Technical Manual for SigmaSpectra

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1 Introduction

SigmaSpectra is a computer program that selects suites of of earthquake ground motions from a library of ground motion such that the median of the suite matches a target response spectrum at all defined periods, and then scales the suite such that the standard deviation agrees with the target standard deviation. The success of the SigmaSpectra in matching the target response spectrum and standard deviation depends on many factors including: the size of the requested suite, the number of motions in the ground motion library, and the appropriateness of the target response spectrum and standard deviation to the motions in the library.

SigmaSpectra is distributed under the GNU General Public License version 3 (GPLv3) which can be found here: `http://www.gnu.org/licenses/gpl.txt`, or in the installation directory of SigmaSpectra. As part of the GPLv3 license the source code has been made available in the installation file.

2 Methodology

The methodology for the scaling of the ground motions used in SigmaSpectra is published in Kottke and Rathje (2007) and Kottke and Rathje (2008). The major limitation of SigmaSpectra is the complete reliance on the response spectrum for the selection. Therefore, aspects of the ground motion that are not captured in the response spectrum are ignored during the selection and need to be selected by the user. The user interaction within the selection process occurs during: the development of the ground motion library (see Section 4.3, the optional step of flagging motions, and the final selection of a ground motion suite.

SigmaSpectra uses a two step process for selection and scaling. Suites of motions are first selected from the library to match the target response spectrum. The suite motions are then scaled to match the target standard deviation while maintaining agreement with the target response spectrum.

2.1 Basics of Scaling

SigmaSpectra computes the scale factor adjust the amplitude of a ground motion and does not modify the frequency content in any manner. A suite of scaled response spectra are typically assumed to be log-normally distributed. Therefore, the median spectral acceleration of the scaled suite ($\overline{S}_a^{\text{scaled}}$) at the i-th period is found by computing the mean log-space:

$$\ln \overline{S}_a^{\text{scaled}}(i) = \frac{1}{n_m} \left[\ln \left(s_1 \cdot S_{a,1}(i) \right) + \ln \left(s_2 \cdot S_{a,2}(i) \right) + \cdots + \ln \left(s_{n_m} \cdot S_{a,n_m}(i) \right) \right]$$

where n_m is the number of motions in the suite, s_n is the scale factor of n-th motion, and $S_{a,n}(i)$ is the spectral acceleration of the n-th motion at the i-th period. Using the properties of logarithms the average response spectrum can be expanded to:

$$\begin{aligned}\ln \overline{S}_a^{\text{scaled}}(i) = \frac{1}{n_m} & \underbrace{\left[\ln s_1 + \ln s_2 + \cdots + \ln s_{n_m} \right]}_{\text{Controls Amplitude}} \\ & + \frac{1}{n_m} \underbrace{\left[\ln S_{a,1}(i) + \ln S_{a,2}(i) + \cdots + \ln S_{a,n_m}(i) \right]}_{\text{Controls Shape}}\end{aligned}$$

The expansion shows that the scale factors control the amplitude of the median response spectrum while the motions that make up the median response spectrum govern the shape. The expansion can be further simplified to:

$$\ln \overline{S}_a^{\text{scaled}}(i) = \frac{1}{n_m} \sum_{j=1}^{n_m} \ln s_j + \frac{1}{n_m} \sum_{j=1}^{n_m} \ln S_{a,j}(i) = \ln \overline{s} + \ln \overline{S}_a(i)$$

This equation shows that the amplitude of the median response spectrum of a suite is controlled by the average of the scale factors ($\overline{s}$). Furthermore, the individual scale factors can be changed without affecting $\overline{S}_a$ as long as the average remains the same.

The optimal average scale factor ($\overline{s}$) for a suite of motions can be found by:

$$\ln \overline{s} = \frac{1}{n_p} \sum_{i=1}^{n_p} \left[\ln \left(S_a^{\text{target}}(i) \right) - \ln \left(\overline{S}_a(i) \right) \right]$$

where n_p is the number of periods in the response spectrum. This average scaled factor represents the least-squares fit of the median response spectrum spectrum.

2.2 Selecting Motions

Before discussion of how suites of ground motions are selected, it is necessary to define a measure of the goodness of fit that can be used to compare two different suites. SigmaSpectra uses the root-mean-square-error to quantify the goodness of fit, and is computed by:

$$\text{RMSE} = \sqrt{\frac{1}{n_p}\sum_{i=1}^{n_p}\left(\ln \overline{S}_a^{\text{scaled}}(i) - \ln S_a^{\text{target}}(i)\right)^2}$$
$$= \sqrt{\frac{1}{n_p}\sum_{i=1}^{n_p}\left(\ln \overline{S}_a(i) + \ln \overline{s} - \ln S_a^{\text{target}}(i)\right)^2}$$

When selecting motions, the optimal scale factor ($\overline{s}$) is first computed, and the RMSE of the suite is computed.

The most rigorous method for selecting a suite of ground motions would be trial of every possible combination. However, depending on the size of the motion library and the required size of the suite, the time required to test each of the trials may be prohibitive (e.g. days to weeks). An alternative approach would be to select a seed motion, and then try each of the remaining motions. Adding the motion that results in the lowest RMSE to the suite. This process is repeated until the desired suite size is achieved. However, this approach suffers from not trying enough combinations.

SigmaSpectra uses a hybrid approach in which the seed combination is generated for a given seed size, and then the iterative approach is used to select the remaining motions. This allows for the number of trials to be tuned by changing the seed size. The rigorous trial of every possible combination can be achieved by setting the seed size to the suite size, or a suite can be built for each motion as a seed motion by setting the seed size to 1.

2.3 Scaling a Motion Suite

Consider a normal distribution, that is separated into four equal area (probability) sections. The centroid of each section is found and represents the expected value within the section. For example, four centroids for standard normal distribution ($\mu = 0$ and $\sigma = 1$) are located at -1.275, -0.325, 0.325, and 1.275. The standard deviation of these values is 0.93, just below the target standard deviation. At a centroid location (ε_i), the target response spectrum for the centroid is computed by:

$$\ln S_a^{\text{centroid}}(i) = \ln S_a^{\text{target}} + \varepsilon_i \left(\beta \sigma_{\ln}^{\text{target}}\right)$$

where β is an scale factor that adjusts standard deviation of the target standard deviation. The motions in the suite are sorted based on the mean response over all periods, where the mean response of the j-th motion is defined as:

$$\overline{S}_{a,j} = \frac{1}{n_p} \sum_{i=1}^{n_p} \ln S_{a,j}(i)$$

The motion corresponding to the smallest $\overline{S}_{a,j}$ is fit to the centroid curve computed by the smallest ε value (e.g., -1.275) using a least-sum-of-squares fit. The same technique is used for each of the remaining motions in the suite. This ordered scaling is used to reduce the relative size of the scale factors (i.e., low intensity motions stay relatively low, high intensity motions stay relatively high).

The suite generated with these scale factors may not be the best fit to the target response spectrum. The standard deviation typically exceeds the target standard deviation because of the added variability of each motion. To solve this problem, the standard deviation scale factor β is adjusted from 0 to 3 and the scale factor that results in the best fit to the target standard deviation is selected. The goodness of fit for the standard deviation is measured by the root-mean-square error, defined by:

$$RMSE_{\sigma_{\ln}} = \sqrt{\frac{1}{n_p} \sum_{i=1}^{n_p} \left(\sigma_{\ln}^{\text{suite}}(i) - \sigma_{\ln}^{\text{target}}(i) \right)^2}$$

3 SigmaSpectra User Interface

This section introduces the SigmaSpectra user interface and provides information regarding each input field.

3.1 Input Dialog

After launching SigmaSpectra, the Input Dialog, shown in Figure 1, is created and contains all of the parameters used in the selection process. The Input Dialog is separated into the following four groups:

1. Target Response Spectrum (Section 3.1.1)
2. Period Interpolation (Section 3.1.2)
3. Library of Motions (Section 3.1.3)

4. Calculation (Section 3.1.4)

The input fields within each group are discussed in the following subsections.

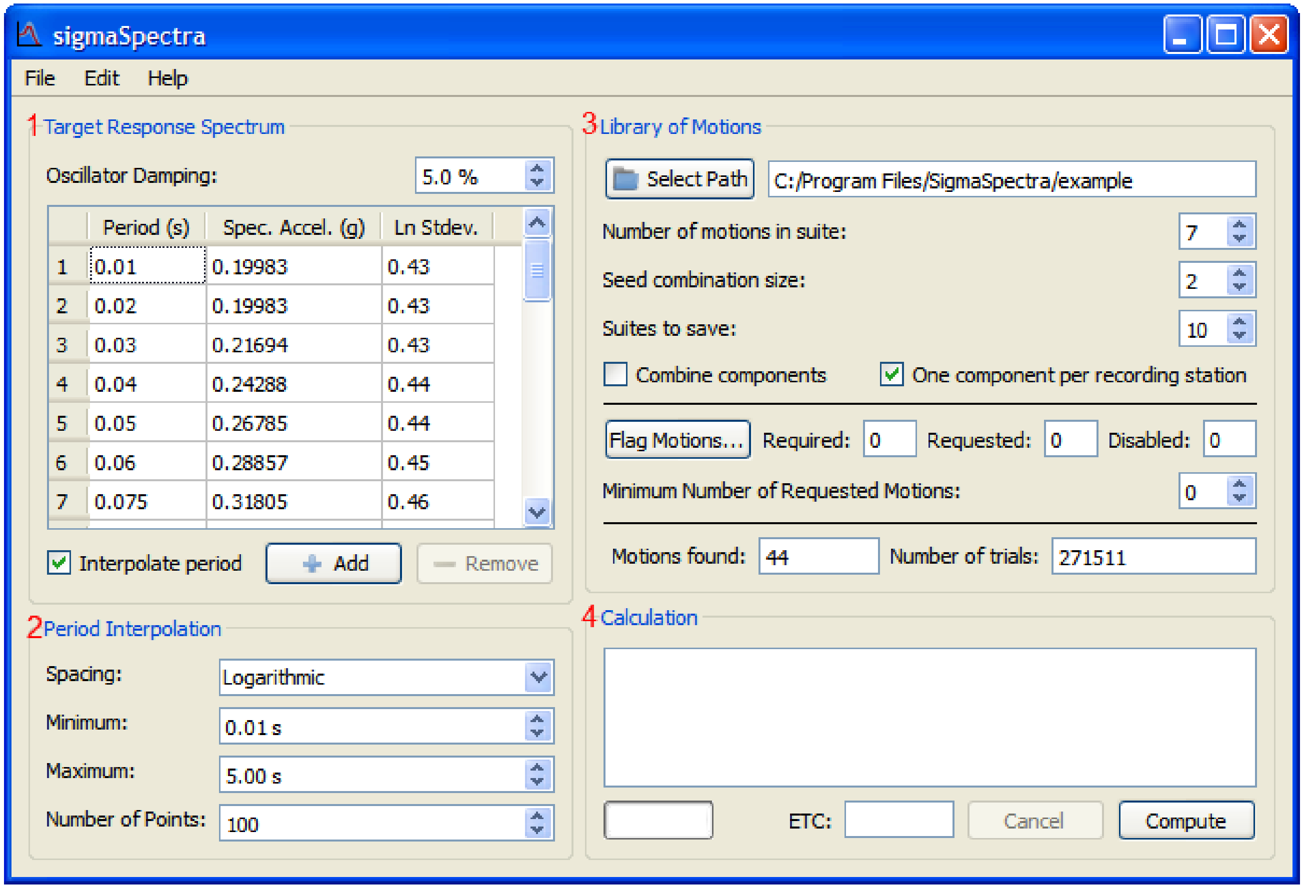

Figure 1: Screen shot of the Input Window.

3.1.1 Target Response Spectrum Group

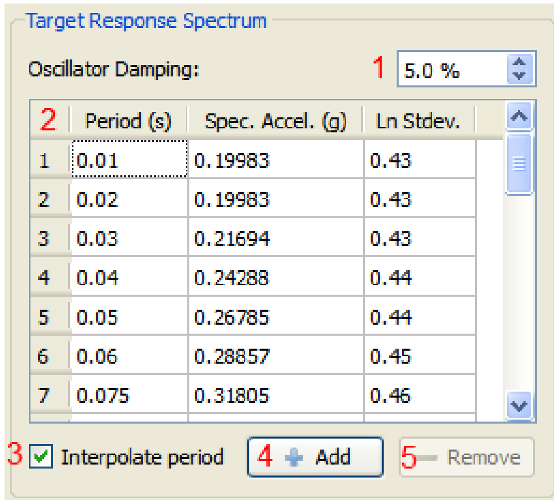

Figure 2: Screen shot of the Target Response Spectrum Group.

The Target Response Spectrum Group is used to define the target response spectrum, and consists of three input fields. The fields are numbered in Figure 2, and described as follows:

1. The oscillator damping of the target response spectrum. This value is typically 5%.

2. The target response spectrum characterized by the spectral acceleration (S_a) and standard deviation ($\sigma_{\ln}$) at a range of oscillator periods. The values must be specified with increasing oscillator periods. Rows can be added to the table by pressing the *Add* button (#4 in Figure 2), or removed by first selecting the row and then pressing the *Remove* button (#5 in Figure 2). A row is selected by selecting all three cells in a row, or by clicking on the row number button. The complete table can be selected by clicking on square button in the upper left corner of the table (#2 in Figure 2). The easiest way to enter information into this table from a spreadsheet is copying the data from the spreadsheet, selecting the table, and pasting the data into the table. The paste action can be activated through the *Edit Menu*, or through the shortcut *Ctrl+v*.

3. This check box is used to control if the target response spectrum is to be

interpolated. The interpolation is done using a cubic spline and may not be appropriate for target response spectrum with abrupt changes (e.g., an IBC response spectrum).

3.1.2 Period Interpolation Group

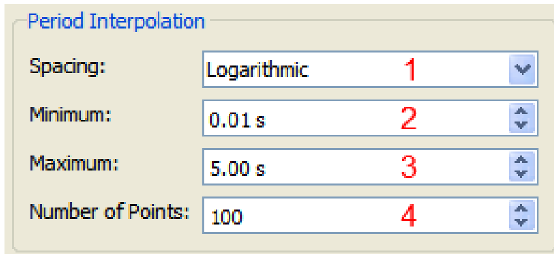

Figure 3: Screen shot of the main Period Interpolation Group.

The Period Interpolation Group characterizes the period spacing to use in the interpolation of the target response spectrum. The Period Interpolation Group is enabled through a check box in the Target Response Spectrum Group (see #3 in Figure 2). The fields are numbered in Figure 3, and described as follows:

1. Controls the spacing the period values. The *Linear* option creates periods that are equally spaced in linear space, whereas the *Logarithmic* option creates periods that are equally space in logarithmic (i.e. $\log_{10}$) space.

2. The minimum period. This value cannot be less than the minimum period of the target response spectrum, or greater than the maximum period (#3 in Figure 3). If the spacing is logarithmic, this value must be greater than zero.

3. The maximum period. This value cannot be greater than the maximum period of the target response spectrum, or less than the minimum period (#2 in Figure 3).

4. The number of periods within the specified range. It is recommended that at least 25 points for each log cycle be used (e.g. 60 points between 0.01 and 5 seconds).

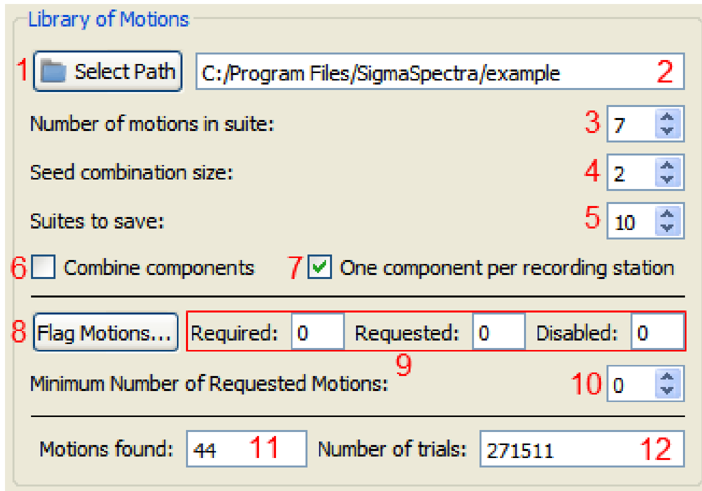

Figure 4: Screen shot of the Library of Motions Group.

3.1.3 Library of Motions Group

The Library of Motions Group is used to specify the library of motions considered, as well as the parameters that govern the selection procedure described in Section 2. The fields are numbered in Figure 4, and described as follows:

1. Opens a dialog that is used to select the path to the folder containing the motions to be considered in the selection procedure. More information regarding collection and required organization of the input motions can be found in Section 4.3.

2. Field to manually specify the file path to the motion library.

3. The number of motions in a suite.

4. The seed combination size. This parameter controls the number of trials will be performed during the selection procedure as described in Section 2.2. The larger this number is the more number of trials are performed.

5. The number of suites to be saved by SigmaSpectra for consideration by the user. For example, if this number were 10 then the suites with the 10 lowest RMSE values are saved.

6. If the horizontal components from a station are to be combined prior to the selection process. The horizontal components (A and B) are combined using the geometric mean ($\sqrt{A \cdot B}$), and then the average spectrum treated as single motion in the selection process. This option would be appropriate for analysis requiring two components of motion. The identification of component pairs is done using the file naming conventions of the PEER NGA database. This option disables the *One component per recording station* check box.

7. If only one component per recording station is allowed in a suite. If this is enabled, then suites are limited to only contain one component per recording station for each event.

8. Opens the Flag Motion Dialog discussed in Section 3.2.

9. The number of the *Required*, *Requested*, and *Disable* motions.

10. The minimum number of*Requested* motions in a valid suite.

11. The number of motions found with the motion library.

12. The number of trials that will be performed during the selection process.

3.1.4 Calculation Group

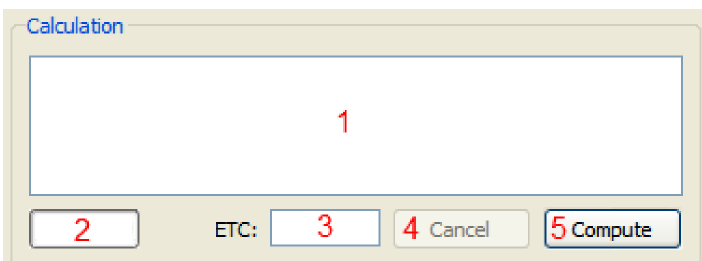

Figure 5: Screen shot of the Calculation Group.

The Calculation Group is used to start and cancel the selection process, as well as report information regarding the process. The fields are numbered in Figure 5, and described as follows:

1. Message window containing information about the status of the selection process.

2. The progress of the selection process.
3. The estimated time at which the selection of suites will be completed.
4. The *Cancel* button used to stop the selection process. Only enabled when the selection process is ongoing.
5. The *Compute* button used to start the selection process. After the selection process is completed, the Suite Selection Dialog (see Section 3.3) is displayed.

3.2 Flag Motions Dialog

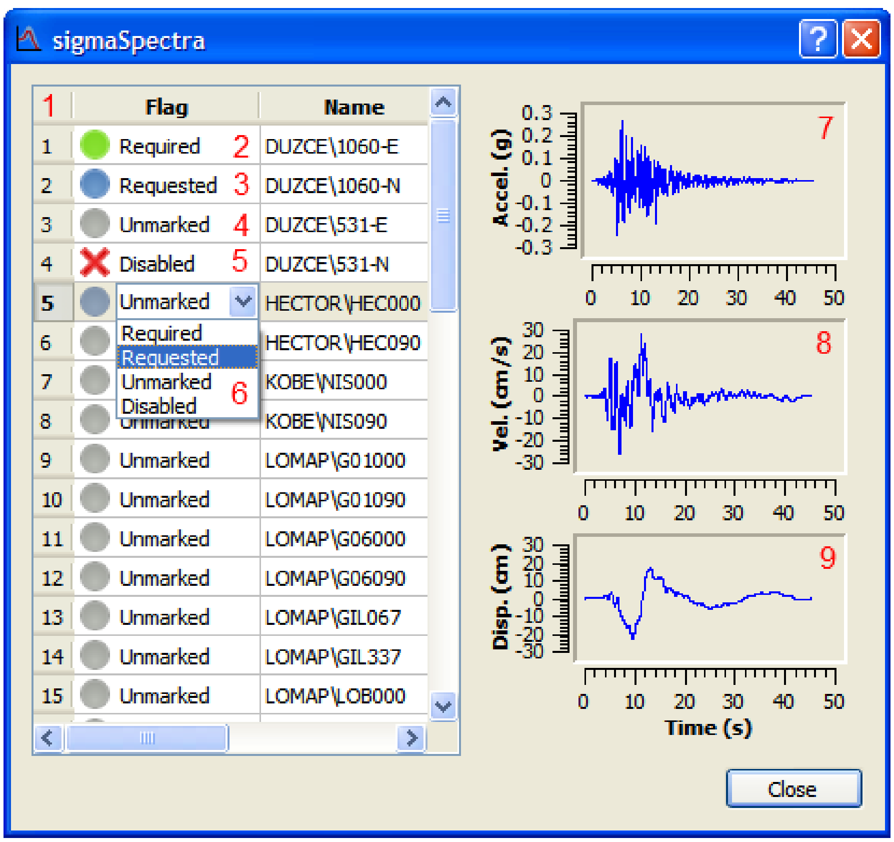

Figure 6: Screen shot of the Flag Motions Dialog.

The Flag Motions Dialog is an optional step that allows the user greater control during the selection process by allowing each motion to be to flagged as either

Required, *Requested*, *Unmarked* (the default state), or *Disabled*. The flags are described as follows:

Required Suite must contain the motion.

Requested Suite must contain at least the number of *Requested* motions defined by the Minimum Number of Requested Motions Spin Box in the Library of Motions Group (see #10 in Figure 4).

Unmarked No preference is given to the motion. This is the default motion flag.

Disable Suite must not contain the motion.

An example of when flagging motions may be useful is when the suite should contain a certain number of motions with directivity pulses. The dialog is launched by pressing button #8 in the Library of Motions Dialog (Figure 4). When the *One component per recording station* check box is enabled, then the horizontal components are grouped together. The dialog is shown in Figure 6, and described as follows:

- Table containing all motions found in the library path.
- A motion listed as *Required*.
- A motion listed as *Requested*.
- A motion listed as *Unmarked*.
- A motion listed as *Disabled*.
- The drop-down list used to flag the motions.
- Acceleration-time series of the motion(s). If the *Combine components* check box (see #6 in Figure 4) is enabled, then both components are plotted.
- Velocity-time series of the motion(s). If the *Combine components* check box (see #6 in Figure 4) is enabled, then both components are plotted.
- Displacement-time series of the motion(s). If the *Combine components* check box (see #6 in Figure 4) is enabled, then both components are plotted.

3.3 Suite Selection Dialog

The Suite Selection Dialog is used to display information about a suite to help the user select a suite of motions. The components of the dialog are shown in Figure 7, and described as follows:

1. The list of suite saved during the selection procedure. The table consists of four columns and can be sorted by any column. The four columns are:

   Export If the suite is to be exported.

   Rank Allows the user to give the suite a numerical rank (*optional*).

   Median Error Root-mean-square-error of the median response spectrum to the target response spectrum.

   Stdev. Error Root-mean-square-error of the standard deviation (σ_{ln}) to the target standard deviation.

2. A list of the motions in the suite and the properties of the scaled motion. Double-clicking on a motion opens the plots of the time series.

3. Plot of the response spectra. The coloring is as follows:

   Red–Solid Target median response spectrum.

   Red–Dashed Target median response spectrum plus/minus one standard deviation.

   Blue–Solid Median response spectrum of the suite.

   Blue–Dashed Median response spectrum of the suite plus/minus one standard deviation.

   Green Currently selected motion.

   Gray Unselected motions.

4. Plot the standard deviation (σ_{ln}). The color is as follows:

   Red–Solid Target standard deviation.

   Blue–Solid Suite standard deviation.

5. Plot of the acceleration-, velocity-, and displacement-time series for the currently selected motion.

6. Export the selected suites (see Section 3.4)

7. Close the dialog.

3.4 Export Dialog

A suite can be saved from the program by pressing the *Export Suites...* button (#6 in Figure 7) which opens the Export Dialog, shown in Figure 8. The dialog consists of the following elements:

1. The output format of the selected suites:

   No Output Nothing for each suite is written. This format option is only useful if the *Include a summary of all generated suites* option (#4 in Figure 8) is also enabled.

   Comma separated values The most complete output option, which includes the scaled response spectra, as well as scale factor and characteristics for each motion within the suite. This file can be easily opened with a spreadsheet program.

   Strata suite file A file consisting of the file path and scale factor separated by a comma for each motion within the suite. This file can be open with the site response analysis program Strata.

   SHAKE2000 suite file A file consisting of the file path and scale factor for each motion within the suite in a fixed width format. This file can be open with the site response analysis program SHAKE2000.

2. The prefix to apply to the created files (*optional*).

3. The folder where the exported files will be created.

4. If a summary of all saved suites should be created.

5. Write the files and close the dialog.

6. Close the dialog without creating the files.

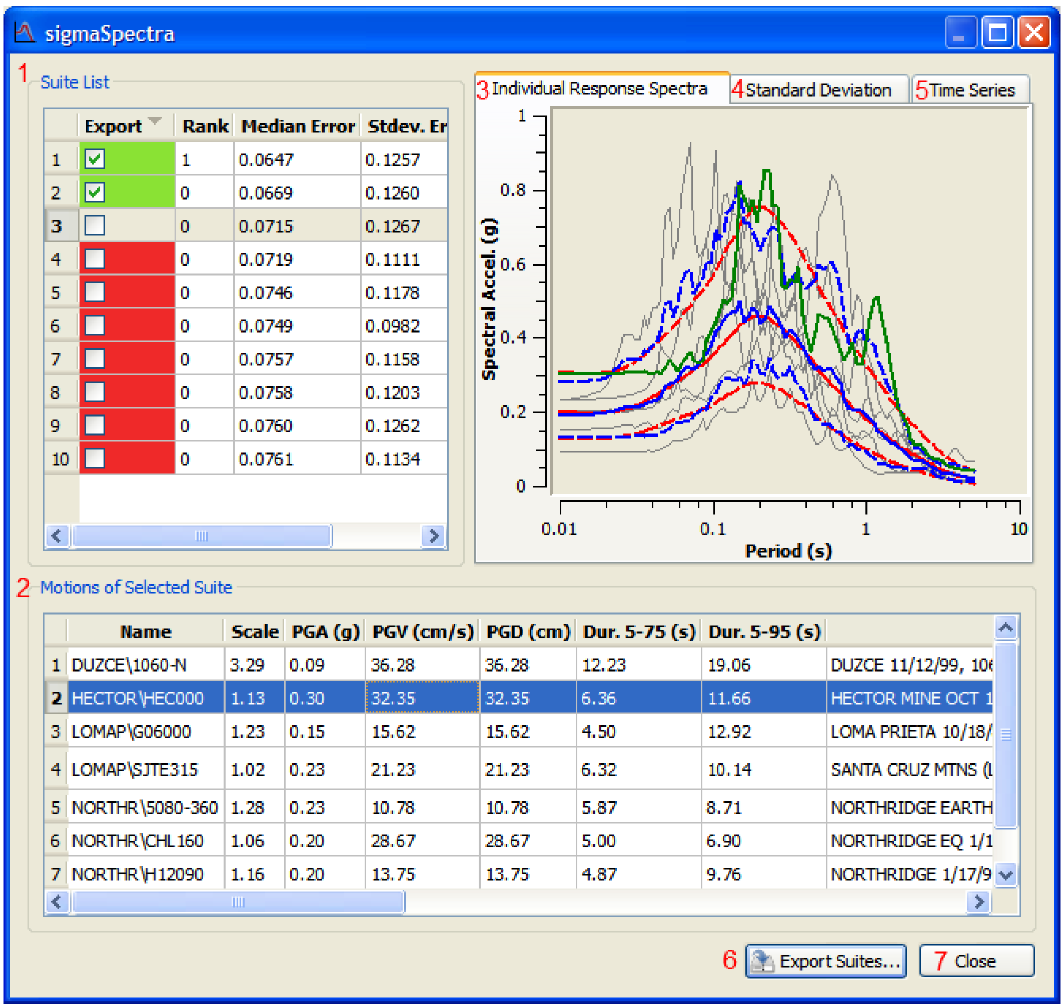

Figure 7: Screen shot of the Suite Selection Dialog.

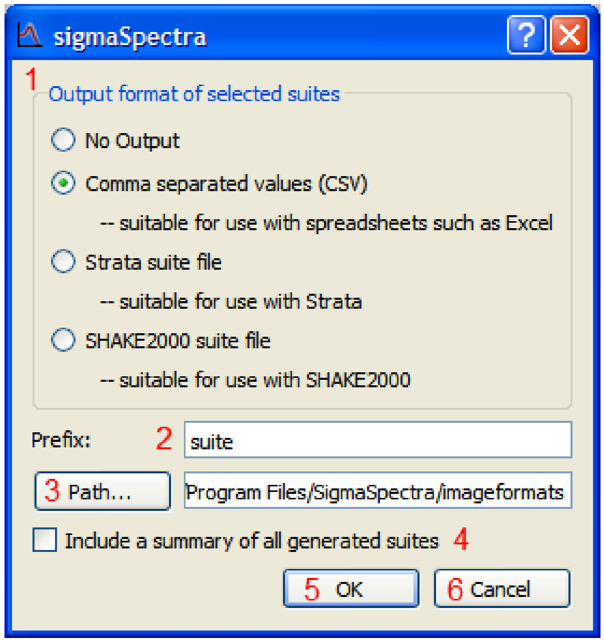

Figure 8: Screen shot of the *Export Dialog*.

4 An Example

The use of SigmaSpectra can be simplified to the following five steps:

1. Define the scenario event and the desired number of motions in the suite.
2. Compute the target response spectrum and standard deviation for the scenario event.
3. Create a library of ground motions suitable for the scenario event.
4. Generate a number of potential suites with SigmaSpectra.
5. Select the suite(s) to be used in the analysis.

Each of these steps will be discussed through the use of an example. This introduction to ground motion selection is not to be considered exhaustive.

4.1 Scenario Event

The scenario event is usually defined by the project. In this example, the scenario event will be a magnitude 7.0 earthquake generated by a strike-slip fault at a distance of 20 km. SigmaSpectra will be used to generate 30 different suites, with each suite containing 10 ground motions. The size of the suite affects the fit of both the median and the standard deviation.

4.2 Target Response Spectrum

Defining a target response spectrum for a scenario event and application requires the use of engineering judgment and will not be discussed here. However, it is important to point out that it may not be appropriate to use SigmaSpectra to fit every response spectrum. If the response spectrum is representative of a threshold response, instead of a median response, then the use of SigmaSpectra is not encouraged.

For the example scenario, the Abrahamson and Silva (1997) attenuation relation was used to compute the target response spectrum and standard deviation presented in Table 1. If the *Example* option was enabled during installation, this target response spectrum can also be opened from the *example-target.csv* file found in the installation directory. The damping used in this in this model is 5%. Because the limited number of periods specified by this model, we will use an interpolated period range. Consistent RMSE values have been found by using at least 60 steps between 0.01 and 5 seconds which corresponds to approximately 25 steps per log cycle. For this example, we will use 100 points from 0.01 to 5 seconds.

4.3 Defining a Library of Ground Motions

Before a suite of ground motions can be selected, a library of potential motions must be developed. Care needs to be taken in the selection of ground motions for this library. Each of the motions should be application to the scenario characterized by the target response spectrum. Because of the challenge in selecting appropriate motions no discussion of the subject will be presented here.

Currently, SigmaSpectra only supports the processing of Next Generation Attenuation (NGA) times series which can be downloaded from `http://peer.berkeley.edu/nga/earthquakes.html`. The NGA database names files based on the *recording station and component only*. Therefore, two time series from the same station and component have the same name for two different earthquakes. In part of the NGA data organization files are stored in directories corresponding to the earthquake event name. For example, recordings from the Northridge earthquake are all found in the *NORTHR* folder. It is recommended that a similar convention be used for organizing files for

Period (s)	**Sa (g)**	**Stdev.** ($\sigma_{\ln}$)
0.010	0.19983	0.430
0.020	0.19983	0.430
0.030	0.21694	0.430
0.040	0.24288	0.440
0.050	0.26785	0.440
0.060	0.28857	0.450
0.075	0.31805	0.460
0.090	0.33892	0.470
0.100	0.35845	0.470
0.120	0.39258	0.480
0.150	0.43705	0.480
0.170	0.45219	0.490
0.200	0.45931	0.500
0.240	0.44796	0.500
0.300	0.41705	0.510
0.360	0.38132	0.520
0.400	0.36087	0.520
0.460	0.32983	0.536
0.500	0.30779	0.540
0.600	0.27312	0.556
0.750	0.22736	0.564
0.850	0.20727	0.578
1.000	0.18158	0.594
1.500	0.12073	0.620
2.000	0.08829	0.640
3.000	0.04781	0.676
4.000	0.02924	0.696
5.000	0.02012	0.716

Table 1: Target response spectrum computed using the Abrahamson and Silva (1997) attenuation relationship.

use by SigmaSpectra. The NGA earthquake name can be found in URL for for the ground motion records. For example, link to download the 95° component recording at the *Wonderland Ave* station for the Northridge earthquake is *NORTHR/WON095* and the url: `http://peer.berkeley.edu/nga_files/ath/NORTHR/WON095.AT2`. I would recommend saving the *WON095.AT2* file to a directory named *NORTHR* to maintain organization.

For the example, a catalog of potential motions was selected by searching the NGA strong motion database using the parameters shown in Table 2. These parameters – magnitude range, distance range, faulting mechanism, and rock site conditions – are specified such that a variety of motions are present in the catalog and that each of the motions in the catalog was generated under conditions similar to the scenario. The search resulted in a total of 44 motions, as summarized in Table 3. The motions were recorded from 6 different earthquakes with a majority (38 out of 44) of the motions being recorded for earthquakes with a magnitude below scenario event. Because of the duration being related to the magnitude, the limited number of motions from large magnitude earthquakes may result in combinations with median durations that are shorter than the expected duration of the scenario. If duration were critical in the analysis, the upper limit on the magnitude range could be extended to include more motions with longer durations.

During the installation the motions for this scenario can be installed by selecting the *Example* option. The motions are then installed into the *example* folder of the installation path. Select this folder by clicking on *Select Path* and selecting the appropriate folder, or by typing in the appropriate path. Once the path is specified, the *Motions found* box will update with the number of motions recursively found within the specified directory. At this time the number of motions in the suite, seed combination size, and suites to save can all be defined.

Parameter	**Values**
Magnitude (M_w)	6.6 to 7.3
Closest Distance	5 to 30 km
Fault Type	Strike-Slip, Reverse
$V_{s,30}$	600 to 2500 m/s
GeoMatrix 1 Class	A, B, and I

Table 2: Parameters used to define motions for consideration in the selection algorithm.

Event	Magnitude	Fault Type	No. of Records
San Fernando	6.61	Reverse	6
Northridge	6.69	Reverse	18
Kobe, Japan	6.9	Strike-Slip	2
Loma Prieta	6.93	Reverse-oblique	12
Hector Mine	7.13	Reverse	2
Duzce, Turkey	7.14	Strike-Slip	4

Table 3: The earthquake events and number of records used in the catalog of motions.

Ground motions are recorded at stations and for each event there are three components of recorded (two horizontal and one vertical). The horizontal components are used in most applications, and are the only components that are loaded by SigmaSpectra. The horizontal components for a given event and station are related to each other. In some cases, it might not be appropriate to create a suite that contains both horizontal components for the same station and event. To limit the suite to only one component per recording station, check the *One component per recording station* check box. In other cases, such as two-dimensional analysis, the user might want to select pairs of components. This feature is enabled by checking the *Combined components* check box. The components are combined in log-space, and the station is then selected instead of the components during the selection process, and the same scale factor is applied to each component.

4.4 Generate Potential Suites

Once the library of the of ground motions has been developed, the parameters for used in the suite selection process need to be defined. The parameters used in this example are tabulated in Table 4. The number of motions in the suite is dependent on the project; for this example ground motion suite will consist of seven motions. The seed combination size is used to adjust how rigorous the search procedure is for the selection of the ground motion suites. If the seed combination size is the same as the number of motions in a suite, then every possible combinations of motions will be tried, but will take a very long time (possibly days to weeks). For most cases, a seed of two or three is appropriate. The motions are being selected for a one dimensional analysis (i.e., components will not be combined). Only one motion per recording station is allowed so that the path effect captured by each motion is independent of the other motions in the suite.

Option	Value
Number of motions in suite	7
Seed combination size	2
Suites to save	10
Combined components	No
One component per recording station	Yes

Table 4: Example selection parameters.

After fully defining the target response spectrum, ground motion library, and parameters governing the selection process press the *Compute* button to start the automated-selection process. Once the suites have been selected, a new will be created with the potential suites to allow the user to make the final decision.

4.5 Selection of Suites

Selection of the final suite(s) requires use of engineering judgment. The user may want to consider the fit of the selected motions to the target response spectrum at various periods, the variability of the suite, and characteristics of the time series. If is suite is deemed to be appropriate, then it is enabled for export in the Suite List Table (#1 in Figure 7).

Suites that have been marked for export are exported with the *Export* button. The suite can be exported in a variety of formats. The most general use is the comma-separated values format as it also includes the response spectra of each ground motion in the suite. Each suite is exported to a different file name, the prefix of which can be specified.

Bibliography

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