

**User Guide for the Southern California Earthquake Center
Community Velocity Model: SCEC CVM-H 11.9.0**

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Overview

The SCEC CVM-H is a 3D model of the elastic structure of southern California. It contains volumetric representations of compressional wave velocity (V_p), shear wave velocity (V_s), and density (ρ). It also contains three primary surfaces: the topological/bathymetric surface, the basement surface, and the Moho surface. The model is constructed from numerous datasets (Süss and Shaw, 2003) and has been used within parallel-computing based wavefield simulations of earthquakes within southern California (e.g., Komatitsch et al., 2004). See Section 6 for details.

Requirements

The system requirements are as follows:

1. UNIX operating system (tested on Linux and SunOs, limited support on Solaris and MacOS)
2. tar for opening the compressed files
3. GNU make (gmake)
4. GNU C compiler (gcc)
5. Optionally GTS (GNU Triangulated Surface Library) for cvmdist <http://gts.sourceforge.net>
6. Optionally GMT (Generic Mapping Tools) to generate plots from vx_slice <http://www.soest.hawaii.edu/gmt/>

Installation

The quick start steps for installing the distribution are:

1. Download package, check md5 sums, and untar distribution ('tar zxvf cvmh-11.9.0.tar.gz')
2. Configure software for your platform ('./configure')
3. Build software with 'make'
4. Check build with 'make check', verifying that all tests pass
5. Install software into target directory with 'make install'

These steps are described in greater detail within the following sections.

Download

Start at SCEC website: <http://scec.usc.edu/scecpedia/CVM-H>. Navigate to the Downloads section of the [CVM-H](#) web page. Click the download link to download the latest source code distribution file. This is typically posted as a tar and gzipped file (tgz format). The source code distribution file is large (500 MB), so the download may take awhile. Click the download link to the latest md5sum file. This file can be used to confirm you have downloaded an undamaged source code distribution file.

Checksum Test

After you've downloaded the two files to your local system, the next step is to compare the checksum of your downloaded file with our pre-computed md5. You should next verify that the *md5sum* command is in your path:

```
$ which md5sum
```

You should get something like `/usr/bin/md5sum`. If you see the message 'no md5sum in...', contact your Linux system administrator and ask to have md5sum added to your path, or add the md5sum to your path yourself by editing your login shell script.

Once you can run the *md5sum* command, you should put the two files you downloaded together in the same directory. The two files will be named something like `cvmh_11.9.0.tar.gz` and `cvmh_11.9.0.tar.gz.md5`. Run the following command to perform the md5 comparison:

```
$ md5sum -c cvmh_11.9.0.tar.gz.md5
```

You should see the message:

```
cvmh_11.9.0.tar.gz: OK
```

If you get "FAILED" instead, re-download the tgz files and try again. When it passes, that means the files were downloaded without error.

Basic Install

Once the file has passed the checksum test, untar into a `./cvmh` subdirectory with this command:

```
$ tar zxvf cvmh_11.9.0.tar.gz
```

Once unpacked, you should see these files:

```
AUTHORS -- Author list
aux-config -- Autoconf config directory
build.xml -- ANT build and compilation script
ChangeLog -- Revision history
configure -- Configure utility
configure.ac -- Autconf config
COPYING -- License and disclaimer
doc -- Documentation directory including user guide
gctpc -- GCTPC projection library
INSTALL -- Installation instructions
m4 -- Autoconf macros
Makefile.am -- Automake makefile template
model -- Model directory containing voxet files
NEWS -- News file
README -- README documentation
scripts -- Directory containing helper scripts
src -- Source directory
test -- Directory containing unit and acceptance tests
```

The package is configured and built by executing the following commands:

```
$ cd ./cvmh-11.9.0
$ ./configure --prefix=${CVMH_INSTALL_DIR}
$ make
```

where:

```
${CVMH_INSTALL_DIR} : target directory where you want the CVM-H package installed
```

The distribution should build in one minute or less. The build can be checked with the following command:

```
$ make check
```

A series of unit and acceptance tests will be executed. They should all pass. The package is installed in the prefix target directory that you specified with `./configure` using the following command:

```
$ make install
```

At this point, you can use CVM-H normally.

Advanced Install

CVM-H may be linked with the optional GTS package which allows the binary executable `cvmdst` to be built. The program `cvmdst` calculates the distance to and the location of the closest points on the topographic/bathymetric, top of the basement, and Moho surfaces which are provided with CVM-H. The input file has the same format as the input file to `vx`, the query code to CVM-H.

The following configure command shows how CVM-H with the optional `cvmdst` may be built:

```
$ cd cvmh-11.9.0
$ ./configure --prefix=${CVMH_INSTALL_DIR} --with-gts --with-gts-lib-path="${GTS_LIB_DIR}" --with-gts-inc
$ make; make check; make install
```

where `${CVMH_INSTALL_DIR}` is the CVM-H installation directory of choice, and `${GTS_LIB_DIR}` and `${GTS_INCL_DIR}` are the paths to the GTS libraries and headers, respectively.

Unit Tests

A set of unit tests may be executed to ensure that the CVM-H software has been compiled and installed correctly. These are organized into three test suites: vx Test Suite, vx_lite Test Suite, and C API Test Suite. Unit test execution time is approximately 1-2 minutes total. These tests are automatically executed as part of a 'make check' but they may also be run separately as described here.

- vx Test Suite: Failure of any of these tests could indicate a problem with either the vx utility, the underlying model, or the reference data set used for comparison.
 - ◆ Extract 8 test points Test

- vx_lite Test Suite: Failure of any of these tests could indicate a problem with either the vx_lite utility, the underlying model, or the reference data set used for comparison.
 - ◆ Extract 8 test points w/o SCEC 1D (in elevation mode) Test
 - ◆ Extract 8 test points w/o SCEC 1D (in depth mode) Test
 - ◆ Extract 8 test points w/ SCEC 1D (in elevation mode) Test

- C API Test Suite: Failure of any of the following tests could indicate a problem with either the C API source, the underlying model, or the reference data set used for comparison.
 - ◆ Initialization of entry structure Test
 - ◆ Initialization of voxel structure Test
 - ◆ Get surface value at 8 test points Test
 - ◆ Get material properties at 8 test points w/o SCEC 1D Test
 - ◆ Get material properties at 8 test points w/ SCEC 1D Test
 - ◆ Register background model Test

All of the unit tests can be executed manually with the following commands, starting in the main CVM-H distribution directory:

```
$ cd ./test
$ ./unittest
```

The tests print results to the screen as they run, and they should complete within 5 minutes. All tests should pass. If any tests do not pass, your operating system or compiler may not be supported. You can report problems to the help email software (at) seec.org and we can provide full information on supported operating system and compiler versions.

Acceptance Tests

A set of acceptance tests may be executed to check the end-to-end functionality of vx and vx_lite. These tests are organized into a single test suite. Acceptance test execution time is approximately 2-5 minutes total depending on system performance. These tests are automatically executed as part of a 'make check' but they may also be run separately as described here.

- Accept Test Suite: Failure of any of these tests could indicate a problem with either the vx/vx_lite utility, the underlying model, or the reference data set used for comparison.
 - ◆ Extract large grid with vx Test
 - ◆ Extract large grid with vx_lite in emulation mode Test
 - ◆ Extract large grid with vx_lite in depth mode Test
 - ◆ Extract large grid with vx_lite in elevation offset mode Test

All of the acceptance tests can be executed manually with the following commands, starting in the main CVM-H distribution directory:

```
$ cd ./test
$ ./accepttest
```

The tests print results to the screen as they run, and they should complete within 5 minutes. All tests should pass. If any tests do not pass, your operating system or compiler may not be supported. You can report problems to the help email software (at) scec.org, and we can provide full details on supported operating system and compiler versions.

Model Description

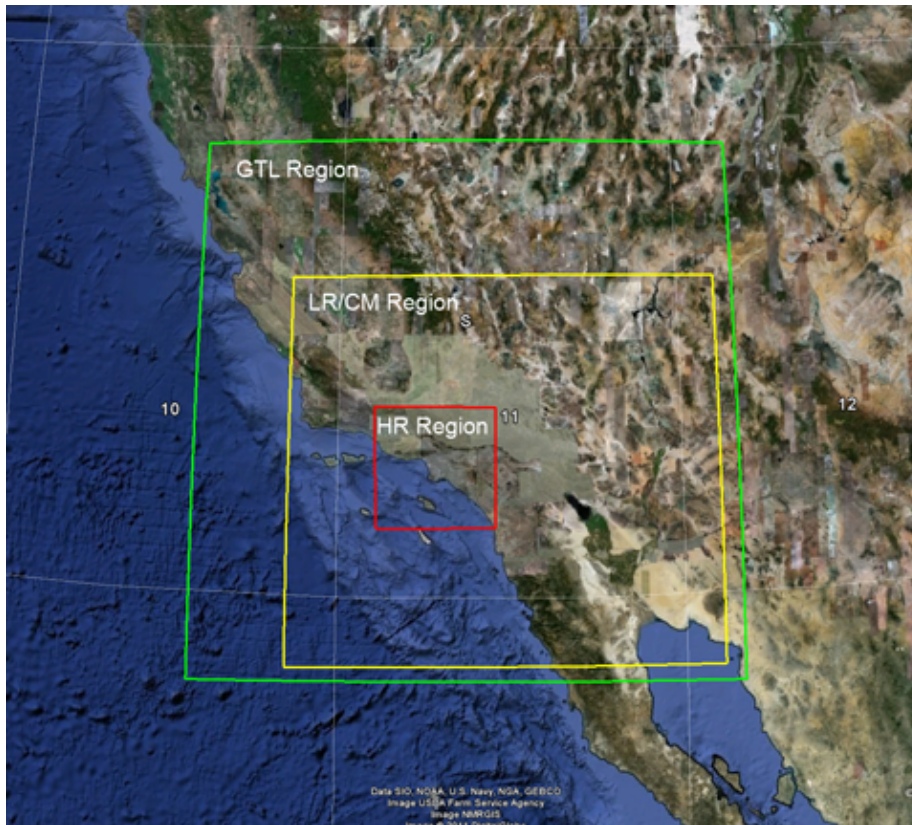
This program originated as a code designed for SCEC-IT to demonstrate the capability of a final interface for the HUSCV-model as described by Süs and Shaw (2003). The code is now available to the community as a simple tool to extract data from the HUSCV-model. In this new version also the High Resolution velocity volume is supported by the code. The Harvard University Southern California Velocity Model (HUSCV 1.0) describes the seismic P-wave velocity structure in the Los Angeles basin and surrounding areas. The model is defined by gridded volumes with higher and lower resolutions, as well as two surfaces used to define the volume of sediments (the top pre-Cretaceous basement and topography/bathymetry). A water-layer with a VP velocity of 1480 m/s is included. No Vs is defined for water, and density is 1000 kg/m³.

The model was designed in a UTM Zone-11 projection with the following coordinates for each model:

Table 1: Model Coordinates

	LR	CM	HR	GTL
Coordinates	Origin (SW) : 131000 3431000 (120d51m43.301sW 30d57m23.387sN) NE-Corner : 828000 4058000 (113d19m58.583sW 36d36m46.622sN)	Same as LR	Origin (NW) : 371053.25 3774000 (-119.322991 / 33.013591) NE-Corner : 417052.25 3774000 (-117.257011 / 33.034954) SW-Corner : 371053.25 3725250 (-119.371155 / 34.770882)	Origin (SW) : -31000.0 3410000.0 NE-Corner : 849000.0 4274000.0 Depth : 0-350m
Resolution	1000m x 1000m x 100m 670 x 400 x 200 grid cells	10000m x 10000m x 1000m 71 x 64 x 186 grid cells	250m x 250m x 100m 185 x 196 x 100 grid cells	250m x 250m

The following diagram illustrates the regions spanned by each model:



The velocity volumes are stored in the GoCAD voxet format.

The program accepts geographic coordinates and UTM zone 11 (NAD27) coordinates. Coordinate transformation is performed by GCTPC2.0, a free projection library by the USGS. Sources for the library are included.

Vs is calculated from Vp using the "mudline" relation and "Brocher's regression line" (Brocher , 2005):

$$V_s = (V_p - 1360) / 1.16 .$$

For $V_p < 1500$ m/s, Vs is fixed at 121 m/s which corresponds to $V_p = 1500$ m/s.

CVM-H contains a geotechnical layer (GTL) that describes the velocity structure in the shallow subsurface, where low shear wave speeds, in particular, can have a significant impact on strong ground motions. The GTL velocity values (both Vp and Vs) and density are derived from the Vs30 map by the algorithm described in Ely (2010).

The models are extrapolated from their data limits to the model boundaries.

The underlying tomographic model is taken from Tape, C., Q. Liu, A. Maggi, and J. Tromp, (2009).

Mantle data were provided by Toshiro Tanimoto (personal communication) and are derived from waveform matching of teleseismic surface waves (Prindle and Tanimoto, 2006).

We adopt the Nafe-Drake scaling relationship to compute density from Vp (Ludwig et al., 1970; Brocher , 2005):

$$\rho = 1.6612 * V_p - 0.4721 * (V_p)^2 + 0.0671 * (V_p)^3 - 0.0043 * (V_p)^4 + 0.000106 * (V_p)^5,$$

where ρ is in g/cm³ and V_p is in km/s.

No specific shear quality factor is predicted by the model. A Q_u of 90 has been used in the sediments by Komatitsch et al. (2004).

The code provides output consistent with directly querying the voxel in the Gocad software, and gives the position of the cell centers from which the data are provided. In addition, elevation of the topographic, basement and Moho surfaces are provided, at the closest grid point to the input coordinates. Flags indicate which voxel was used to extract data, and what the provenance of the data points within a given voxel is. 1D background, mantle, tomography, basins, and air are distinguished as possible data sources.

Geotechnical Layer

A near-surface geotechnical layer (GTL) exists in the `vx_lite` utility and C API, derived from a V_s30 map of southern California as described in (Ely, et al. (2010)). The V_s30 map was constructed from two datasets: an interim high-resolution rasterized V_s30 map for California described in (Wills and Clahan (2006)), and a V_s30 map for points outside of California described in (Wald, et al. 2007). The two datasets were combined with no interpolation.

The GTL extends from the free surface down to a transition depth of at least 350m. V_p , V_s , and density (ρ) at the free surface are derived from the V_s30 values with the following relations:

```

Vs = 1/2 * Vs30

Vp = 0.9409 + Vs30 * (2.0947 - Vs30 * (0.8206 - Vs30 * (0.2683 - Vs30 * 0.0251)))

rho = Vs30 * (1.6612 - Vs30 * (0.4721 - Vs30 * (0.0671 - Vs30 * (0.0043 - Vs30 * 0.000106))))
if (rho < 1000.0) {
    rho = 1000.0;
}

```

V_p and ρ are taken from Brocher (2005).

Between depth 0m and the transition depth (≥ 350 m), V_p , V_s , and ρ are interpolated between the above material properties and the V_p , V_s , and ρ as reported by the CVM-H LR/CM/HR/1D model at the transition depth. The non-linear interpolation relation is described in Ely et al. (2010). The transition depth is nominally 350m but may be greater to accommodate points in which $\text{topo} - \text{mtop} > 350$ m. At these points, the transition depth is increased to $\text{topo} - \text{mtop}$ so that data is guaranteed to be available.

The GTL may be turned off in source code. Set the `ENABLE_GTL` flag in `./src/vx_sub.c` to `False`, and recompile, to disable the V_s30 -derived GTL with `vx_lite` and the C API. The `vx` utility does not support a GTL at this time.

SCEC 1D Background Model

The CVM-H coverage region may be extended by an optional Hadley-Kanamori 1D background model. The following table describes the depth- V_p relationship:

Table 2: Depth-Vp relation for optional SCEC 1D background model

Depth (km)	Vp (km/s)
0-1	5.0
5	5.5
6	6.3
10	6.3
15.5	6.4
16.5	6.7
22.0	6.75
31.0	6.8
33.0	7.8

The velocity Vp at the desired depth is linearly interpolated between the two velocities of the surrounding depth brackets. The final Vp, Vs, and rho are then derived from the interpolated Vp with the following relations:

$$V_p = V_p * 1000.0$$

$$\rho = 1865.0 + 0.1579 * V_p$$

$$V_s = V_p * \sqrt{(0.5 - \nu) / (1.0 - \nu)}$$

where nu is from the relation:

```

if (rho < 2060.0) {
  nu = 0.40
} else if (rho > 2500.0) {
  nu = 0.25
} else {
  nu = 0.40 - ((rho - 2060.0) * 0.15 / 440.0)
}

```

The velocities Vp and Vs are measured in (m/s), and rho is measured in (kg/m³).

The surface elevation in the SCEC 1D background is considered to be 0.0 m.

Application of this 1D background model becomes complicated when CVM-H is queried by elevation. In this query mode, valid data responses may include material properties for air and water and these cannot be interpolated with a soil 1D background. In these regions, air/water material properties are simply extended outward from the core LR/CM models without modification.

Smoothing Between Models

Smoothing (interpolation) is performed programmatically at many interfaces between models in CVM-H. These are summarized in the table below, along with the applicable interpolation distance:

Table 3: Smoothing Between Models

Point Falls Within	Interp. w/ LR	Interp. w/ CM	Interp. w/ HR	Interp. w/ GTL	Interp. w/ 1D
GTL (and HR/LR/CM), Case 1	If within LR model, use voxel at depth 350 m	If within CM model, use voxel at depth 350 m	If within HR model, use voxel at depth 350 m	None	None
GTL (and 1D), Case 2	If within 50km of LR, use Case 1 at closest LR point with same dep/elev	If within 50km of CM, use Case 1 at closest CM point with same dep/elev	None	None	1D properties at depth 350 m (performed before LR/CM interp)
1D only, Case 3	If within 50km of LR, and depth > 350 m, and LR has voxels at same depth/elev, use closest voxel at same elev/depth	If within 50km of CM, and depth > 350 m, and CM has voxels at same depth/elev, use closest voxel at same elev/depth	None	If within 50km of GTL, and depth <=350m, use Case 2 at closest GTL point	None

There are several details to keep in mind:

- All smoothing is linear interpolation between the material properties at the point of interest, weighted against the material properties at the closest voxel/point in the other model by the inverse of the distance between the two points.
- Smoothing between the GTL and the LR/CM/HR/1D models along the z axis has been described in the geotechnical layer description.
- Smoothing is performed with respect to the current query mode. When querying by elevation, smoothing is performed along points of equal elevation. Similarly, querying by depth causes smoothing to be performed along points of equal depth.
- When interpolating the GTL with LR/CM and the 1D with LR/CM, either LR or CM is chosen as the interpolation target depending upon which model contains a voxel at the z value of interest. For example, at shallow depths, the GTL will typically be interpolated with LR, and at greater depths (> 20 km) the GTL will be interpolated with CM.
- Since CVM-H has the concept of a "no data" value for Vp, Vs, and rho at any particular point, there may be regions within the model where no smoothing can be performed due to this missing data. This missing data may lead to discontinuities or other artifacts in the smoothed areas.
- As mentioned previously, smoothing between air/water and the SCEC 1D when querying CVM-H by elevation is not meaningful. In this situation, air and water properties are extended outward from the LR/CM models without any modification.

Topography Flattening

CVM-H offers three Z axis modes for querying the underlying model: elevation, elevation offset (from the free surface), and depth. In depth mode, z values may be specified as a positive (or zero) depth value in meters. Querying by depth has the effect of stripping away the topography (as well as air and water) embedded within CVM-H. It is useful for extracting 3D meshes for sub-surface anelastic wave propagation simulations.

Note: The vx utility does not support topography flattening. These capabilities are only available in the vx_lite utility and the C API.

CVM-H must determine the elevation of the free surface at the x/y (lon/lat) point of interest when depth query mode is used. This is required in order to convert depth to elevation, since the model is internally represented as a collection of 3D volumes delineated by elevation along the Z axis. The method by which this free surface elevation is determined is different if the GTL is enabled or disabled.

By default, the Vs30-derived GTL is enabled. In this case, the free surface is taken to be the value reported by the topographic map at that point (the 'topo' value). When the GTL is disabled, the free surface is first determined by this algorithm:

```
free_surf = min( topo(x,y) , mtop(x,y) )
```

where:

```
topo: elevation as reported by topo model at x,y  
mtop: uppermost elevation of data available at x,y
```

However, there are regions in the model with empty voxels at mtop, so that when queried at (x ,y, free_surf), the "no data" placeholder will still be returned. This is undesirable for many applications. So the surface elevation is adjusted further by the following recursive algorithm:

```
data = query( x , y , free_surf )  
for i in 1..MAX_STEPS {  
  if ( data == NO_DATA ) {  
    switch (data.model):  
      case LR:  
        free_surf = free_surf - 100m  
      case HR:  
        free_surf = free_surf - 100m  
      case CM:  
        free_surf = free_surf - 1000m  
        data = query( x , y , free_surf )  
  } else {  
    break for loop  
  }  
}
```

The free surface is stepped down, voxel by voxel, until a data voxel is found. The point at which data is available is then assigned to be the free surface elevation at point (x,y). With the free surface known, the user depth can be converted to elevation and the model can be queried for material properties.

See the vx_lite Utility and C API sections later in this guide for instructions on how to enable this optional query mode.

Extracting Values from CVM-H

Two methods are provided for extracting material properties from CVM-H: command-line tools, and a C API. These are described in the sections below. The following table summarizes the model features supported by each interface:

Table 4: Model feature support by interface

Interface	GTL	Query by Elevation	Query by Elevation Offset	Query by Depth	SCEC 1D	Smoothing
vx	No	Yes	No	No	No	No
vx_lite	Optional (default on)	Yes	Yes	Yes	Yes	Yes
C API	Optional (default on)	Yes	Yes	Yes	Yes	Yes

Extracting Values on the Command Line

Two utilities are provided for querying the community velocity model, vx and vx_lite. The vx utility is the original interface to Harvard's model. The vx_lite utility is an updated interface that supports additional functionality.

vx Utility

The vx code provides output consistent with directly querying the voxel in the Gocad software, and gives the position of the cell centers from which the data are provided. Also, elevation of the topographic, basement and Moho surfaces are provided, at the closest grid point to the input coordinates. Additional details are listed in Tables 5 and 6. For usage details, type vx -h. From the `/${CVMH_INSTALL_DIR}/model` directory, try feeding the test points into the program. The test file (`./test/test_data/test.dat` from the s/w distribution), contains eight input points:

```
-125 35 -7777
-118.56 32.55 -2450
360061 3750229 -1400
-118.52 34.12 -1400
-116.40 32.34 -1000
376592 3773379 -1770
376592 3773379 -17700
408669 3766189 -3000
```

Note that the input can be either (lon, lat, elevation) or (UTMx-11, UTM_y-11, elevation). Execute vx with the test file using this command:

```
$ cd ${CVMH_INSTALL_DIR}/model
$ ../bin/vx < ${CVMH_UNTAR_DIR}/test/test_data/test.dat
```

where:

```
${CVMH_INSTALL_DIR}: CVM-H installation directory (defaults to /usr/local, or set with --prefix flag)
${CVMH_UNTAR_DIR}: Location where you unpacked the CVM-H distribution.
```

The output has 8 rows and 18 columns (Table 5) and should look like this (here the columns are truncated):

```

      X           Y           Z     ...   tag      vp      vs      rho
-125.000000    35.000000   -7777.00 ... -99999.00 -99999.00 -99999.00 -99999.00
-118.560000    32.550000   -2450.00 ... 2.00    5575.15  3132.10  2631.81
360061.000000  3750229.000000   -1400.00 ... 2.00    4554.52  2313.56  2469.78
-118.520000    34.120000   -1400.00 ... 2.00    5066.61  2916.30  2545.10
-116.400000    32.340000   -1000.00 ... 2.00    5372.79  3024.30  2595.55
376592.000000  3773379.000000   -1770.00 ... 3.00    4181.37  2432.22  2418.45
376592.000000  3773379.000000  -17700.00 ... 2.00    6533.31  3776.40  2841.47
408669.000000  3766189.000000   -3000.00 ... 2.00    4997.06  2889.03  2534.30
```

The values for the eighth row are listed below, in transpose form, and with some annotations:

```

408669.000000
3766189.000000
-3000.00
408669.00
3766189.00
408625.00
3766125.00
93.89 --> elevation of topo/bath surface
50.00 --> elevation of top of model (below which there is data)
-2820.45 --> elevation of basement surface
-29799.86 --> elevation of Moho surface
hr
408552.25
3766250.00
-3000.00
2.00 --> value from tomography model
4997.06 --> Vp
2889.03 --> Vs
2534.30 --> density
```

Note that there is a discrepancy between the top of the model (50.00 m) and the topography (93.89 m). The "real" top of the model is defined by mtop, and there may be minor discrepancies between mtop and topo.

Table 5: Columns of the output produced by vx. Queries which fall outside of the model area return -99999, the no-data value, for all fields.

Column Index	Variable	Description
1	X	Input X (longitude or UTM coordinate)
2	Y	input Y (latitude or UTM coordinate)
3	Z	input Z (elevation, meters above sea level, i.e., positive up)
4	utmX	UTM coordinate (zone 11), easting
5	utmY	UTM coordinate (zone 11), northing
6	elevX	X coordinate of center of the cell which provided data value for elevations
7	elevY	Y coordinate of center of the cell which provided data value for elevations

8	topo	topographic/bathymetric elevation in m
9	mtop	top of model in m, below this depth there are data
10	base	basement elevation in m (generally negative)
11	moho	Moho elevation in m (always negative)
12	hr/lr/cm	flag to indicate whether high- (hr), low-resolution (lr) or lower crust/mantle voxel was used; (nr) if no data available
13	cellX	X coordinate of center of cell which provided velocity data value
14	cellY	Y coordinate of center of cell which provided velocity data value
15	cellZ	Z coordinate of center of cell which provided velocity data value
16	tag	provenance of data point (see Table 6)
17	vp	compressional wave velocity in m/s
18	vs	shear wave velocity in m/s
19	rho	density in kg/m ³

Table 6: Provenance tags

Index	Description
1	mantle data
2	tomography
3	basins
4	air
5	basin GTL
6	extrapolated tomography
7	water
8	basement GTL
9	basin-background transition in outer area (no basin model)
10	air in outer area
11	filled-in mantle
12	filled-in crust
13	extrapolated mantle
14	background model
15	Vs30 derived GTL

vx_lite Utility

The vx_lite utility is a new SCEC-developed interface which supports a number of enhancements, including query by depth, extension of the coverage region with a SCEC 1D model, and replacement of the original GTL with a Vs30-derived GTL. The command line format for vx_lite is as follows:

vx_lite - (c) Harvard University, SCEC
Extract velocities from a simple GOCAD voxel. Accepts
geographic coordinates and UTM Zone 11, NAD27 coordinates in
X Y Z columns. Z is expressed as elevation offset by default.

```
usage: vx_lite [-g] [-s] [-m dir] [-z dep/elev/off] < file.in
```

Flags:

```
-g disable GTL (default is on).  
-s directs use of SCEC 1D background and topo.  
-m directory containing model files (default is '.').  
-z directs use of dep/elev/off for Z column (default is offset).
```

Output format is:

```
X Y Z utmX utmY elevX elevY topo mtop base moho hr/lr/cm cellX cellY cellZ tg vp vs rho
```

where file.in is a list of 3D points specified as either (lon, lat, z (meters)) or (easting, northing, z (meters)), space delimited. Input coordinates can be specified interactively or redirected to stdin from a file.

Note: Specifying no Z coordinate option instructs vx_lite to interpret the z coordinate as elevation offset from free surface.

The query data is printed to stdout, and this may be redirected to a file.

CVM-H defines a set of sample test points (given in ./test/test_data/test.dat of the s/w distribution):

```
-125 35 -7777  
-118.56 32.55 -2450  
360061 3750229 -1400  
-118.52 34.12 -1400  
-116.40 32.34 -1000  
376592 3773379 -1770  
376592 3773379 -17700  
408669 3766189 -3000
```

These may be submitted to vx_lite with this command:

```
$ cd ${CVMH_INSTALL_DIR}/bin  
$ ./vx_lite -s -z elev -m ../model < ${CVMH_UNTAR_DIR}/test/test_data/test.dat
```

where:

```
${CVMH_INSTALL_DIR}: CVM-H installation directory (defaults to /usr/local, or set with --prefix flag)  
${CVMH_UNTAR_DIR}: Location where you unpacked the CVM-H distribution.
```

The example above selects the model directory to use (../model), selects elevation coordinate mode, and enables the SCEC 1D background model. The material properties at the sample points will be printed to stdout. You can expect to see the following output, annotated here with column headers (the columns are truncated):

X	Y	Z	...	tag	vp	vs	rho
-125.000000	35.000000	-7777.00	...	14.00	6300.00	3637.31	2859.77
-118.560000	32.550000	-2450.00	...	2.00	5575.15	3132.10	2631.81
360061.000000	3750229.000000	-1400.00	...	2.00	4554.52	2313.56	2469.78
-118.520000	34.120000	-1400.00	...	2.00	5066.61	2916.30	2545.10
-116.400000	32.340000	-1000.00	...	2.00	5372.79	3024.30	2595.55
376592.000000	3773379.000000	-1770.00	...	3.00	4181.37	2432.22	2418.45
376592.000000	3773379.000000	-17700.00	...	2.00	6533.31	3776.40	2841.47
408669.000000	3766189.000000	-3000.00	...	2.00	4997.06	2889.03	2534.30

Table 7: Columns of the output produced by vx_lite. Queries which fall outside of the model area return -99999, the no-data value, for all fields.

Column Index	Variable	Description
1	X	Input X (longitude or UTM coordinate)
2	Y	input Y (latitude or UTM coordinate)
3	Z	input Z (elevation, meters above sea level, i.e., positive up)
4	utmX	UTM coordinate (zone 11), easting
5	utmY	UTM coordinate (zone 11), northing
6	elevX	X coordinate of center of the cell which provided data value for elevations
7	elevY	Y coordinate of center of the cell which provided data value for elevations
8	topo	topographic/bathymetric elevation in m
9	mtop	top of model in m, below this depth there are data
10	base	basement elevation in m (generally negative)
11	moho	Moho elevation in m (always negative)
12	hr/lr/cm/gt/bk	flag to indicate whether high- (hr), low-resolution (lr) or lower crust/mantle voxet was used, (gt) for GTL, (bk) for 1D background; (nr) if no data available
13	cellX	X coordinate of center of cell which provided velocity/Vs30 data value
14	cellY	Y coordinate of center of cell which provided velocity/Vs30 data value
15	cellZ/Vs30	Z coordinate of center of cell which provided velocity data value; Vs30 value if value derived from GTL
16	tag	provenance of data point (see Table 6)
17	vp	compressional wave velocity in m/s
18	vs	shear wave velocity in m/s
19	rho	density in kg/m3

Extracting Values in a C Program

SCEC has extended the interface to CVM-H with a C programming interface (C API). The C header file containing the datatype and function definitions is located in `./src/vx_sub.h`. By including this header in your source, and the `libvxapi.a` library at link time, your program can directly query CVM-H.

The following C code example shows how to initialize and query CVM-H programmatically. This example also illustrates the use of the SCEC 1D background and query by depth.

```

/* Source: Example.c */

#include <stdio.h>
#include <stdlib.h>
#include "vx_sub.h"

int main (int argc, char *argv[])
{
    vx_entry_t entry;
    double depth;

    /* Perform setup */
    if (vx_setup(argv[1]) != 0) {
        printf("Failed to init vx\n");
        exit(1);
    }

    /* Register SCEC 1D background model */
    vx_register_scec();

    /* Query by depth */
    vx_setzmode(VX_ZMODE_DEPTH);

    /* Query by lat/lon */
    entry.coor_type = VX_COORD_GEO;

    /* Setup point to query */
    entry.coor[0] = -118.0;
    entry.coor[1] = 34.0;

    /* Work-around for Trac issue #6: Depth value over-written in vx_getcoord() */
    depth = 100.0;
    entry.coor[2] = depth;

    /* Query the point */
    vx_getcoord(&entry);

    /* Print results */
    printf("Lon: %lf, Lat: %lf, Z: %lf, Vp: %lf, Vs: %lf, Rho: %f", entry.coor[0], entry.coord[1], depth, e

    /* Cleanup */
    vx_cleanup();

    return(0);
}

```

Extracting Distances to Surfaces in CVM-H

There is an additional program, `cvmdst`, to compute the the distance to, and the location, of the closest points on the topographic/bathymetric, top of the basement, and Moho surfaces which are provided with CVM-H. The input file has the same format as the input file to `vx`, the query code to CVM-H. To use this capability, you need GTS (GNU Triangulated Surface Library), available from <http://gts.sourceforge.net> (using a Linux-Ubuntu platform, it may be as simple as installing all "gts" packages from the Synaptic Package Manager) and rebuild CVM-H. See the Advanced Install section on how to do this.

Once built, try the program with the same test data as before (note that you must be in the model directory):

```
$ cd ${CVMH_INSTALL_DIR}/model
$ ../bin/cvmdst < ${CVMH_UNTAR_DIR}/test/test_data/test.dat > ofile2.dat
```

where:

```
${CVMH_INSTALL_DIR}: CVM-H installation directory (defaults to /usr/local, or set with --prefix flag)
${CVMH_UNTAR_DIR}: Location where you unpacked the CVM-H distribution.
```

The output file `ofile2.dat` has 17 columns described in the table below. Note that the basement surface is not defined over the entire area of the model.

Table 8: Columns of the output produced by `cvmdst`

Column Index	Variable	Description
1	X	Input X (longitude or UTM coordinate)
2	Y	input Y (latitude or UTM coordinate)
3	Z	input Z (elevation, meters above sea level, i.e., positive up)
4	utmX	UTM coordinate (zone 11), easting
5	utmY	UTM coordinate (zone 11), northing
6	t_x	X coord of location of the closest point on the topographic/bathymetric surface
7	t_y	X coord of location of the closest point on the topographic/bathymetric surface
8	t_z	X coord of location of the closest point on the topographic/bathymetric surface
9	t_dst	distance to the closest point on the topographic/bathymetric surface
10	b_x	X coord of location of the closest point on the basement surface
11	b_y	Y coord of location of the closest point on the basement surface
12	b_z	Z coord of location of the closest point on the basement surface
13	b_dst	distance to the closest point on the basement surface
14	m_x	X coord of location of the closest point on the Moho surface
15	m_y	Y coord of location of the closest point on the Moho surface
16	m_z	Z coord of location of the closest point on the Moho surface
17	m_dst	distance to the closest point on the Moho surface

Extracting a Horizontal Slice from CVM-H

The `vx_slice` utility is a new SCEC-developed interface for extracting horizontal slices from CVM-H that are suitable for plotting. The command line format for `vx_slice` is as follows:

```
vx_slice - (c) Harvard University, SCEC
```

```
Extract a map of velocities from a simple GOCAD voxel for a regular
grid within the specified region at the specified depth/elev. Accepts
geographic/UTM coordinates for the geographic region. Outputs gridded
data suitable for plotting in MATLAB or GMT.
```

```
usage: vx_slice [-g] [-s] [-m dir] [-z dep/elev/off] [-r gridsize] [-f outfile] -- <x1> <y1> <x2>
```

Flags:

```
-g disable GTL (default is on).
-s directs use of SCEC 1D background and topo.
-m directory containing model files (default is '.').
-z directs use of dep/elev/off for Z column.
-r flag is gridsize in degrees/meters. Defaults to 0.1.
-f flag specifies filename to save x,y,z values. Otherwise stdout is used.
```

Arguments:

```
<x1> <y1> is SW corner of region to extract in geo/utm coords
<x2> <y2> is NE corner of region to extract in geo/utm coords
<z> is elev_offset, depth, or elevation depending on mode
<value> is one of: vp, vs, rho.
```

Output format is:

```
X Y value
```

Note: Specifying no Z coordinate option instructs `vx_slice` to interpret the z coordinate as elevation offset from free surface.

The plotting script `./scripts/viz/plot_hslice.sh` illustrates how `vx_slice` can be used to generate a GMT plot from CVM-H at a fixed depth.

CVM Evaluation Testing

SCEC community 3D seismic velocity models, like CVM-H, are used in deterministic earthquake wave propagation simulations. Wave propagation simulations of moderate-sized historical California earthquakes generate synthetic seismograms that can be compared to observed seismograms. An accurate CVM will produce a good match between synthetics and observed data.

SCEC has established a CVM evaluation system designed to evaluate currently available southern California 3D velocity models. SCEC's CVM evaluation systems uses earthquake wave propagation simulations to help evaluate the performance of a velocity model.

Current evaluations are based on simulations of a m5.4 Chino Hills earthquake. The CVM under evaluation is used to build a velocity mesh needed to run a 1Hz Chino Hills earthquake simulations. Then, the earthquake simulation results are compared against observational data for the Chino Hills earthquake. The simulation results are shown in Goodness of Fit plots. The expectation is that as the CVM's are updated, the goodness of fit performance of the CVM's will improve.

The SCEC CVM evaluation systems is designed to evaluate alternative CVM's. CVM developers can register their CVM with the SCEC evaluation system. The CVM software is used to create a velocity mesh for the 1Hz simulation. Results are posted on the CVM evaluation sites together with links to download the CVM software.

The CVM evaluation system continues to develop and improve. Current information about the SCEC CVM evaluation system is available through the SCEC wiki pages.

History of CVM-H Releases

Please reference at least Süss and Shaw (2003) if you use this model. The latest model, CVM-H 11.1.0, contains several components that may warrant referencing, depending on the objectives of a particular study. For example, the background crustal tomography model is from Tape et al. (2009), the upper mantle model is from Prindle and Tanimoto (2006), and the Moho surface is obtained primarily from Yan and Clayton (2007). Additional references for basins within the high-resolution model are within these papers: Komatitsch et al. (2004), Lovely et al. (2006), Munster (2007). References for the Vs30-derived GTL are Ely (2010).

Table 9 documents the references for each release (up to Plesch et al. (2009)), as well as references for new components associated with each release. The CVM-H model has also been presented at these SCEC meetings: Stidham et al. (2001a), Suess and Shaw (2002), Shaw et al. (2004).

Table 9: History of CVM-H releases

Version	Date	Reference	New Mantle	New Moho	New Crust	New Basins	New GTL
CVM-H 1.0	2003	Süss et al. (2003)	-	-	-	SS2003	-
CVM-H 2.0	Sept 2005	Suess and Shaw (2005)	1D	-	H2000	K2004, L2006	-
CVM-H 4.0	Sept 2006	Suess and Shaw (2006)	-	-	-	-	-
CVM-H 5.0	Sept 2007	Plesch et al. (2007)	PT2006	-	L2007	M2007	M2000, M2002
CVM-H 5.5	Sept 2008	Plesch et al. (2008)	-	-	-	-	BJ1997
CVM-H 6.0	Sept 2009	Plesch et al. (2009)	-	YC2007	T2009	-	-
CVM-H 6.2	Jan 2010	Plesch et al. (2009)	-	-	-	-	-
CVM-H 6.3	Sept 2010	Plesch et al. (2009)	-	-	-	-	Removed
CVM-H 11.2.0	Feb 2011	-	-	-	-	-	E2010
CVM-H 11.9.0	Sep 2011	Plesch et al. (2011)	-	P2011	-	P2011	-

References

- BJ1997 (Boore and Joyner , 1997)
- E2010 (Ely, 2010)
- H2000 (Hauksson, 2000), L2007 (Lin et al., 2007)
- L2006 (Lovely et al., 2006)
- K2004 (Komatitsch et al., 2004)
- M2000 (Magistrale et al.,2000)
- M2002 (Magistrale, 2002)
- M2007 (Munster, 2007)
- PT2006 (Prindle and Tanimoto, 2006)
- P2011 (Plesch et al., 2011)
- SS2003 (Süss and Shaw, 2003)
- T2009 (Tape et al., 2009, 2010)
- YC2007 (Yan and Clayton, 2007)
- 1D (Kanamori and Hadley, 1975; Dreger and Helmberger , 1991; Wald et al., 1995)

Acknowledgements and Contact Info

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Contributions to this manual were made by: Andreas Plesch, Carl Tape, John Shaw, Patrick Small, Geoff Ely, Thomas Jordan, and Philip Maechling.

Please email software@scec.org for help on downloading and using CVM-H, and for any suggestions for the delivery of the code or for this manual.

Please reference at least Süss and Shaw (2003) if you use this model; other references should be considered, depending on the purpose (see History of CVM-H releases section).

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Miscellaneous Technical Notes

This section contains notes on previous versions of the CVM-H model. Note that the information here does not necessarily apply to the current model.

Log file from 6/2007 onward:

- 06/2011 AP: Revised Moho, open Santa Maria basin to W, smooth transition at S border of HR to LR model, San Bernardino basin, various former GTL related cleanups.
- 09/2010 AP: GTL removed
- 10/2009 AP: minor update of Moho surface in CM, corresponding update to changed cells, truncated border by one cell in LR, fixed VP/VS in interpolation area
- 09/2009 AP: replaced LR and HR data files with Tape et al. (2009) m16 model as background, replaced Moho data with update, changed tagging
- 06/2009 AP: returned GTL cells in Salton trough to original CVM-H values, higher coordinate output precision
- 03/2009 AP: changed density scaling to Nafe-Drake (Brocher, 2005)
- 09/2008 AP: fixed VS in buffer zone, used model VP/VS, not interpolated VS, in core zone to be consistent with VP there
- 08/2008 AP: enlarged area to fit TeraShake box, added model VS in all voxets, no tt file creation
- 01/2008 AP: replaced striped artifacts offshore San Diego with depth-basin depth-seafloor calibrated model data
- 11/2007 AP: clarified geodetic datum with P. Suess
- 10/2007 AP: added VS voxel for lower crust/mantle, switched to Brocher (2005) VS in LR/HR, truncated min. VP at 121 m/s, made HR consistent with LR for nodata points.
- 9/2007 AP: updated lower crustal/mantle voxel to include Socal background VP
- 9/2007 AP: added lower crustal/mantle voxel, elevation voxets; updated background tomographic model
- 6/2007 AP: modified to be consistent with direct query of voxel in gocad, provide cell center

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