries.

SPICE Subset SD I
Simplest canonical models with standard friction laws (slip weakening, velocity weakening, rate-and-state friction):

Figure 1. The simplest canonical models.

SPICE Subset SD II
Canonical models that include principal problem configurations:

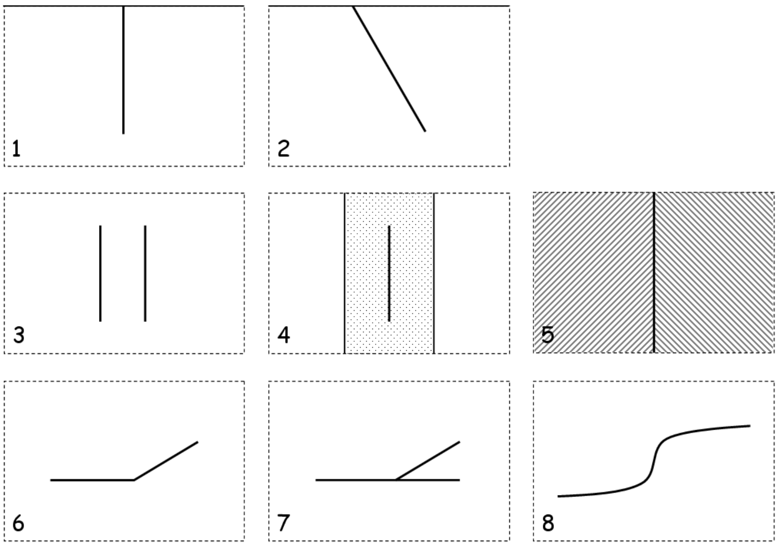

Figure 2. Canonical models.

SPICE Subset SD III
Realistic models including standard friction laws, fluid interactions, thermal effects, damage mechanics:

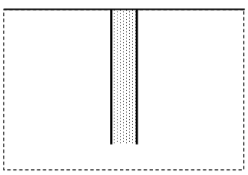

Figure 3. Realistic models.

3. Quantitative Misfit Criteria for Comparison of Seismograms

Each submitted solution will be compared with a reference solution for a given problem, and, possibly, with other submitted solutions, using the quantitative misfit criteria. A set of time-frequency, time-dependent, frequency-dependent, and single-valued criteria were developed by Kristekova, Kristek, Moczo and Day (2006). The criteria are based on the time-frequency representation of seismograms. The time-frequency representation is obtained using the continuous wavelet transform.

4. Short-Term SPICE Code Validation

Within the time of the SPICE project only a limited number of models can be a subject of test calculations. The model set includes:

Unbounded homogeneous space (elastic, viscoelastic)
Homogeneous halfspace (elastic, viscoelastic)
Layer over halfspace
- constant velocity (point DC source, finite kinematic source)
- velocity gradient

Two homogeneous layers over halfspace (H1 / H2 = ($\sqrt{5}$ -1) / 2)
3D soft inclusion in the halfspace (croissant valley)
3D free-surface topography (Gaussian hill)
Realistic model (Grenoble Valley – ESG 2006 benchmark)
Source dynamics model

5. Interactive Web Interface

The interactive web interface has been developed by the SPICE team at the Comenius University in Bratislava. The interface (http://www.nuquake.eu/SPICECVal) will serve to organizers and voluntary participants of the SPICE Code Validation.

The use of the interface is easy and the web pages navigate participant step by step from the registration and model selection up to comparison of a solution with a reference or any other selected solution. Each participant can, in principle, use several computational methods/codes and upload several solutions for each model.

The web-interactive procedure includes the following steps:

A. Registration of a participant and a method, Figure 4.
B. Selection of a model, download of the model description, Figure 5. An example of the model description is shown in Figure 11.
C. Conversion of the solution into the upload format, Figure 6.
D. Upload of the solution, Figure 7.
E. Comparison of the uploaded solution to selected solution(s). This includes selection of a model, solution(s), option to plot seismograms and/or evaluate time-frequency misfits, selection of a component and receiver. The web-interface windows and plots of seismograms and misfits are illustrated in Figures 8, 9, and 10.

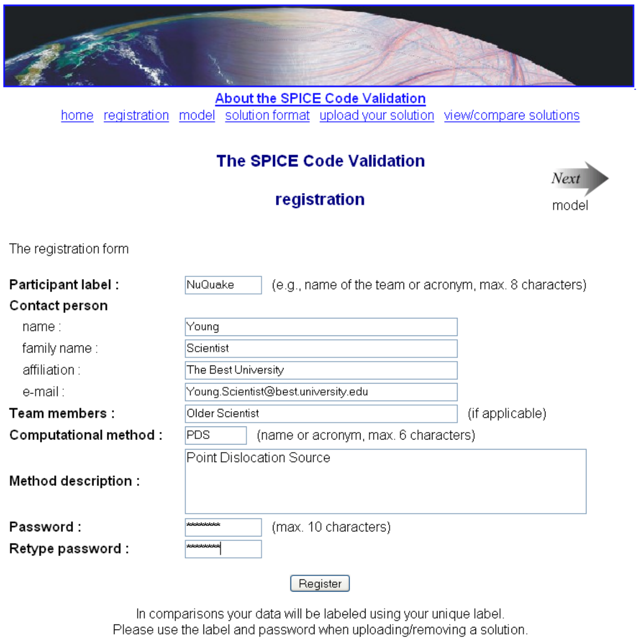

Figure 4. The registration form

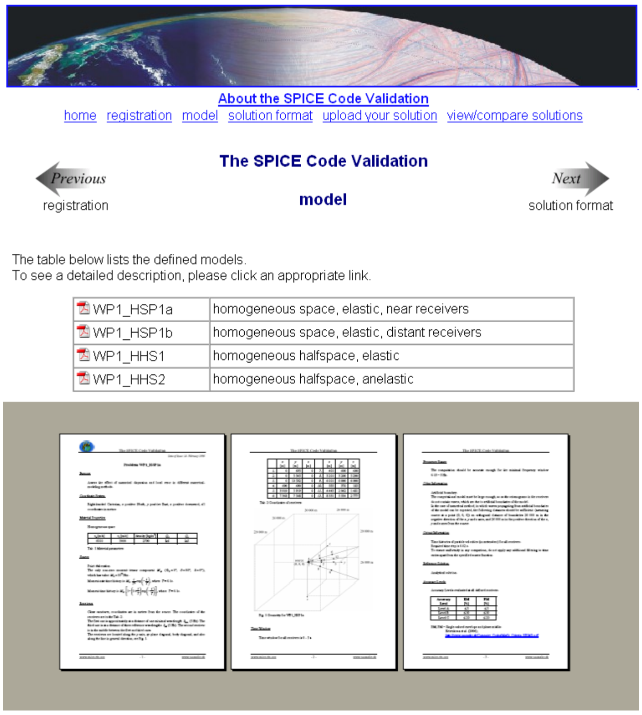

Figure 5. Model description download.
See details of the model specification in Fig. 11.

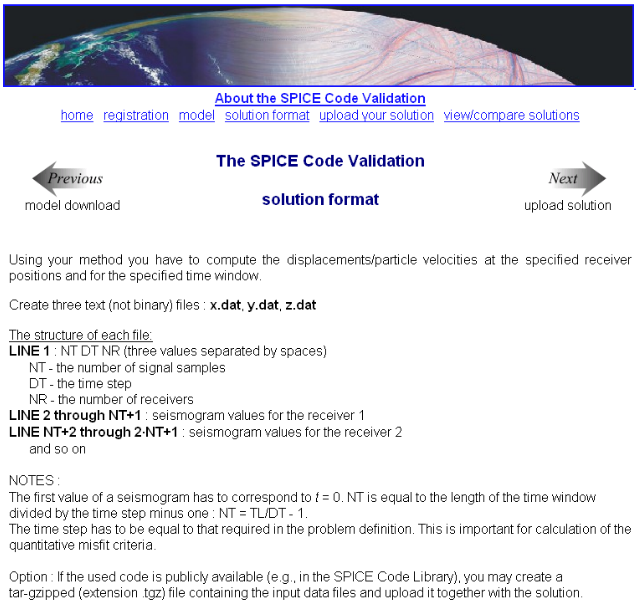

Figure 6. The upload format.

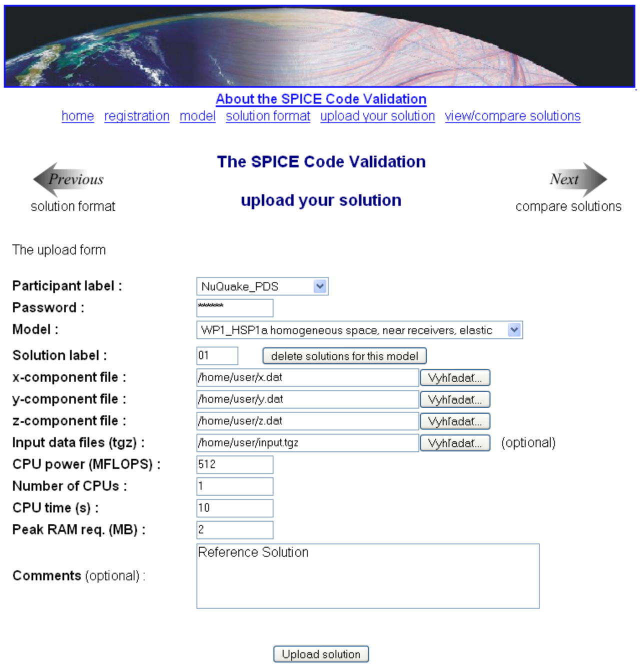

Figure 7. The upload form.

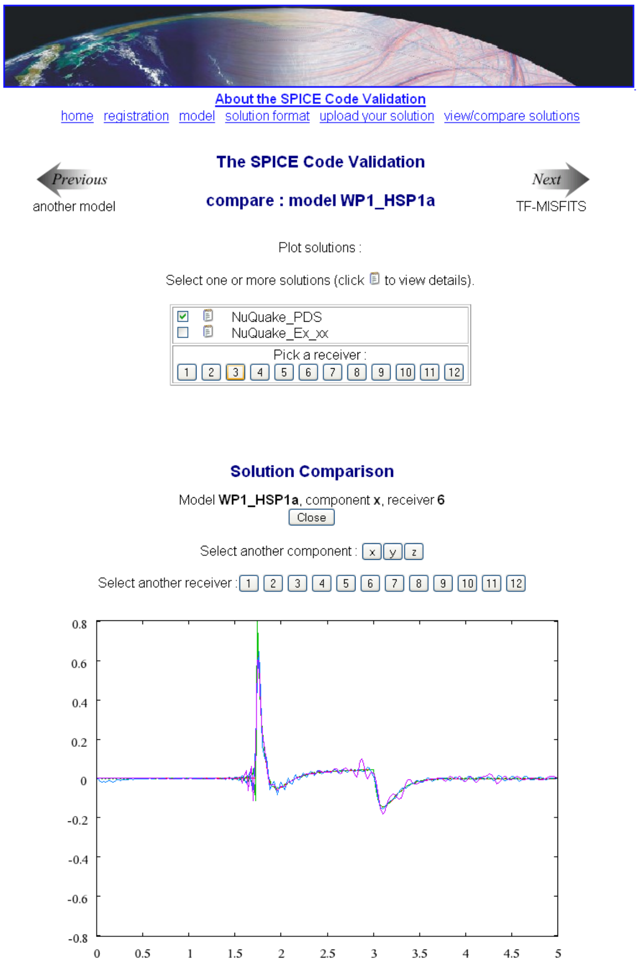

Figure 8. Plot of four selected solutions (an example).

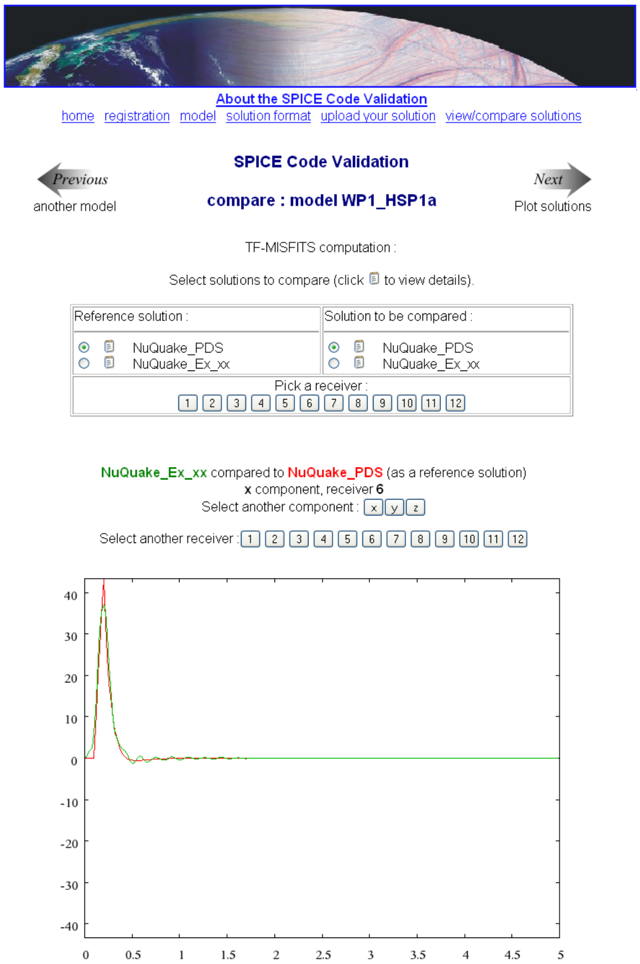

Figure 9. Plot of two seismograms for which TF-misfits are shown in Figure 10.

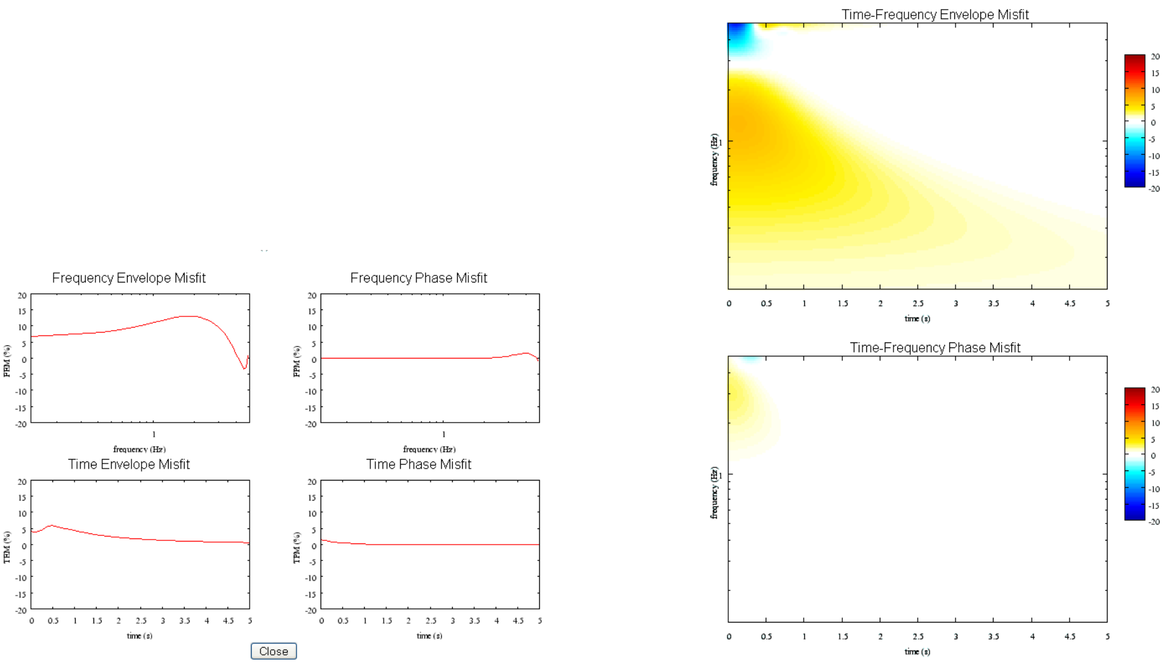

Figure 10. TF-misfits for two seismograms shown in Figure 9.

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Problem WP1_HSP1a

Purpose

Assess the effect of numerical dispersion and local error in different numerical-modeling methods.

Coordinate System

Right-handed Cartesian, x positive North, y positive East, z positive downward, all coordinates in meters.

Material Properties

Homogeneous space

v_P [m/s]	v_S [m/s]	density [kg/m^3]	Q_P	Q_S
6000	3464	2700	Inf.	Inf.

Tab. 1 Material parameters

Source

Point dislocation.
The only non-zero moment tensor component M_{xy} ($\Phi_S = 0°$, $\delta = 90°$, $\lambda = 0°$), which has value $M_0 = 10^{18}$ Nm.

Moment-rate time history is $M_0 \cdot \frac{t}{T^2} \exp\left(-\frac{t}{T}\right)$, where $T = 0.1$s.

Moment time history is $M_0 \cdot \left[1 - \left(1 + \frac{t}{T}\right)\exp\left(-\frac{t}{T}\right)\right]$, where $T = 0.1$s.

Receivers

Close receivers, coordinates are in meters from the source. The coordinates of the receivers are in the Tab. 2.
The first one is approximately at a distance of one minimal wavelength λ_{min} (5 Hz). The third one is at a distance of three reference wavelengths λ_{ref} (1 Hz). The second receiver is in the middle between the first and third ones.
The receivers are located along the y axis, xy plane diagonal, body diagonal, and also along the line in general direction, see Fig. 1.

	x [m]	y [m]	z [m]		x [m]	y [m]	z [m]
1.	0	693	0	*7.*	400	400	400
2.	0	5 543	0	*8.*	3 200	3 200	3 200
3.	0	10 392	0	*9.*	6 000	6 000	6 000
4.	490	490	0	*10.*	555	370	185
5.	3 919	3 919	0	*11.*	4 443	2 962	1 481
6.	7 348	7 348	0	*12.*	8 331	5 554	2 777

Tab. 2 Coordinates of receivers

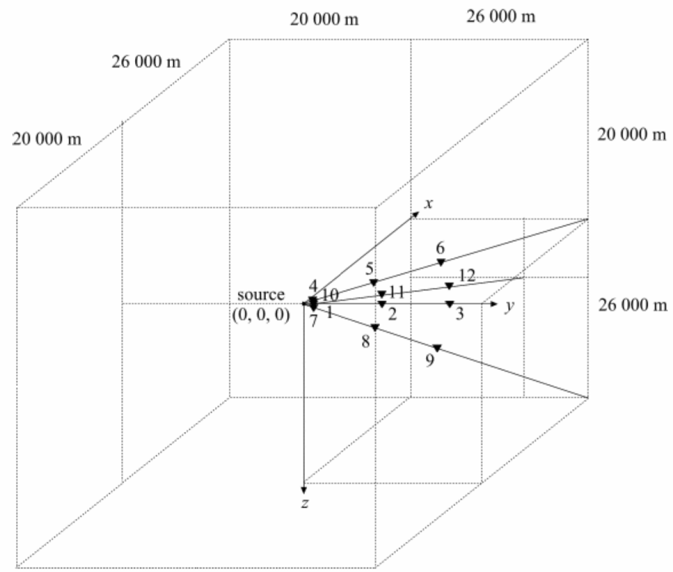
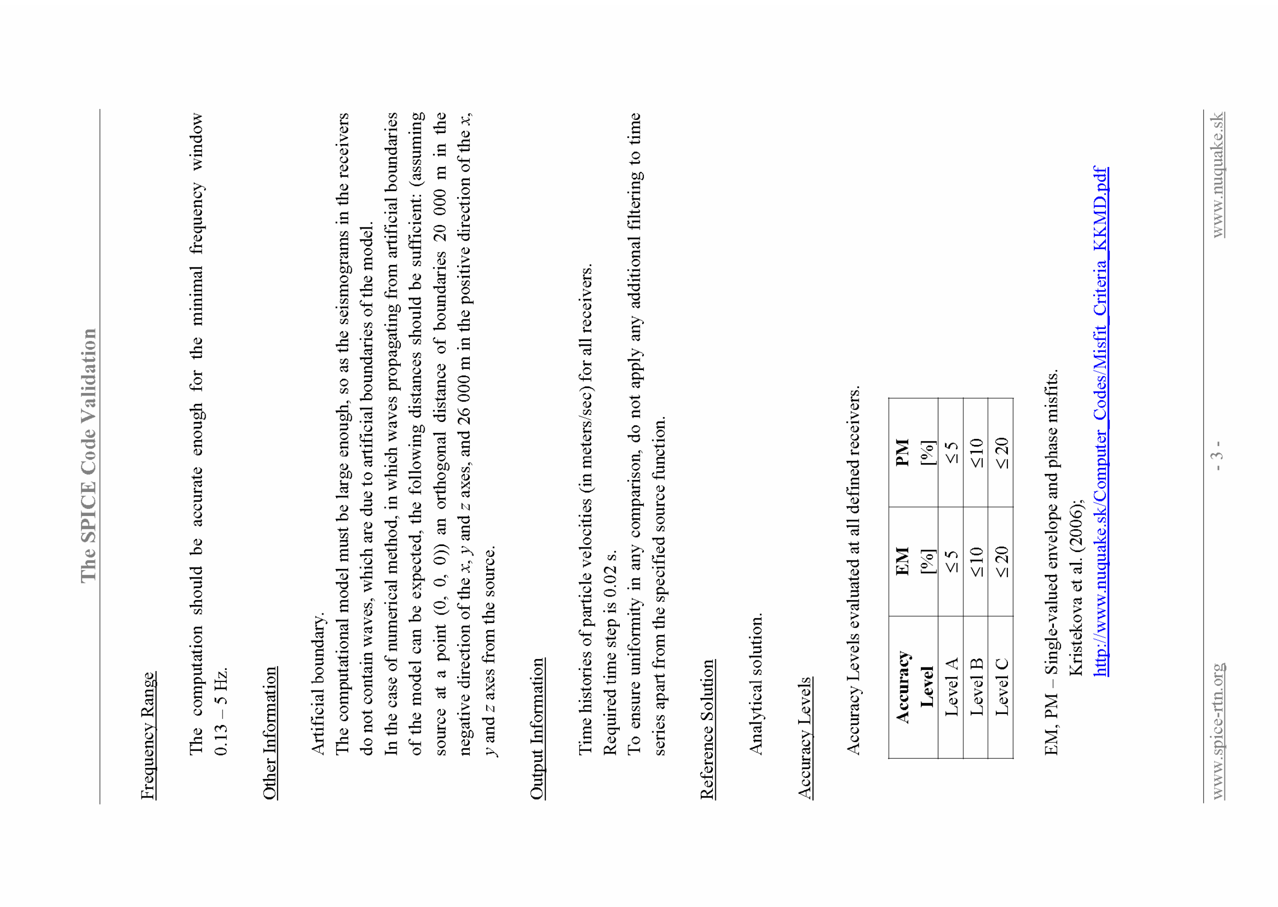


Fig. 1 Geometry for WP1_HSP1a

Time Window

Time window for all receivers is 0 - 5 s.



The SPICE Code Validation

Frequency Range

The computation should be accurate enough for the minimal frequency window 0.13 – 5 Hz.

Other Information

Artificial boundary.
The computational model must be large enough, so as the seismograms in the receivers do not contain waves, which are due to artificial boundaries of the model.
In the case of numerical method, in which waves propagating from artificial boundaries of the model can be expected, the following distances should be sufficient: (assuming source at a point (0, 0, 0)) an orthogonal distance of boundaries 20 000 m in the negative direction of the x, y and z axes, and 26 000 m in the positive direction of the x, y and z axes from the source.

Output Information

Time histories of particle velocities (in meters/sec) for all receivers.
Required time step is 0.02 s.
To ensure uniformity in any comparison, do not apply any additional filtering to time series apart from the specified source function.

Reference Solution

Analytical solution.

Accuracy Levels

Accuracy Levels evaluated at all defined receivers.

Accuracy Level	EM [%]	PM [%]
Level A	≤ 5	≤ 5
Level B	≤10	≤10
Level C	≤ 20	≤ 20

EM, PM – Single-valued envelope and phase misfits.
Kristekova et al. (2006);
http://www.nuquake.sk/Computer_Codes/Misfit_Criteria_KKMD.pdf

www.spice-rtn.org - 3 - www.nuquake.sk

Figure 11. Example of the model description.

6. Conclusions

The SPICE Code Validation provides an unprecedented opportunity in Europe (and possibly not only in Europe) to test and compare methods and computer codes for modeling of seismic wave propagation, earthquake ground motion, and seismic exploration. Thus, it can be a useful tool in development of more accurate and computationally efficient methods.

7. Acknowledgement

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8. References

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Kristekova, M., J. Kristek, P. Moczo, and S. M. Day (2006). Misfit Criteria for Quantitative Comparison of Seismograms. *Bull. Seism. Soc. Am.*, in press.