The Unified Community Velocity Model Software Framework

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Abstract

This paper presents the Unified Community Velocity Model (UCVM) software framework developed by the Southern California Earthquake Center. UCVM is a collection of software tools and application programming interfaces designed to provide standard access to multiple seismic velocity models used in seismology and geophysics research. Seismic velocity models are key components of current research efforts dedicated to advancing our knowledge of the Earth's crustal structure and its influence on the ground response during earthquakes, including both the regional deep geology and local effects due to the geometry, spatial distribution, and material composition of sediments in basins and valleys. In general, the UCVM software framework is designed to facilitate all research activities involving the use of seismic velocity models, but its development has been particularly driven by applications for deterministic physics-based earthquake ground-motion simulation and seismic hazard analysis. The UCVM has been extensively used in modeling and simulation activities in southern California. Here we describe the background that led to the development of the UCVM and its various software components, including advanced high-performance computer tools available within UCVM, and its capabilities in terms of product deliverables and performance. We also present examples of recent applications that use UCVM tools or output datasets.

Keywords:
seismic velocity models, earthquake simulation, high-performance computing, meshing

1. Introduction

The quantitative understanding of the physical world is an essential goal of geoscience research. We use mathematical abstractions to represent the behavior of systems under static and dynamic conditions; and properties such as density and elastic moduli to characterize the capacity of materials to absorbe or transmit forces in stationary and transient processes. In seismology and geophysics, our understanding of physical phenomena associated to earthquakes, their genesis, and effects, depends in a good measure on our knowledge and accurate representation of the geometry and material properties of the Earth's structure, as well as on our capacity to represent the mechanical characteristics of the rupture process that takes place when a seismic fault breaks and the subsequent seismic wave propagation problem. For the former case, we use stress conditions and dynamic rupture models to describe the faulting process. On the other hand, for the latter case, we use seismic velocity and attenuation models to describe the geologic structure of the mantle and crust, and the mechanical properties of the materials in the different geologic units that compose these structures to describe the propagation of seismic waves through basins and sedimentary deposits, and thus determine the characteristics of the ground motion.

Source models and seismic velocity models are therefore the basic input to earthquake simulation. We are interested on how seismic velocity models are built and made available to geoscientists, and in particular, on how these models can help advance physics-based earthquake simulation. We call physics-based earthquake simulation, the modeling approaches that use deterministic numerical techniques—such as the finite element, finite difference, or spectral element methods—to simulate the ground motion in ways that incorporate the physics of earthquake processes explicitly. That is, methods that explicitly solve the associated wave propagation problem. The use of physics-based earthquake simulation has increased considerably over the last two decades thanks to the growth—in capacity and availability—of high-performance computing (HPC) facilities and applications (e.g., Aagaard et al., 2008; Olsen et al., 2009; Bielak et al., 2010; Cui et al., 2010). These simulations have specific applications of great impact in seismology and earthquake engineering in aspects such as the assessment of regional seismic hazard (e.g., Graves et al., 2011).

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Recent simulations have highlighted the importance of velocity models in the accuracy of simulation results (e.g., Taborda and Bielak, 2014). Numerous seismic velocity models have been built for specific regional or local structures and used in particular simulations over the years (e.g., Frankel and Vidale, 1992; Brocher, 2008; Graves, 2008). The need for these models in simulation gave way to the conception of the community velocity models (CVMs). CVMs are seismic velocity models that have been developed, maintained, advanced and used by a community of interested investigators. Some examples of CVMs for the regions of southern and northern California, Utah, and the central United States are those models developed by Kohler et al. (2003); Brocher et al. (2006); Magistrale et al. (2006) and Ramírez-Guzmán et al. (2012).

CVMs have been typically distributed in the form of datasets or collections of files, or in the form of computer programs that can dynamically operate on these datasets and files to provide information about the geometry and material properties of the crust in a particular region. However, these datasets and computer programs have not always been thought carefully from a computational perspective. In addition, recent advances in earthquake simulations, powered by the increasing capability of supercomputers, have increased significantly the computational demand placed on CVMs as input to these simulations.

This paper presents the Unified Community Velocity Model (UCVM), a software framework designed to provide standardized and computationally efficient access to seismic velocity models, developed and maintained by the Southern California Earthquake Center (SCEC). UCVM is a collection of software tools and application programming interfaces (APIs) that facilitate the access to the material properties stored in CVMs. Although UCVM was conceived as a tool to aid physics-based earthquake ground-motion simulation and regional seismic hazard assessment, it can be used in other geosciences and engineering applications. Here, we describe the development of UCVM and its various software components, including features for use in high-performance parallel computers, and present examples of recent applications of UCVM tools in earthquake research.

2. The UCVM Software Framework

The primary functionality provided by UCVM is the ability to query a wide array of CVMs for material properties in standardized formats, independently of the particularities of each dataset or CVM. UCVM achieves this by registering datasets and velocity models into the framework. Registration of a velocity model or dataset consists of creating the appropriate programming application interface (API) to facilitate the communication between the framework utilities and tools, and the velocity models and datasets. Once a velocity model or dataset has been registered with UCVM, a client can use the framework utilities to retrieve information from the models at any geographic point within the coverage region of the model. A client can be either a user or another software. The primary data-point typically retrieved by a client consists of a float triplet with the seismic velocities (V_P and V_S), and the material's density (ρ). At times we refer to this triple as the payload. The UCVM can then be used to produce standardized output in the form of three-dimensional (3D) volumetric datasets, two-dimensional (2D) vertical cross-sections and horizontal slices, and individual data-points. A client can also use other UCVM utilities for plotting and transforming models and datasets.

In order to facilitate access to the models, UCVM conceals each model's local coordinate system behind a generic querying interface. Data points are queried through this interface by geographic latitude and longitude, and a vertical z-coordinate. The framework allows defining the z-axis as either depth below the free surface (in meters, positive downward) or elevation relative to mean sea level (where zero is at sea level, positive upward and negative downward). The framework further extends the standardized interface by allowing multiple velocity models to be aggregated into a single composite model. Composition is accomplished by tiling two or more velocity models in three dimensions according to a user-specified priority ordering. To support this flexible query mechanism consistently across all models, UCVM includes a high-resolution digital elevation model (DEM). The DEM is synthesized from the USGS National Elevation Dataset (citation needed) and the ETOPO1 Global Relief Model (citation needed). An additional advantage to providing the built-in DEM is that the client can retrieve the surface elevation at any query point in addition to the default data-point payload (V_P, V_S), ρ).

With the exception of the Wasatch Front (Utah) CVM, currently the primary focus of UCVM has been on models available for the State of California (and portions of neighboring States). However, the framework has been designed to be easily modified to cover any arbitrary region of the Earth's surface, provided adequate resolution velocity and elevation models exist. Additional details about the models available through UCVM are given in the following section on Community Velocity Models. Subsequent sections provide further information on the main UCVM utilities and APIs. However, due to space limitations, not all UCVM utilities and options can described here. General and advanced users should refer to on-line manuals and documentation. Table 1 provide URL addresses linking to supporting material. The last section of the paper is dedicated to additional aspects on the computational performance of the UCVM framework and two recent case applications.

3. Supported Velocity Models and Datasets

Velocity models vary considerably in terms of area of coverage, depth extent, composition, and resolution. The UCVM framework is flexible in its support for such variability and has been designed to integrate different velocity models, as well as to interact with their individual features seamlessly. UCVM has built-in support for a number of standard CVMs, which the platform utilities identify through through a series of corresponding string labels. Table 2 lists the models currently supported in the UCVM framework and provides additional details and references, along with their string labels. While all these models are supported by UCVM, only a fraction of them are included in the automated installation package, the remaining ones need to

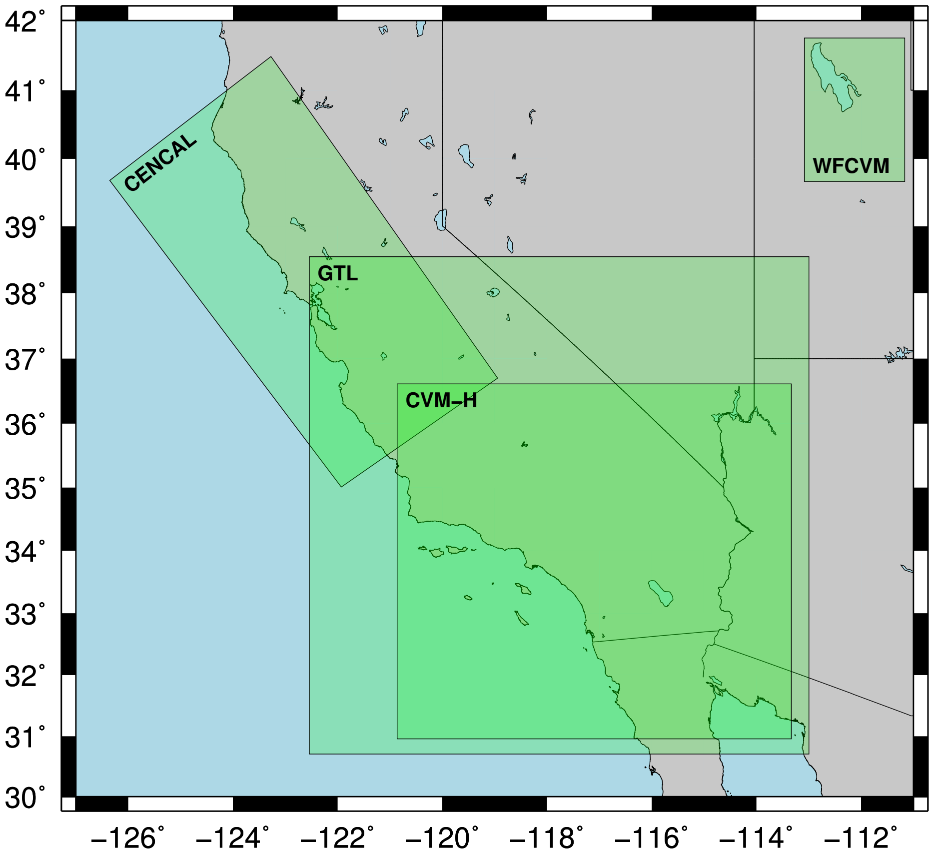

Figure 1: Temporary mock-up figure done in GMT to be improved later once we have all the boxes in Table 2. Surface horizontal projection of the areas covered by the various standard velocity models supported by the UCVM platform.

Table 1: Electronic addresses to UCVM on-line documentation.

Description	URL Address
General Documentation	http://scec.usc.edu/scecpedia/UCVM
General User Guide	http://scec.usc.edu/scecpedia/UCVM_User_Guide
Latest Version (14.3) Guide	http://scec.usc.edu/scecpedia/UCVM_14.3.0_User_Guide
Advanced User Guide (14.3)	http://scec.usc.edu/scecpedia/UCVM_14.3.0_Advanced_User_Guide
Tutorial (14.3)	http://scec.usc.edu/scecpedia/UCVM_14.3.0_Tutorial

Table 2: Question marks indicate fields that need to be completed. This list needs to be checked carefully. List of velocity models currently supported by the UCVM platform.

Model Name	Region	String Label	Installation	Coverage Coordinates	References
SCEC CVM-H	Southern California	cvmh	Automated	?	Plesch et al. (2011a) Plesch et al. (2011b) ?
SCEC CVM-S	Southern California	cvms	Automated	?	Magistrale et al. (1996) Magistrale et al. (2000) Kohler et al. (2003)
SCEC CVM-S4.26	Southern California	?	Automated	?	?
Hadley-Kanamori 1D	?	1d	Automated	?	?
Carl Tape SoCal	Southern California	tape	Manual	?	?
Broadband 1D	Whittier Narrows	?	Automated	?	?
Graves	Cape Mendocino	cmrg	Manual	?	?
USGS CenCalVM	Central California	cencal	Automated	?	Brocher (2005) Brocher et al. (2006)
SCEC CVM-NCI	?	cvmnci	Manual	?	?
Lin-Thurber	California Statewide	lt	Manual	?	?
USGS WFCVM	Wasatch Front, Utah	wfcvm	Manual	?	Magistrale et al. (2006)

be installed manually before they can be accessed through the platform. We indicate in the table which of the models are included in the automated installation and which require manual installation. Figure 1 shows a map with the coverage areas of various CVMs in Table 2.

Velocity models need to be enabled at installation time. UCVM is distributed with an easy installation method which runs a Python script (`ucvm_setup.py`) that prompts the user about which of the automated models are to be installed. If the user wants to enable other velocity models at a later time, the installation process needs to be repeated to enable the desired additional models. Advanced users can also customize the installation to include other models, including user-defined velocity models, which can be added in the form of an *etree* (Tu et al., 2003) databases or as *patch* (rasterized) models. These advanced features are described in detail in the UCVM Advanced User guide (see Table 1).

In addition to the velocity models in Table 2, UCVM includes two geotechnical layer (GTL) models. These models are intended to supplement (replace) the near-surface information in the original velocity models for a smoother transition from the softer near-surface soil deposits to the stiffer bedrock basement. The first of the two GTL models implements a V_{S30}-based interpolation from the free surface down to a given depth z, following Ely et al. (2010). The second GTL model is a generic one-dimensional (1D) model identical the 1D crustal model. Two interpolation schemes can be used to smooth GTL material properties with the underlying crustal model material properties: a linear interpolation, or the interpolation relationship used by Ely et al. (2010). As in the case of the CVMs, the GTLs and interpolation schemes are identified with string labels, namely `elygtl` and `1dgtl` for the V_{S30}-based and the 1D models, respectively. Similarly, the interpolation schemes are identified with the labels `ely` and `linear`. The Ely GTL and interpolation models are used in the CVM-H model by default, with a reference depth of $z = 350$ m. This option can be turned on or off by setting the model flag `USE_GTL = true/false`.

To support the V_{S30}-based GTL models, UCVM has two built-in standard maps for California at 1 arcsec resolution (following USGS NED standards). These maps contain elevation data and V_{S30} data for the region following Wald and Allen (2007) and Wills and Clahan (2006), and are referenced sing the labels `ucvm` (default) and `yong`. The following table lists the labels for these predefined maps. These are reserved labels and cannot be used for a user-defined map.

Similarly to the GTL models, UCVM provides a background 1D model to support queries at points outside and below the domains covered by standard CVMs with a bounding box. This option is inactive by default and can be controlled by setting the model flag `USE_1D_BKG = true/false`.

4. Utilities

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