SCEC WORKSHOP REPORT

The Next Leap Forward for SCEC Community Velocity Models

Conveners: Cliff Thurber and Christine Goulet
Date: October 2, 2018
Location: Kellogg West Conference Center, Pomona, California
SCEC Award: 18118
Website: https://www.scec.org/workshops/2018/cvm

This workshop brought together a group of 19 people plus three remote participants to discuss (1) the historical development and status of the SCEC Community Velocity Models (CVMs) and the Unified CVM (UCVM) framework that provides access to these models and (2) potential avenues for continued development and assessment of the SCEC CVMs. The workshop agenda and participant list are appended at the end of this report.

Session 1: Overview and CVM/UCVM status

The workshop began with brief introductions by SCEC Director J. Vidale and workshop convener C. Thurber on the need for and importance of CVMs and the key goals for the workshop to lead to a revival and coordination of efforts to improve the CVMs. One of the most importance uses of CVMs is for ground motion simulations, for example with Cybershake, in the estimation of earthquake hazards. Basins and small-scale heterogeneity, and in particular the very near surface, are critical parts of CVMs that need more accurate representation, especially as simulations are steadily pushed to higher and higher frequencies.

Two SCEC CVMs have been developed for southern California, using different approaches: CVM-H and CVM-S. Both of these models have evolved over time. The development history and current status of the two models were presented and the software framework for extracting information from these and other models (UCVM) was described.

A. Plesch described the top-to-bottom construction of CVM-H, currently at version 15.1.0. Some of its key characteristics are the incorporation of borehole velocity log information and seismic reflection constraints on P-wave seismic velocities (Vp) and basement depths, as well as potential field data. The deeper velocity structure is constrained by tomographic methods for velocities and by receiver functions for the Moho. S-wave velocity is derived via empirical relationships of Brocher (2005). A recent paper documenting CVM-H in detail is Shaw et al. (2015).

C. Goulet summarized the development and current status of CVM-S, now at version 4.26, with some options available regarding the representation of the near surface structure. The original version 1 rule-based model (Magistrale et al., 1996) was updated by Magistrale et al. (2000) and Kohler et al. (2003), followed by updates to San Bernardino Valley and the Salton Trough region and the incorporation of a new Vp-density empirical relation to create version 4 (CVM-S4). Subsequently, CVM-S4 was updated via a sequence of 26 Full 3D Tomography (F3DT) inversions, producing model CVM-S4.26 (Lee et al., 2014). An additional version (CVM-S4.26-M01) has the option of a geotechnical layer. Versions of CVM-S4 have been used for ground motion simulations for seismic hazard estimation (Graves et al., 2010).

P. Maechling closed this session by describing the capabilities of the UCVM framework and the 3D velocity models that are currently available through it. These models are almost all in very different forms and formats, so the UCVM was designed to allow the user to query any of the models, or some combination of them, to extract physical properties (Vp, Vs, Qp, Qs, density) in a desired region on a specified grid. This is particularly valuable for assembling models for comparative studies of simulations based on different models. The paper by Small et al. (2017) documents the UCVM and its capabilities (see also https://www.scec.org/research/ucvm).

Session 2: SCEC CVMs - moving forward

This session consisted of "lightning talks" by meeting participants on four topics: new data sources, new tomography methods, model validation and uncertainty, and computational aspects. The presentations were as follows:

Lise Retailleau, Contributions from ambient field correlations (development of surface-wave Green's functions and ultimately tomographic models from ambient noise)

Arben Pitarka, Use LargeN array data to constrain statistical properties of small scale shallow structure variability in basins (use of data from dense nodal arrays and multiple source types, such as active sources, earthquakes, and noise, for tomographic imaging)

Kim Olsen, Constraints on statistics of small-scale heterogeneities from sonic borehole logs (assess spatial correlation lengths of heterogeneity from borehole data) and high-frequency ground motion simulations (at higher frequencies, can clearly see effects of heterogeneity and frequency dependent Q on spectral accelerations)

Rob Clayton, Local/regional studies (detailed structure from cross-correlations and auto-correlations of dense nodal array data)

Cliff Thurber, Distributed Acoustic Sensing (i.e., DAS; capability of DAS arrays for recording earthquake data)

Avinash Nayak, Towards joint Inversion of Rayleigh wave group velocities and body-wave travel times in CCSP Study Area (development of surface-wave Greens functions and ultimately tomographic models from ambient noise and earthquake body-wave data)

Alan Juarez, Data functionals for Full 3D Tomography (development of an end-to-end workflow for F3DT)

Chengping Chai, Smoothed receiver functions for joint inversion (strategy for joint surface-wave receiver-function inversion by smoothing structure from receiver functions)

Carl Tape, Model validation (discussion regarding issues of frequency and computational limitations, the need for more data, independent constraints, and benchmarked datasets)

Egill Hauksson, Comparing the CVM-S4.26 with the standardized Brocher seismic velocity and composition relation (comparison reveals issues and discrepancies, such as apparent constancy of Vp/Vs, systematic deviations of Vp versus density from predicted, and Vp/Vs that is too low near the surface)

Rob Graves, Deterministic CVM features required for high-frequency (> 1 Hz) simulations (reported that 2 Hz simulations show the effect of greater heterogeneity of CVM-H versus CVM-S, and discussed important aspects such as fault damage zones, sediment velocity variability, and the top kilometer in high-frequency simulations)

Chengping Chai, Interactive visualization of seismic data and models (presented a web tool that allows for vertical and depth slices and depths profiles in a simple user interface)

David Okaya, Stretch and azimuthal angles within Transverse Mercator (UTM) during extraction of CVM gridded volumes (described subtle problems related to representing 3D models that cross boundaries of UTM zones and presented solutions)

Session 3: Focused discussions

The next session was a wide-ranging plenary discussion of four key questions directly related to the lightning talk topics:

1. What are the most promising new data sources?
2. What is needed in terms of tomography method development?
3. How can we best accomplish model validation and assess model uncertainty?
4. What computational aspects will present the biggest challenges, and how can they be overcome?

There was an extensive discussion of both dense nodal arrays and distributed acoustic sensing (DAS) for obtaining data for high-resolution constraints on structure, both near-surface and basin structures and fault zone structure. Different types of nodal experiments were suggested. There was some discussion of the merits of single-component versus 3-component data. Marine nodal sensors are also now available. There is a growing number of publications on the use of DAS for earthquake and structure studies. Further documentation of the usefulness of existing fiber-optic cables (e.g., telecommunications) for DAS is an important task. Other potential sources of data include PG&E "SmartMeters," the Community Seismic Network (both lower quality but dense), and strong motion network data, and in particular new Earthquake Early Warning instruments. An effort to increase access to and use of strong motion data is warranted. Data from major field projects such as the Salton Sea Seismic Imaging Project should be utilized to improve the CVMs.

Ambient noise Greens functions (ANGFs) are another source of structural constraints, especially for upper crustal structure and seismically quiet areas. ANGFs can be included in tomographic inversions or used as validation data. It was suggested that SCEC assemble relevant ANGF results and make them available as a library for the community. Some benchmarking would be valuable, for example comparing results from different groups to validate their quality.

Further discussion of model validation and uncertainty focused on the need for test datasets, acceptable metrics for assessing model accuracy, accessible software and computational resources for model meshing and waveform forward modeling, and direct comparisons of the structure of the current versions of the two main models, CVM-H and CVM-S, especially outside the basins where it is known that they will be significantly different. It was noted that, for the current models, CVM-H is generally a bit slower than CVM-S. The study by Taborda et al. (2016) was pointed to as an example of the type of work that needs further pursuit. Archiving the data and simulations done by Taborda et al. (2016) and making them available is a high priority task, if they have been preserved. A means for identifying where a particular CVM is or is not accurate is needed, in the process providing the impetus for obtaining new data for

particular areas. In addition, the issue of how to merge a new model for a local area into a SCEC CVM and then compare the original and new models was identified as a critical issue. For example, could the CVM-H basins be embedded into the CVM-S model and tested for possible improvement? It was also noted that uncertainty estimates are desired for velocity values as well as the locations of boundaries. Many of the above aspects fall into the category of computational needs.

Topography emerged as a topic of great significance and challenge. CVM-H explicitly includes topography, but the top surface of CVM-S is flat. This is obviously an issue when these two models are to be compared, or new local models are to be imbedded into these models. Some kind of "stretching" or "squashing" may be required, and it is not clear how to best accomplish that. On the computational side, some waveform modeling and inversion codes can incorporate topography and others cannot, although some codes are being extended to include topography.

A number of other questions and issues arose during the discussion. Should SCEC evolve towards a single CVM or a preferred CVM? How can a useful model of attenuation structure be developed? Can better deterministic constraints on small-scale heterogeneity be obtained, especially for near-surface structure? How can high-resolution information on fault zone structure, in particular damage zones, be incorporated into the CVMs? What types of joint inversions can contribute the most to improving CVMs? Participants were alerted to a relevant workshop planned for the 2019 SSA annual meeting on tools for working with 3D models. The IRIS Earth Model Collaboration (EMC) was also mentioned as a potentially useful resource for archiving and visualizing 3D models.

Session 4: How do we get there - new projects and funding

In the closing session, there was an open and wide-ranging discussion of projects and specific tasks that could be pursued in order to revitalize the development of improved CVMs. Much of the focus was on potential new sources of data and ways to integrate new "local" models into existing CVMs and validate the modified models. The hierarchy of potential sources of funding include SCEC for small projects, the USGS Earthquake Hazards Program for intermediate-scale projects, and NSF for large-scale projects. SCEC has also benefited from support from a variety of other sources (e.g., foundations, industry), and such sources should continue to be pursued.

Potential action items, with those of highest priority listed first:

- Develop end-to-end F3DT tomography code and workflow
- Develop an approach and tools for integrating new models into current models and examining quality of the modified model for validation (through data analyses and 3D visualization of model properties)
- Make detailed comparisons between the current CVM-S and CVM-H models (velocity values, depths to key isosurfaces, power spectra, etc.)
- Develop strategies for dealing with topography in creating, modifying, or comparing models
- Relocate earthquakes in the current CVM-S and CVM-H models for Community Fault Model assessment
- Explore approaches for determining near-surface structure and fine-scale heterogeneity

- Explore strategies for imbedding high-resolution near-surface structure and fault zone models into CVMs
- Develop and share SCEC ANGF data (from SCEC's Stanford team and other sources)
- Pursue the potential of joint geophysical inversions to improve CVMs
- Request suite of real and synthetic data used and developed by Taborda et al.
- Establish libraries of (1) data used to develop SCEC CVMs and (2) real and synthetic Green's functions
- Incorporate Salton Sea experiment data into next round of model updates
- Work to increase availability of continuous strong motion data
- Develop approaches for assessing model uncertainty
- Submit the current CVM-S and CVM-H models to the IRIS EMC

Although not discussed at the workshop, a logical next step is the formation of a SCEC Technical Activity Group (TAG) and a TAG workshop associated with the 2019 SCEC Annual Meeting to help stimulate renewed activity on CVMs by the broader SCEC community. C. Thurber plans to submit a TAG proposal, and will solicit information and assistance from others.

References

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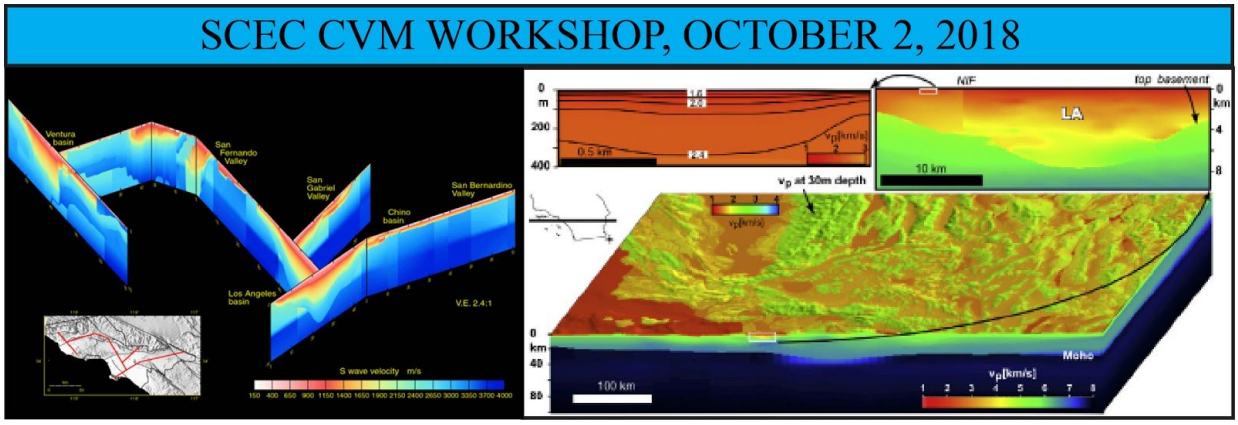
The Next Leap Forward for SCEC Community Velocity Models



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SUMMARY: The SCEC Community Velocity Models (CVMs) are among the most mature of the SCEC community models, but there is no question they can still be meaningfully refined and improved, and uncertainties better quantified. A 1-day workshop will be held on October 2, 2018 to formulate a plan for continued development and validation of the SCEC Community Velocity Models (CVMs). Key elements of the plan should include:

- Collecting new and/or tapping existing seismic and other datasets that can be used to improve and/or assess the CVMs,
- Developing computational workflows for producing CVM updates and estimated model uncertainties,
- Defining procedures for validating and potentially accepting updated CVMs,
- Identifying sources of funding that can help support CVM development.

Expected outcomes of this workshop will be (1) a set of specific action items for further CVM development and (2) proposal ideas for individuals or coordinated groups that respond to the 2019 SCEC Science Plan.

To promote discussion and due to logistics, the workshop is limited to 25 participants. Limited funds are available for travel support from outside the Los Angeles area, with priority for invited presenters, students, early career scientists. We anticipate participation by scientists with expertise in (1) body-wave, surface wave, and full waveform tomography, (2) model validation, (3) seismic and other data sources, (4) 3D model integration and representation, and (5) high-performance computing. If you (or someone you know) can make significant contributions to this effort, please contact the conveners.

TUESDAY, OCTOBER 2, 2018

09:00 - 09:30	Workshop Check-In	
09:30 - 10:55	**Session 1: Overview and CVM/UCVM status** Moderator: Cliff Thurber and Reporter: Alan Juarez	
09:30	Welcome and Overview of Workshop Objectives (PDF, 985KB)	Cliff Thurber / John Vidale
09:40 - 10:00	Status of SCEC CVM-H (PDF, 2.6MB)	Andreas Plesch
10:00 - 10:20	Status Status of SCEC CVM-S (PDF, 2.1MB)	Christine Goulet
10:20 - 10:40	The SCEC UCVM framework (PDF, 2MB)	Phil Maechling
10:40 - 10:55	Break	
10:55 - 12:30	**Session 2: SCEC CVMs - moving forward** Moderator: Carl Tape and Reporter: Ashton Flinders	
10:55 - 11:00	Lightning talks procedure	Cliff Thurber
	Lightning talks: New data sources	
11:00	Contributions from ambient field correlations	Lise Retailleau
11:05	Use LargeN array data to constrain statistical properties of small scale shallow structure variability in basins (PDF, 2.4MB)	Arben Pitarka
11:10	Constraints on statistics of small-scale heterogeneities from sonic borehole logs (PDF, 1.7MB)	Kim Olsen
11:15	Local/regional studies (PDF, 5.3MB)	Rob Clayton
11:20	Distributed Acoustic Sensing (PDF, 975KB)	Cliff Thurber
	Transitional talk: new data/tomography	
11:25	Towards joint Inversion of Rayleigh wave group velocities and body-wave travel times in CCSP Study Area	Avinash Nayak
	Lightning talks: Tomography methods	
11:30	Data functionals for Full 3D Tomography	Alan Juarez
11:35	Smoothed receiver functions for joint inversion	Chengping Chai
11:40	New twists on joint inversions (time permitting)	Cliff Thurber
	Lightning talks: Validation and uncertainty	
11:45	Model validation (PDF, 1.9MB)	Carl Tape
11:50	Comparing the CVM-S4.26 with the standardized	Egill Hauksson
11:55	Constraints on statistics of small-scale heterogeneities from high-frequency ground motion simulations (PDF, 1.2MB)	Kim Olsen
	Transitional talk: validation/computation	
12:00	Deterministic CVM features are required for high-frequency (> 1 Hz simulations) (PDF, 522KB)	Rob Graves
	Lightning talks: Computational aspects	
12:05	Interactive visualization of seismic data and models	Chengping Chai

12:10	Stretch and azimuthal angles within Transverse Mercator (UTM) during extraction of CVM gridded volumes (PDF, 1MB)	David Okaya
12:30 - 13:30	Lunch	
13:30 - 15:30	**Session 3: Focused discussions** Moderator: Cliff Thurber	
13:30 - 13:40	Group discussion goals	Cliff Thurber
13:40 - 14:10	What are the most promising new data sources?	Reporter: Avinash Nayak
14:10 - 14:40	What is needed in terms of tomography method development?	Reporter: Carl Tape
14:40 - 15:10	How can we best accomplish model validation and assess model uncertainty?	Reporter: Cliff Thurber
15:10 - 15:40	What computational aspects will present the biggest challenges, and how can they be overcome?	Reporter: Kim Olsen
15:40 - 16:00	Break	
16:00 - 17:00	**Session 4: How do we get there — new projects and funding** Moderator: Christine Goulet and Reporter: Cliff Thurber	
16:00 - 16:05	Goals for wrap-up discussions	Christine Goulet
16:05 - 16:50	Open discussion on new projects, funding possibilities	*All*
16:50 - 17:00	Closing Discussion: Recommendations and Action Items	Cliff Thurber
17:00	Workshop Adjourns	

PARTICIPANTS

*Brad Aagaard (USGS)
*Tom Brocher (USGS)
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**Remote Participants*