Marine Mammal Scientific Support Research Programme MMSS/001/11

MR 8.2:

Sound Exposure Explorer Tool Manual

Sea Mammal Research Unit
Report to
Scottish Government

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Sound exposure explorer tool

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1   Introduction

The purpose of the Sound Exposure Explorer (SEE) is to provide a simple interactive utility which can be used to explore simple sound exposure scenarios, especially those involving cumulative exposures to moving animals. Using the tool, the cumulative exposure of animals can be calculated and plotted for different exposure scenarios; the "starting ranges" at which acoustic doses received over the course of an exposure scenario will exceed particular predetermined thresholds are also calculated. The *intention is **not** to replace more sophisticated products* which may incorporate complicated models of propagation loss and animal movements but to provide a straightforward, readily-understood and easy-to-use tool which can be used to make a first broad assessment of a sound exposure scenario and can provide a benchmark against which the conclusions from more complicated modelling exercises can be compared.

In its current form the utility focuses on the calculation of cumulative exposure for an animal which moves through a sound field created by one or more sound sources.

The conceptual framework of the SEE generally follows that laid out by Southall et al 2007 and many of the thresholds and parameters they propose are available as pre-set values or defaults within the utility.

SEE is open source; thus any developer can check or enhance the underlying Java source code. Our intention in planning and designing the SEE has been to provide a basic functionality within an architecture that will allow for future development and expansion as required.

2   Installation

Sound Exposure Explorer is written in Java. ***The Java run time engine (version 8 or higher) must be installed to allow the program to run.***

The Java run time engine (JRE) can be downloaded from https://java.com/en/download/index.jsp. Make sure you download the 64 bit version.

Source code for the Sound Exposure Explorer is found at:
https://sourceforge.net/p/soundexplorer/code/HEAD/tree/trunk/

2.1   Setting up a Scenario

To use the tool the user must first set up a sound exposure scenario.

(Currently only one class of scenarios exist, the 'Single Animal Exposure Scenario', which is for a single animal moving through a sound field from one or more sound sources. The structure of the program allows different scenarios to be added in the future to include for example multiple animals).

For a Scenario to be fully described in the SEE, four sets of conditions need to be specified. There are four control panels (specified by tabs) in the utility, labelled "Propagation", "Sound Sources", "Animal" and "Animal Track". Each needs to be completed in turn.

 The "Scenario Control" panel (RHS of screen) provides controls for running scenarios once a full set of parameters has been specified and for saving output. The scenario length should be specified. This is the cut off length at which cumulative sound expose will cease, even if individual sound durations suggest that sound sources are still transmitting at this time. This allows users to quickly change lengths of exposures.

Running the sound exposure scenario calculates the total cumulative sound exposure for a single specified animal moving through a sound field created by one or more sound sources.

Parameters must be specified for:

- One or more sound sources with a specified level for source energy for a single pulse, spectrum, ramp up and timeline
- Propagation conditions, for each of the sound sources.
- The characteristics of the animal being tested including:
  - an appropriate species "filter" which defines relative vulnerability of the animal to the effects of sound in different frequency bands
  - Acoustic thresholds for effects of interest such as Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS)
  - Movement: how the animal moves during the exposure scenario.

2.2 Propagation

The Propagation Panel allows users to specify the propagation loss model to apply to *each* sound source. Propagation loss can vary substantially between different environment and sound sources.

Three sources for propagation loss could be used in different situations.

- Simple geometric models
- Simple empirically derived equations
- Imported values derive from complex site specific models
- Site-specific empirical observations.

Only the Geometric Spreading and empirically derived equations modules are currently implemented.

2.2.1 Geometric Spreading

This simple model involves geometric spreading term and frequency dependent absorption loss in the simple equation:

$$TL = b * log_{10}(R) + c * R$$

where TL is the transmission loss in dB, b is the propagation constant (generally 20 for spherical spreading and 10 for cylindrical spreading), c is the absorption loss coefficient which is dependent on frequency and R is the range in meters.
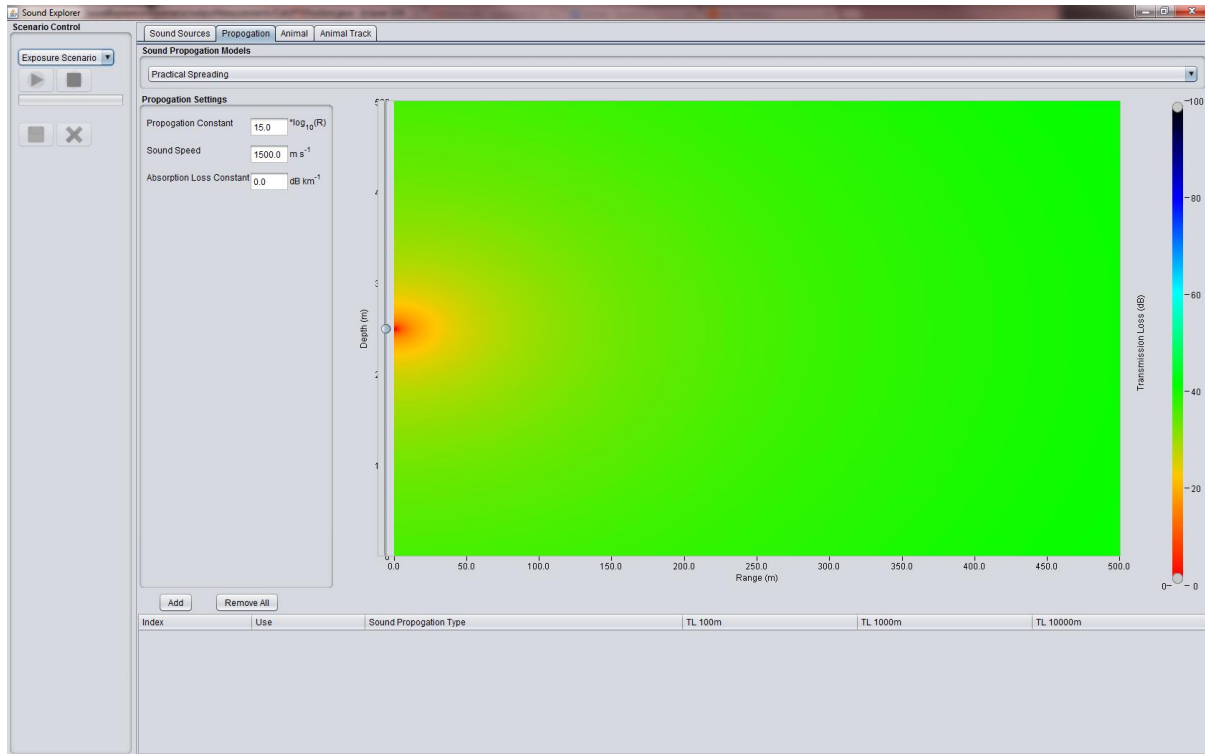

Figure 1. The sound propogation panel for Geometric spreading. Three paramters can be set, the propogation constant, sound speed and absorption loss coefficient.

The sound propagation panel shows a preview of transmission loss on a colour map, the x axis shows the range from source, the y axis shows depth and the colour indicates transmission loss. The depth slider allows users to change the depth of a sound source in order to preview propagation conditions; it does not change any parameters in the sound propagation itself. The colour slider can be used to change the colour scale of the transmission loss colour map.

Once the sound propagation scenario has been set it should be saved by clicking the 'Add' button. The propagation type along with estimates of transmission loss with certain ranges will be shown in the table at the bottom of the tab panel. These saved propagation loss scenarios can now be associated with particular sound sources in the sound sources panel. To do this click on the propagation table cell A menus showing all the saved propagation scenarios is shown and clicking on one of these associates it with the sound source (Figure 2).
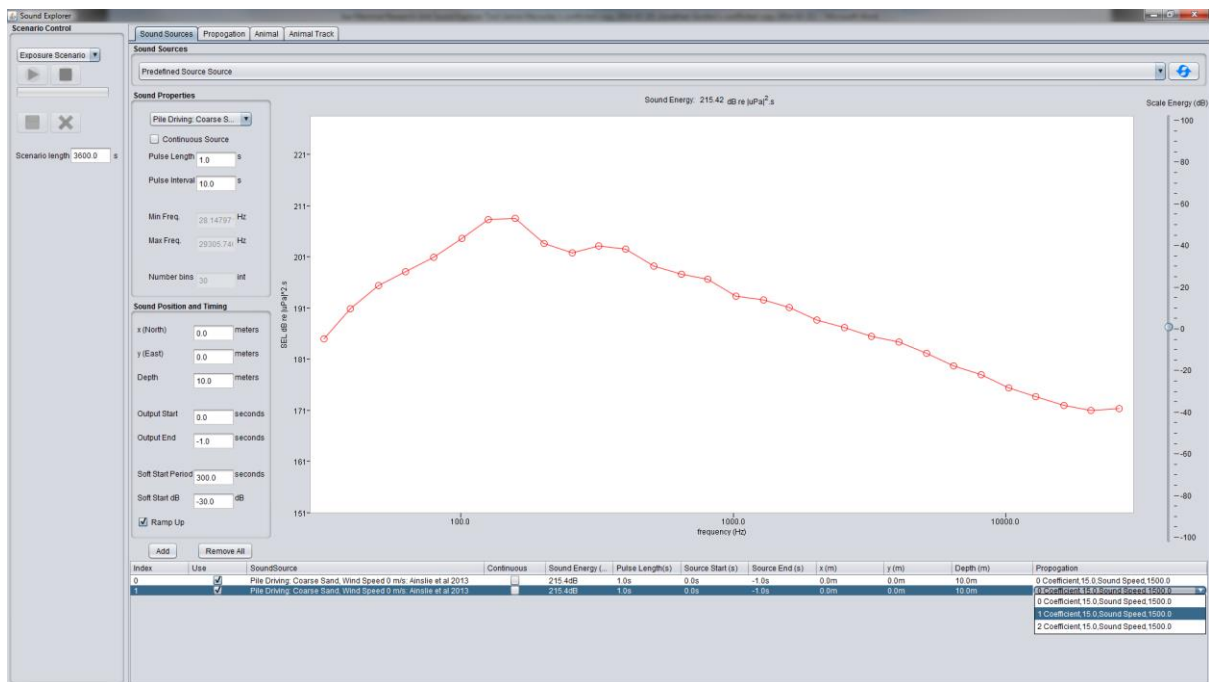
Figure 2. The sound source panel. A typical sound source panel is divided into 5 main sections. This is an example of the *Adjustable Sound Source* but the same panels are available for sound source displays for a source types. The highlighted areas are 1) *Sound Properties* which allows users to change the properties of the sound source such as pulse length and interval, frequency min/max and the number of bins in the frequency spectrum. 2) The *Sound Position and Timing* panel allows users to change the position of the source, when it starts/stops and whether it has a soft start period. *The Sound Spectrum Panel* shows the sound spectrum and total sound energy in dB re Pa^2.s and allows users to drag individual frequency bins to manually change spectrum. 3) The *Sound Scale Panel* allows users to scale the spectrum, increasing or decreasing the overall Sound Energy. The *Added Sound Sources Table* shows a summary of *all* added sound sources.

Once sound propagation scenarios have been added in the propagation panel it is possible to associate them with different sound sources in the sound source panel. To do this click on the propagation table cell for a sound source. This will bring up a drop down menu which can be used to select a sound propagation of the particular sound source.

Sound Sources

Sound sources are described by the pulse energy spectrum in dB re 1uPa^2.sper pulse. The drop down combo box in the 'Sound Sources' panel provides three options.

- Using a predefined sound source
- Importing a new sound source from an excel spread sheet
- Configuring a synthetic "User Adjustable" sound source

Panel 1: Sound Properties

All current sound sources show a spectrum and energy for *one pulse*. This panel allows users to change various properties of the sound source. The most important parameters are ***Pulse Length***, i.e. how long a single pulse of sound lasts and ***Pulse Interval***, the time interval between different pulses. The pulse length is useful as an animal may move during longer pulses. If this occurs then the total energy received will change compared to a stationary animal. For a **continuous** sound sourcethe pulse length and pulse interval should be the same.

(Three controls are only available for the Synthetic Sound Source:***Min Freq***, the minimum frequency of the sound source spectrum to be synthesised; **Max Freq**, the maximum frequency of the sound source spectrum the number of frequency bins (***Number bins***) for the synthesised sound source.)

Panel 2: Sound Location and Timeline

The position and time line for a sound source is specified in the 'Sound Position and Timing' panel. Locations are in meters on a Cartesian co-ordinate grid were **y** points north, *x* points east and *z* is depth. A. flat earth is assumed for all calculations.

The time, in second relative to the start of the scenario, at which a source starts and stops producing sound are entered in the **Output Start** and **Output End** boxes. If the source continues to the end of the scenario then -1 can be entered as the end time.

In addition, for sound sources whose output energy initially increased with time, due to a ramp up or soft start for example, this can be specified. Currently the utilityallows for a linear change in dB energy of each pulse. For example, to specify a 10 minute ramp up with a source level 30dB lower at the start, define the **Soft Start dB'**as -30 and set the **Soft Start Period** to 600 seconds.

Panel 3: Scale Spectrum

The slider bar allows users to scale the spectrum, i.e. increases or decrease the total sound energy whilst maintaining the relative energy of the different frequency components. This may be useful for exploring alternative scenarios especially in cases where there is uncertainty about source levels. In addition, a user may wish to scale a spectrum calculated from their own recordings using a program such as Adobe Audition to match a known total pulse energy from the literature. (See Box 1).

Panel 4: Refresh Button

The refresh button can be used to return a sound source is to its default settings. This will only affect the current sound source and won't change sound sources the sound source table.

Source Spectrum Panel

The source spectrum panel shows a sound pule energy spectrum as a plot of sound energy (dB re Pa^2.s) v frequency (Hz) graph. It is possible to change individual frequency bins by dragging points on the graph. The total **Sound Energy** label at the top of the graph will change when frequency bins are adjusted.

Added Sound Sources Table

This shows all the sound sources added to the scenario. The **Propagation** column in the table allows users to associate a different sound propagation to each sound source. To do this, click the propagation cell and select a sound propagation from the drop down menu.

Figure 3. Each sound source has to have a sound propagation associated with it. A sound propagation type is added to each source by clicking the drop down menu in the *Propagation* cell in the *Sound Sources Table.*

> **Hint:** The *Propagation* column in the table allows users to associate an appropriate sound propagation to each sound source. To do this, click the propagation cell and select a sound propagation from the drop down menu. Propagation loss scenarios are set up on a different (the sound propagation) panel and is described in the propagation section of this help file. Any of the established propagation loss models can be applied from a drop down menu in this timeline panel and this can be done at any time.

2.2.2   Synthetic sound source.

The synthetic sound source allows users to create their own spectrum and define a 'synthetic source'.

2.2.3   Pre-defined Sound Source:

Pre-defined sound sources are stored within the programan can be chosen from a drop-down list. Currently 8 predefined sound sources based on source characteristics taken from the published literature and reports are provided.
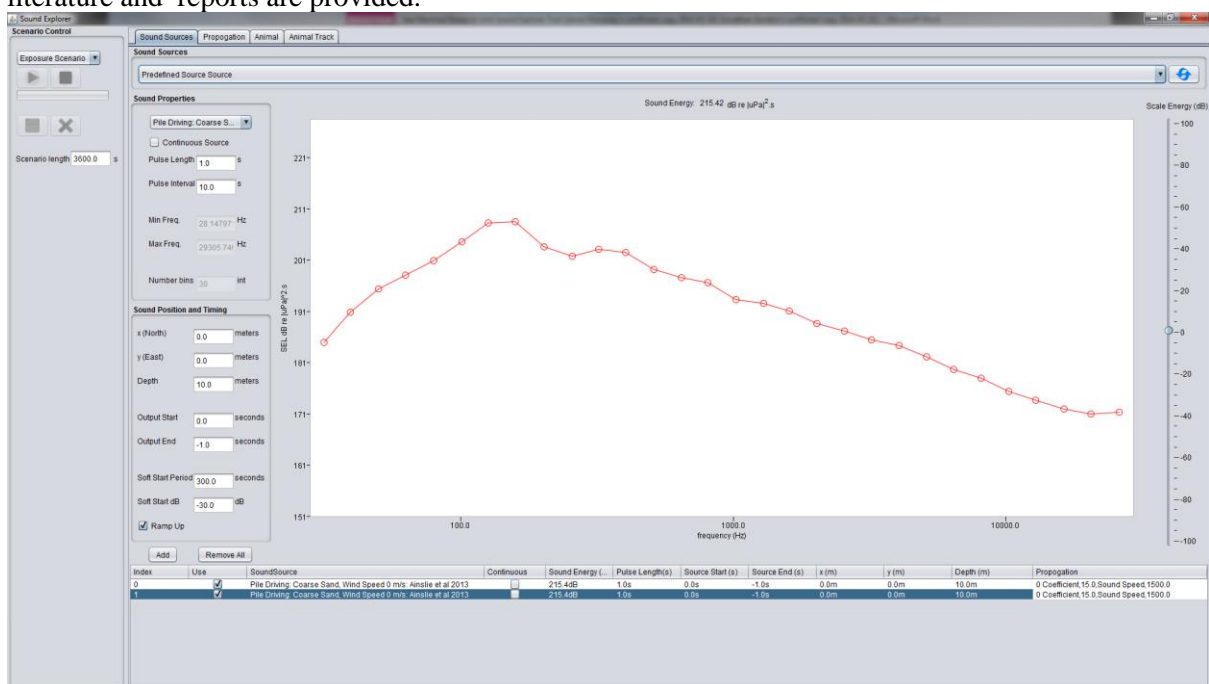

Figure 4. A pre-defined sound source. Pre-defined sound sources are generally based on measurements from the literature and other reports. Pre- defined sound sources have a specified total energy, but this can be scaled using the dB scale bar on the right side of the source panel. An updated total energy level is shown above the spectrum source
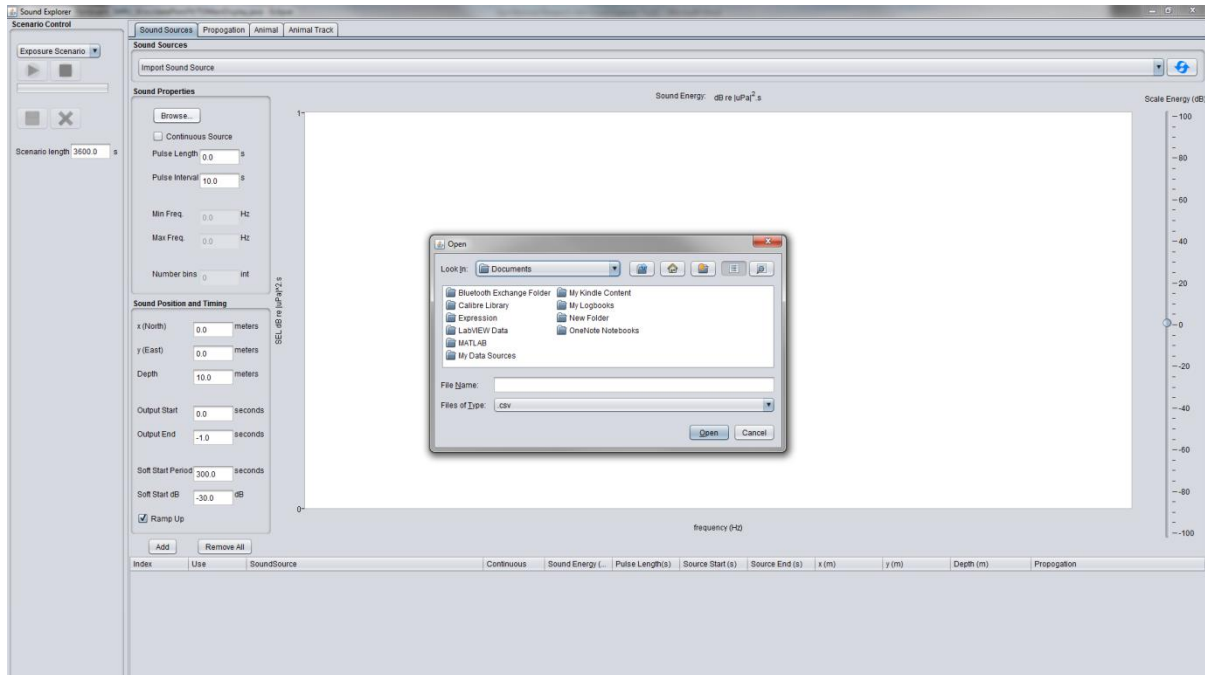
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Import Sound Source

Figure 5

The import sound source function allows the user to import sound source spectra from .csv files. This might be based on the users own measurements or new measurements provide in literature.
The file to be imported must be either of the following format.

Column 1: frequency bin start (Hz)
Column 2: frequency bin end (Hz)
Column 3: sound energy level for each bin in dB re $|\mu Pa|^2$

or

Column 1: frequency centre bin (Hz)
Column 3: normalised sound energy level for bin dB re $|\mu Pa|^2$
e.g. in excel this will look something like

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31.26954	185.7742
40.02418	191.7077
49.88089	196.1216
63	198.9436
79.56955	201.4161
101.1697	205.5282
127.7783	209.3632
162.4653	209.4356
202.4754	205.3835
259.1632	203.6469
325.149	205.5282
413.4149	205.0941
508.3972	202.2721
646.4082	201.6932
805.5983	200.8249
1003.992	198.6541
1285.083	198.22
1590.91	197.4964

Frequency centre bin in Hz

Sound Energy Level in bin dB re 1μPa^2.s m

Hint: Some example spreadsheets are included with Sound Explorer. Go to the sound explorer folder to find them.

2.2.4   Importing your own sound source

It is relatively easy for a user to generate a sound energy spectrum from their own recordings using an program such as Adobe Audition which will calculate a power spectrum and export values as a cvs files. This power spectrum data could then be imported into Sound Explorer using "*Import Sound Source*" and then scaled using the energy slider bar to match a known pulse energy value. This allows users to calculate a relative power spectrum, perhaps from a non-calibrated recording, and scale it to match a known pulse energy value for that particular sound source. Next users should define the pulse length of their sound source and the pulse interval. The pulse length is simply how long it takes for a sound source to output the energy specified in your spectrum. (For example a pile driver may output a 1 second pulse with a measured energy of 250 dB re 1μPa^2.s every 10 seconds. Therefore your total energy spectrum should be scaled so that it's total energy is 250 dB re |uPa|2.s, the pulse length is 2 seconds and the pulse interval is 10 seconds.

2.2.5   Box1. A worked example of importing and scaling a spectrum from a recording

On occasions a user might have a value for source energy level for a sound pulse and wish to combine this with a spectrum from an un-calibrated sound recording to derive a an acoustic energy spectrum. Here we provide a simple worked example using Adobe Audition 3 to generate an energy spectrum for an Airmar ADD from a field recording.

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Adobe audition 3 can be downloaded for free from
http://www.adobe.com/downloads/cs2_downloads/index.html

Start by using the editing tools in Audition to find a clean example of a sound pulse to make measurements from. The user might wish to use some of the built in tools to pre- process the data. This might involve normalising the amplitude and applying a filter around the frequency band of the sound source to minimise extraneous noise.Figure 1 for example shows the use of "Scientific Filters" to provide a band pass filter around the main frequencies of an Airmar ADD. Select *Effects> Filters and EQ > Scientific Filters*
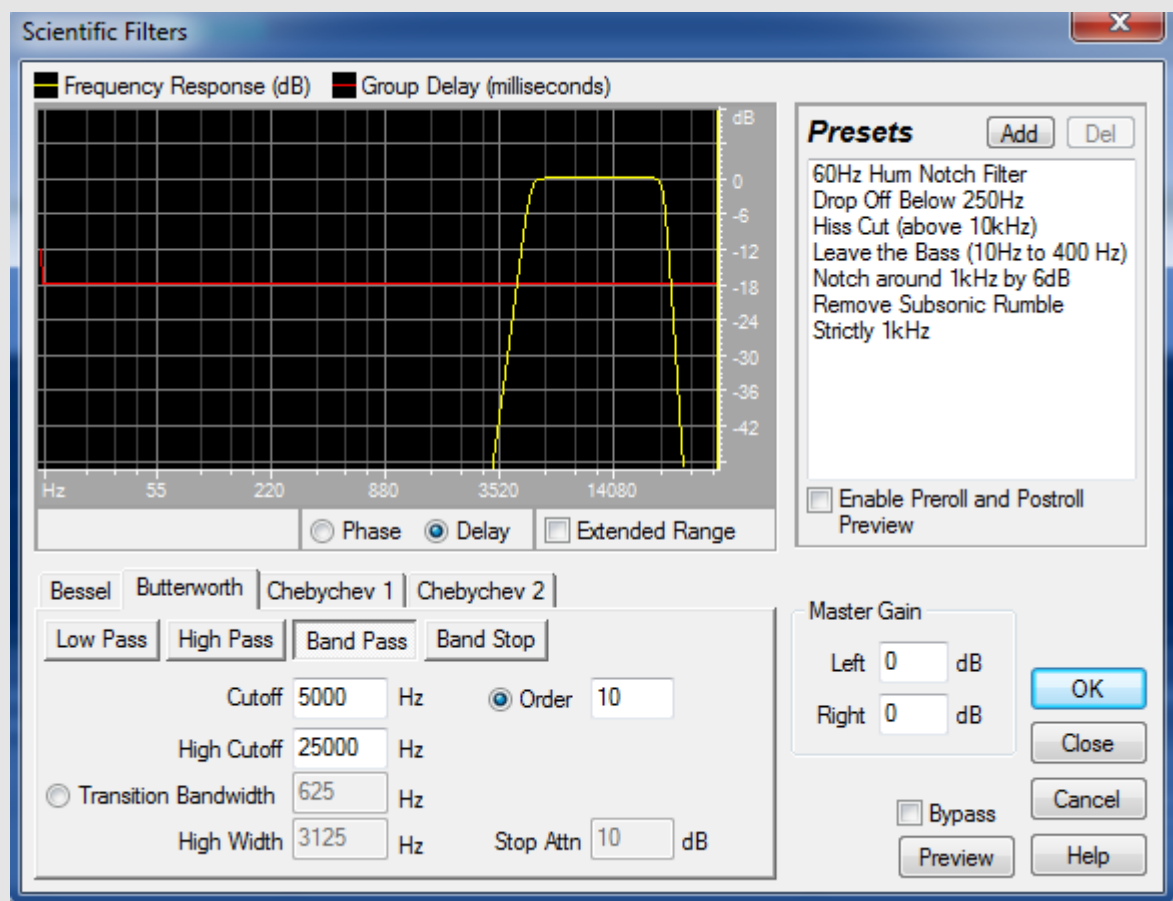

Figure 1.Scientific Filers to remove extraneous noise.

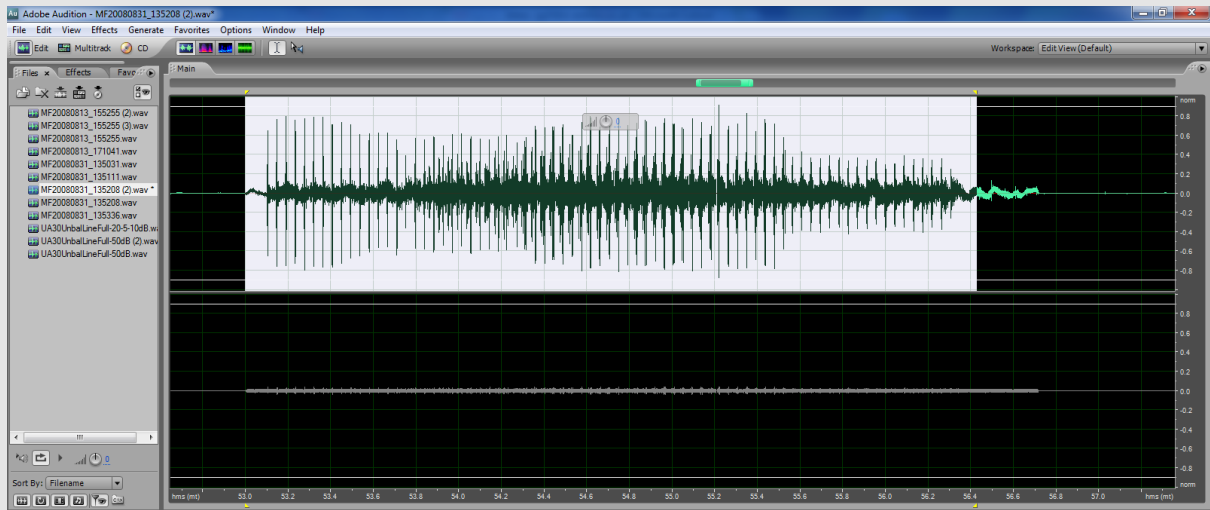Using editing tools zoom in to the sound of interest and select the section to be analysed, Figure 2.

Figure 2 Select the sound to be analysed

To calculate a spectrum select *Windows> Frequency Analysis* or *Alt Z*

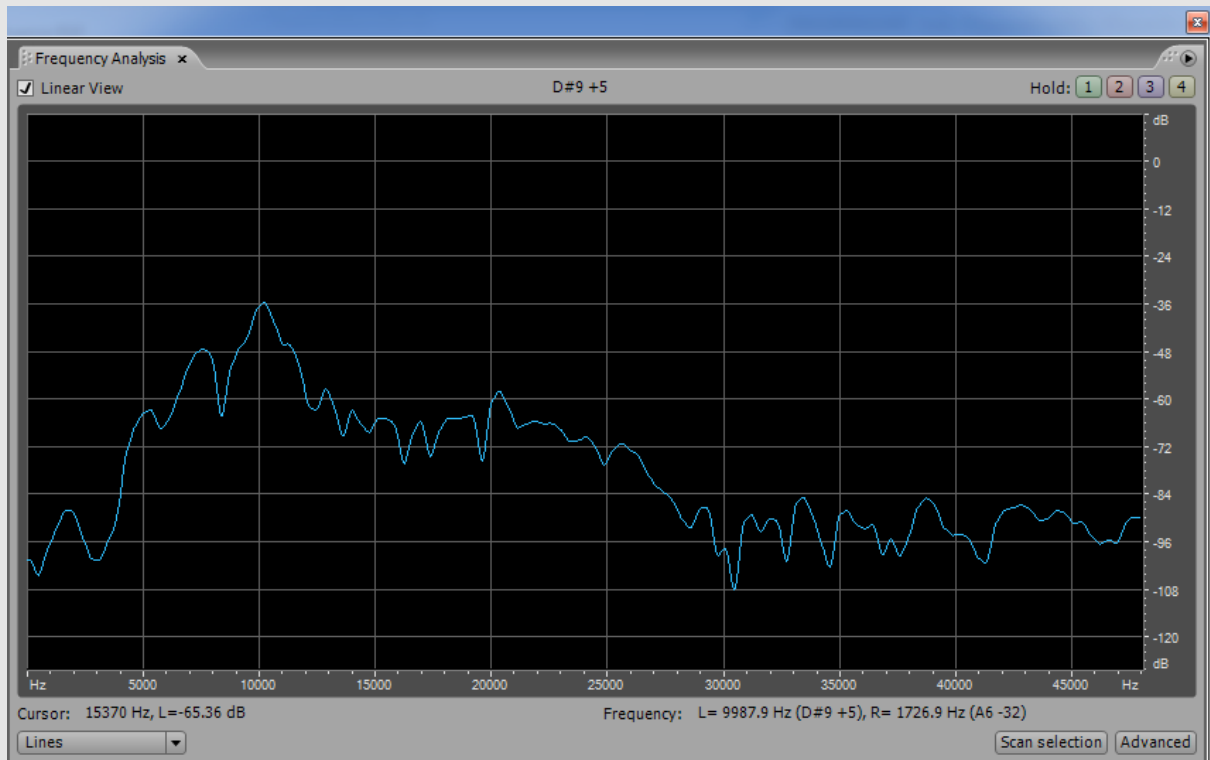*Figure 3   Spectrum plot*

Check the *Advanced tick box.* Choose appropriate spectral parameters (FFT size and filter type) and press *Scan Section* to generate a spectrum for the entire seletion.
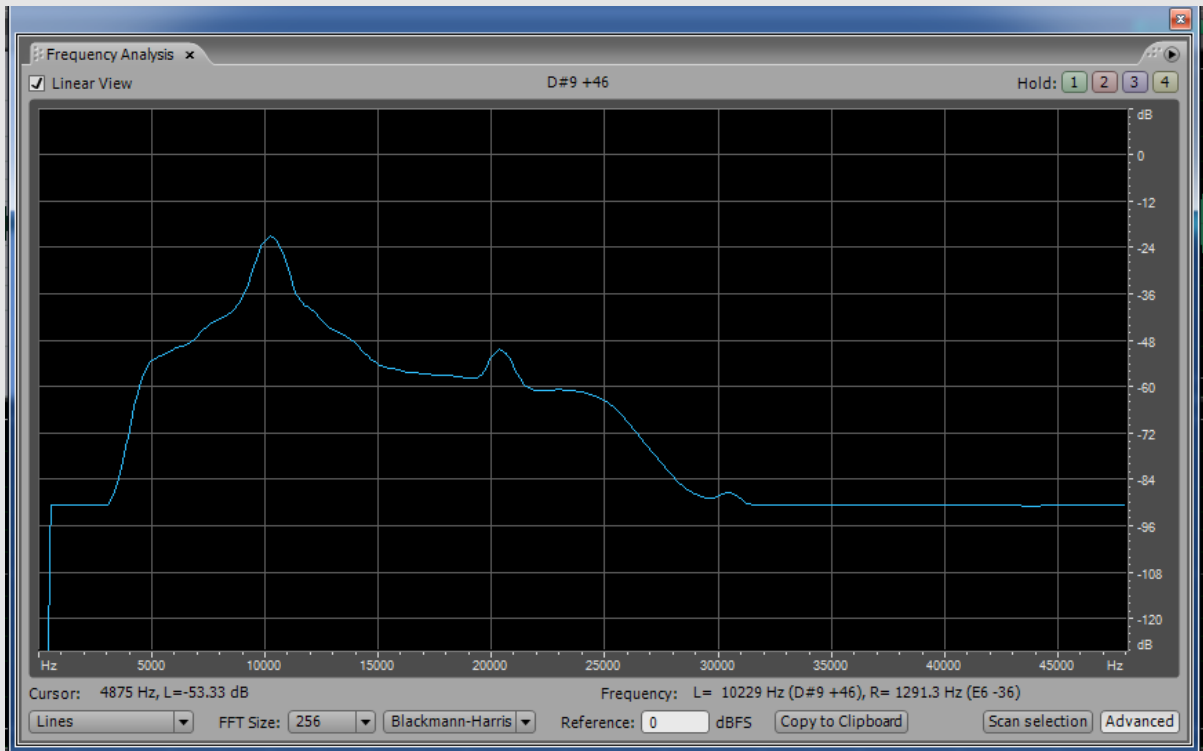

Figure 4. Spectral plot for complete selection

Click *Copy to clipboard* to copy the spectrum data to the clipboard. Now open Microsoft *Excel* or an equivalent program. Choose cell A:1 and paste

	A	B	C
1	Freq	Mono (Left)	
2	0	-588.0772705	
3	93.75	-33.14213181	
4	187.5	-42.68015671	
5	281.25	-48.30242157	
6	375	-46.8332634	
7	468.75	-47.37741089	
8	562.5	-48.10432816	
9	656.25	-48.94064331	
10	750	-50.79341126	
11	843.75	-52.72119904	
12	937.5	-53.85743332	
13	1031.25	-54.49634171	
14	1125	-55.46873093	
15	1218.75	-56.27044296	
16	1312.5	-56.83541489	
17	1406.25	-57.12096024	
18	1500	-57.3961525	
19	1593.75	57.24550247	

A table of frequency and decibel power levels for the spectrum can now be seen in the spreadsheet. The decibel levels are all negative however and the next step is to add a value to these to bring the maximum within 100 dB of the pulse total energy (the slider control in Sound Explorer can be used for final adjustments). Examine the spectrum plot in Audition to gauge what value to add.

In Excel move column B to Column D

Ctrl X > Ctrl V

In the empty column enter a formula to add an appropriate value, in this case 160, to D

	A	B	C	D	
1	Freq		#VALUE!	Mono (Left)	
2	0		=D2+160	-588.077	
3	375		69.08435	-90.9156	
4	750		69.11406	-90.8859	
5	1125		69.09444	-90.9056	
6	1500		69.00009	-90.9999	
7	1875		68.91393	-91.0861	
8	2250		68.88923	-91.1108	
9	2625		68.96658	-91.0334	
10	3000		69.72904	-90.271	
11	3375		75.48294	-84.5171	
12	3750		85.01694	-74.9831	
13	4125		95.67309	-64.3269	
14	4500		103.1526	-56.8474	
15	4875		106.6731	-53.3269	

Then copy this formula to all the cells in Column C

Next select and copy the whole of column C and paste it as values to column B using the option in *Paste Special*.

Column C and D should now be deleted and the resulting two column sheet can be imported in the Sound Explorer.

Import into Sound Explorer

Select the **Import Sound Source** pane, click the **Browse** button and import your .csv file. You should now see the imported spectrum in the spectrum graph The next stage is to scale the total energy of across the spectrum (shown above the spectrum plot) to equal the known pulse source level. This can be achieved using the scale bar on the right side of the graph. You will see the total energy of the spectrum change above the plot as you move the slider.

For this example we used a source level from

Move the slider to the correct energy, select the correct pulse length and interval and add the source to the scenario.
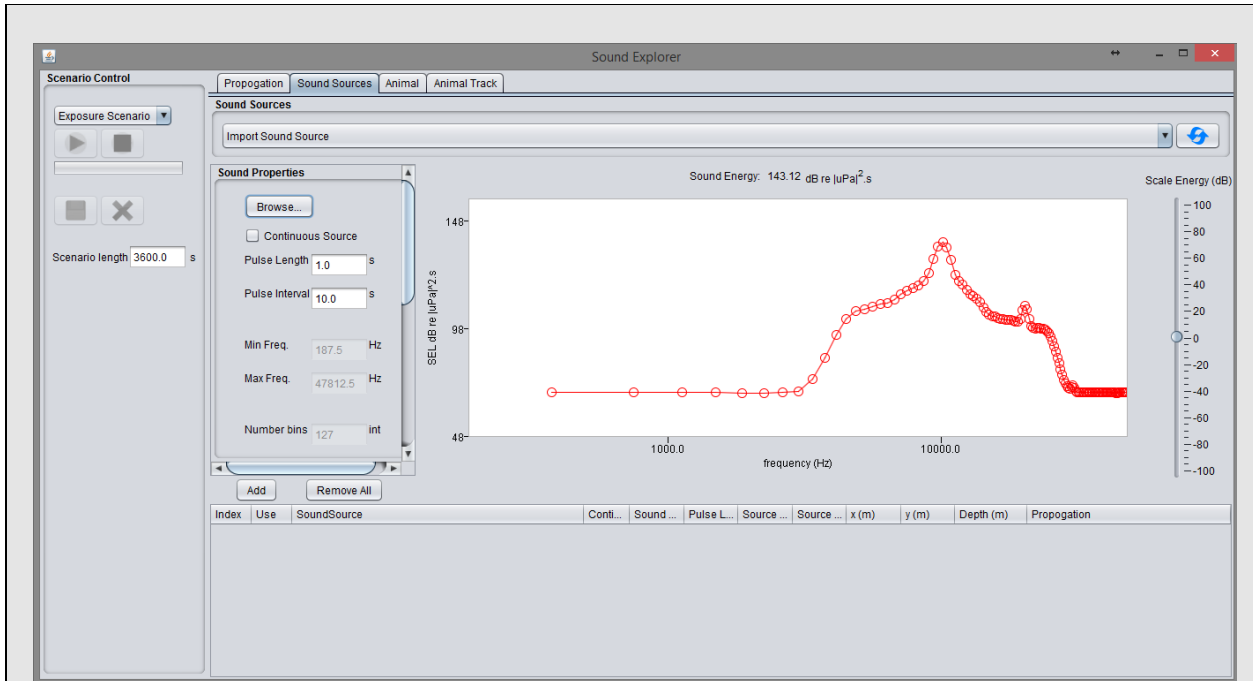
Figure 6. After importing into Sound Explorer, the ADD energy spectrum will look like this.

Use the slider bar to adjust levels until the total pulse energy (across the whole spectrum) is equal to the known pulse energy. In this case we use values for Airmar ADD characteristic from(Lepper *et al.,*, 2004) whoa source power level 192dB re µPa RMS @ 1m and a pulse length 2.25 seconds. To calculate the acoustic energy in the pulse we add$10\log_{10}(2.25)$ to 192 dB to get 195.5 dB re JAMIE $|µPa|^2$. Now you have an imported spectrum ready to use.

2.3   Animal

The "animal" pane allows parameters relating to the subject's frequency specific acoustic vulnerability weightings and thresholds for onset of impacts such as temporary and permanent threshold shifts to be specified. The frequency weighting and thresholds for the five functional group proposed by (Southall *et al.,*, 2007), often termed "M" weightings, are provided as lookup values and other values can be specified by the user.

M Weighting and Specifying Alternative Functions

Southall et al, (2007) provided frequency weightings for four underwater marine mammal groups and a fifth group of pinnipeds in air.

Theses functions are all described by an equation of the form

$$M(f) = k + 20log_{10}\left(\frac{f_{high}^2 f^2}{(f^2 + f_{high}^2)(f^2 + f_{low}^2)}\right)$$

Were: $M(f)$ is the frequency dependent filter in dB for animal hearing

k is a constant, f is the frequency,

f_{high} is a defined maximum frequency and

f_{low} is a defined lowest frequency and.

The values proscribed by Southall et al (2007) are shown in the table below,

Functional Hearing Group	K	f_{low}(Hz)	f_{high}(Hz)
Low Frequency Cetaceans	0	7	22000
Medium Frequency Cetaceans	0	150	160000
High Frequency Cetaceans	0	200	180000
Phocids in Water	0	75	75000
Phocids in Air	0	75	30000

Customised weighing functions can be calculated by substituting alternative values for these parameters.

Southall et al (2007) also proposed thresholds for the onset of temporary threshold shift (TTS) and Permanent threshold shift (PTS) for each marine mammal group.

Functional Hearing Group	PTSdB re |uPa|^2	PTSdB re |uPa|^2
Low Frequency Cetaceans	198	215
Medium Frequency Cetaceans	198	215
High Frequency Cetaceans	198	215
Phocids in Water	186	203

NOAA currently have revised guidelines out for review. Once these have been accepted they could be incorporated as a different type of animal.
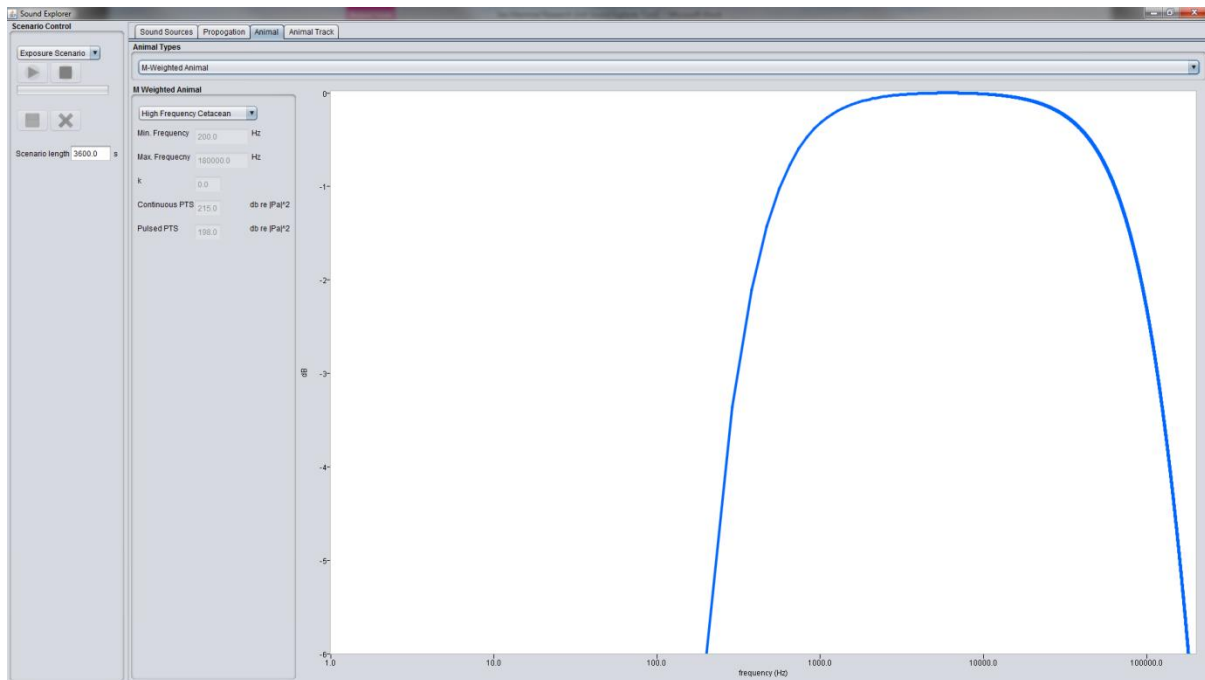
Figure 7 A marine mammal weighting function.

2.4 Animal movement

The final parameter to specify is how the animal will move over the course of a noise exposure. Currently Sound Explorer has one type of animal movement, ' Escape Tracks': the subject moves away from the sound source over the course of the exposure at a constant net speed, starting from a specific location while maintaining a constant depth.

Because movements of animals in response to sounds are poorly known and likely to be variable it will always be sensible to specify a range of escape speeds. These can be defined in the 'Escape Track' panel by specifying a minimum and maximum speed and the number of of equally spaced speeds between these values for which to run the simulation. By default, the escape track simulates an animal moving away on a single bearing directly away from the sound source. However multiple bearings can also be specified by defined a min angle, max angle and no. of angles to test between these values. Multiple bearing might be considered when sound sources are not all located at (0,0,z).

NOTE Bear in mind that the escape speed is the net rate at which the animal moves away from the sound source. It will be somewhat less than speed through the water because the animal's course may not be a straight line and there is likely also be a vertical component to their movementresulting from the animal's diving behaviour.

Animal Depth. Currently the utility only allows for the animal to remain at a single depth. To be precautionary, this should be set to the depth of the loudest sound source.

3 Run

Once all of the sound sources and a propagation model for each have been added, a set of animal tracks has been defined and an animal type selected the scenario is ready to be run and the ***Run*** button will turn green. Clicking the run button will start calculations and a progress bar will show the progress of the run. Once the run is completed a series of graphs showing results will appear. Currently there are three sets of results calculated for the Exposure Scenario: the total sound exposure v animal speed the minimum range before PTS occurs v animal speed and the total sound exposure versus animal range from sound source(s).

SEL v speed.

Sound exposure level (SEL) is the total cumulative sound exposure over time. All energy received by the animal is summed to give a final SEL in dB re $|\mu Pa^2|$.s The results shown indicate the total sound exposure for different track speeds. In scenarios with more complex tracks values for the average track speed are plotted.
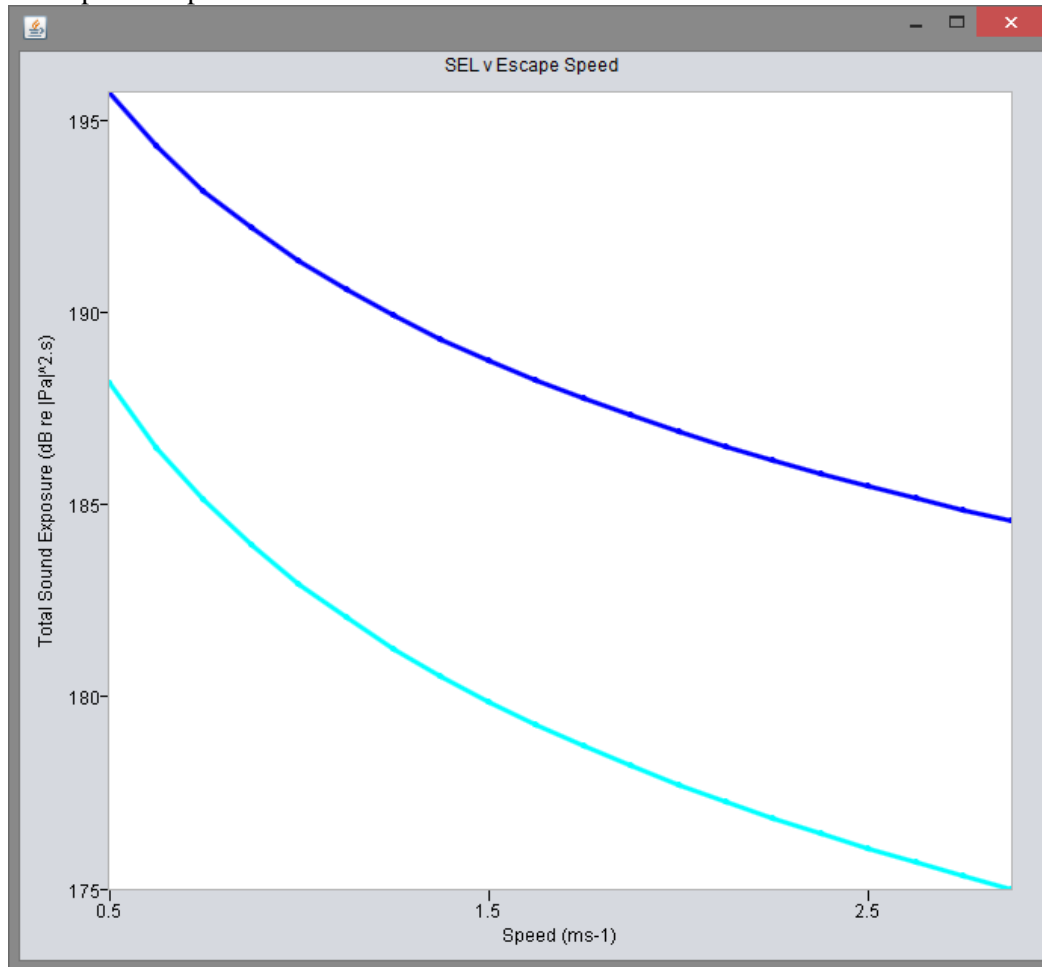

Figure 8. Graph of cumulative sound exposure over the scenario period versus average speed of animal track. Here two scenarios have been run with different propagation conditions, hence there are two results on the graph.

Maximum PTS Range. The maximum PTS range is the greatest initial starting range in meters that an animal can be at the beginning of a sound exposure scenario for the thresholds for PTS or TTS to be exceeded. For example, if the minimum range is 100m for 1ms^{-1} then animals moving away at 1ms^{-1} from the sound source at 100m or less will exceed the specified total SEL PTS threshold while animals at greater ranges will not. This can be considered as a minimum value for a safety exclusion zone for animals at the start of a noisy activity under the assumption that animals move away from it at the specified (or greater) speed.

The results graph shows three possibilities. 1) Along the defined track there is a range at which, if exceeded means the animal will not exceed PTS threshold. This is shown by a data point on the graph. 2) At every range calculated along the track PTS occurs. This results in a red data point . 3) At no point on the track PTS occurs. This results in a green data point at range 0.
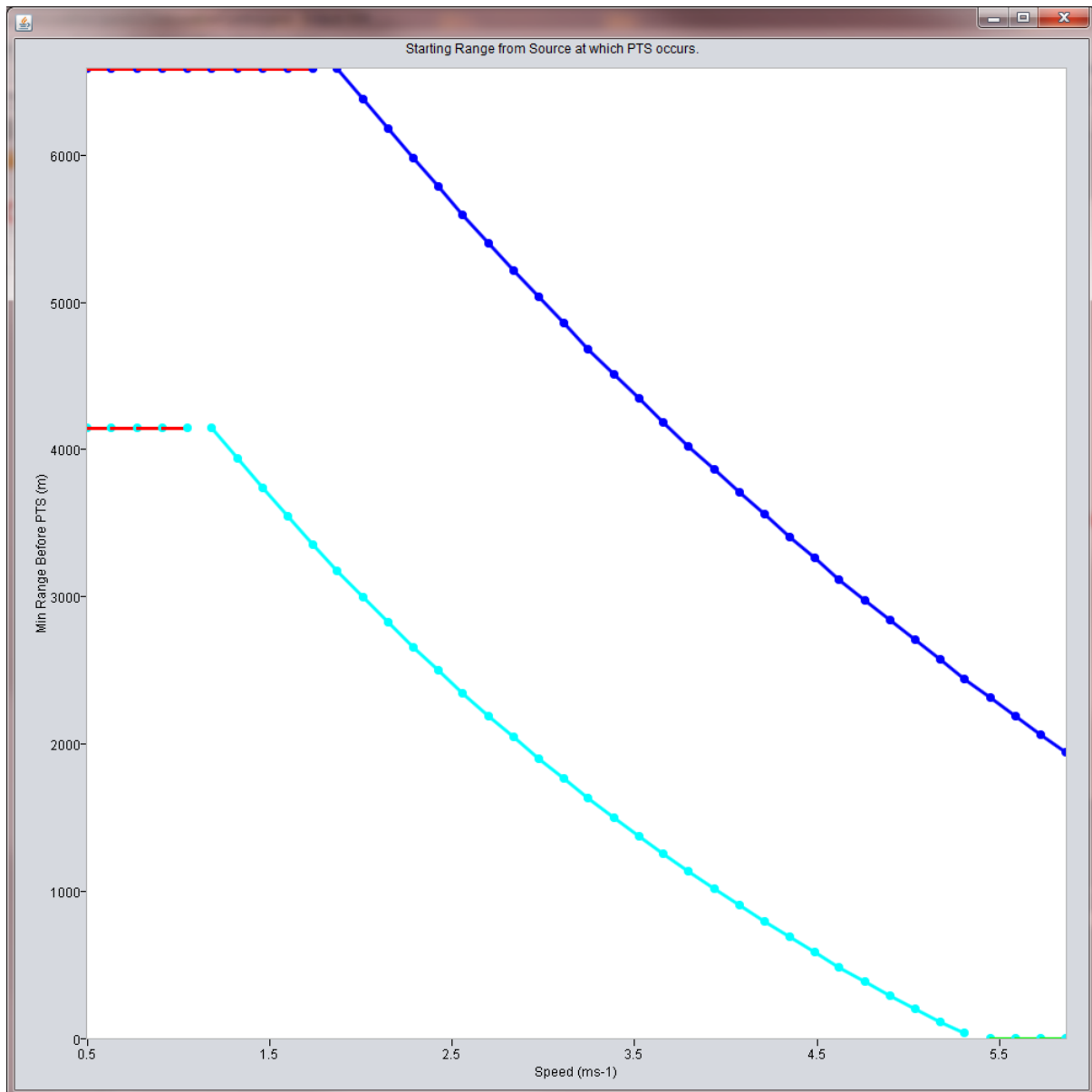
Figure 9. Graph showing the minimum range to the source before total sound exposure will exceed the animal's PTS threshold. The PTS results graph shows three possibilities. 1) Along the defined track there is a range at which, if exceeded means the animal will not exceed PTS threshold. This is shown by a standard data point on the graph. 2) At every range calculated along the track PTS occurs. This results in a red data point. 3) At no point on the track PTS occurs. This results in a green data point at range 0.

Total Sound Exposure v Starting Range of Individual tracks.

The total sound exposure v starting range calculates and plots the total sound exposure for animals with a series of different starting ranges. For more complex tracks the algorithm finds the first point on the track which is at the correct range and then analyses total exposure from there. The graph will have a line for each track which has been added to the scenario.
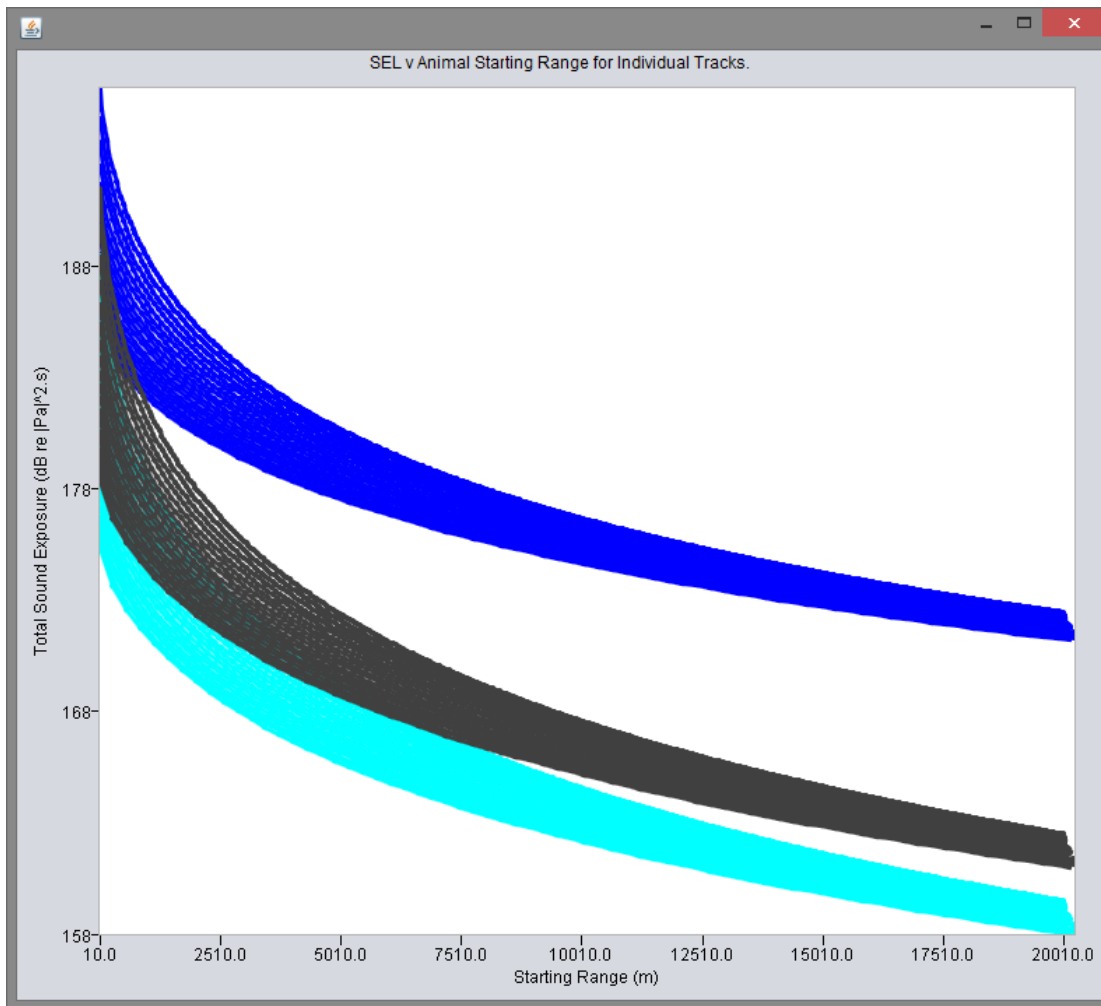
Figure 10. For each run the animal has a different range to the sound source at the start of the scenario. Total exposure is then calculated for each of these different ranges. This mean that each track has an individual line on the graph.

3.1 Multiple runs

Sound Explorer can run a set of scenarios multiple times with different sets of parameters. Results from different runs are plotted on the same graphs using different coloured lines as shown in Figure 8 and Figure 10. To delete all runs and start again press the *delete all* runs button below the run and scenario selection panel. Note this will delete all runs permanently unless the results have already been saved.

3.2 Saving runs

The results from all runs remain in memory until the delete button is pressed and these can be saved at any time by pressing the save button. A dialog box will appear asking for a folder in which to save results to be selected. Runs are numbered incrementally and each run also has a metadata file summarising settings for that run. These raw data are then available to be plotted in different ways using alternative programs and/or for further analysis

> **Hint :** To clear all results from memory press the red clear results button next to the save icon. This will delete all data from memory and the graphs- if not saved results are irrecoverable.

3.3 Using saved results

Results from sound explorer are saved in .csv files. These can be opened in most spreadsheet type applications, including Microsoft Excel. Results for each graph are saved to a folder. If multiple runs have occurred then .csv files for each output graph contain the results data for each run. These are labelled run 0, run 1, run 2 etc. When saved a metadata file will also be created for each scenario run, detailing settings for that scenario run, including the sound source spectrum(s) used.
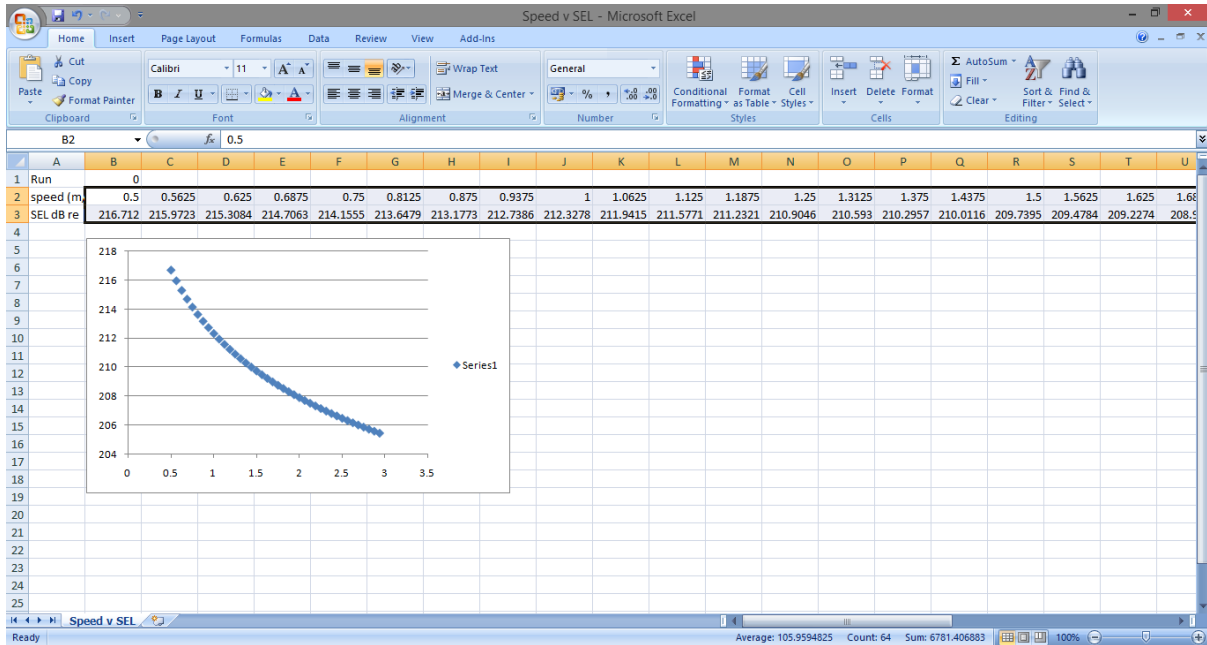

Figure 11. In Excel it is easy to plot exported results. Simply drag a box over a the results for a run, go to Insert Tab, click the scatter button and choose the 'scatter with markers' graph.
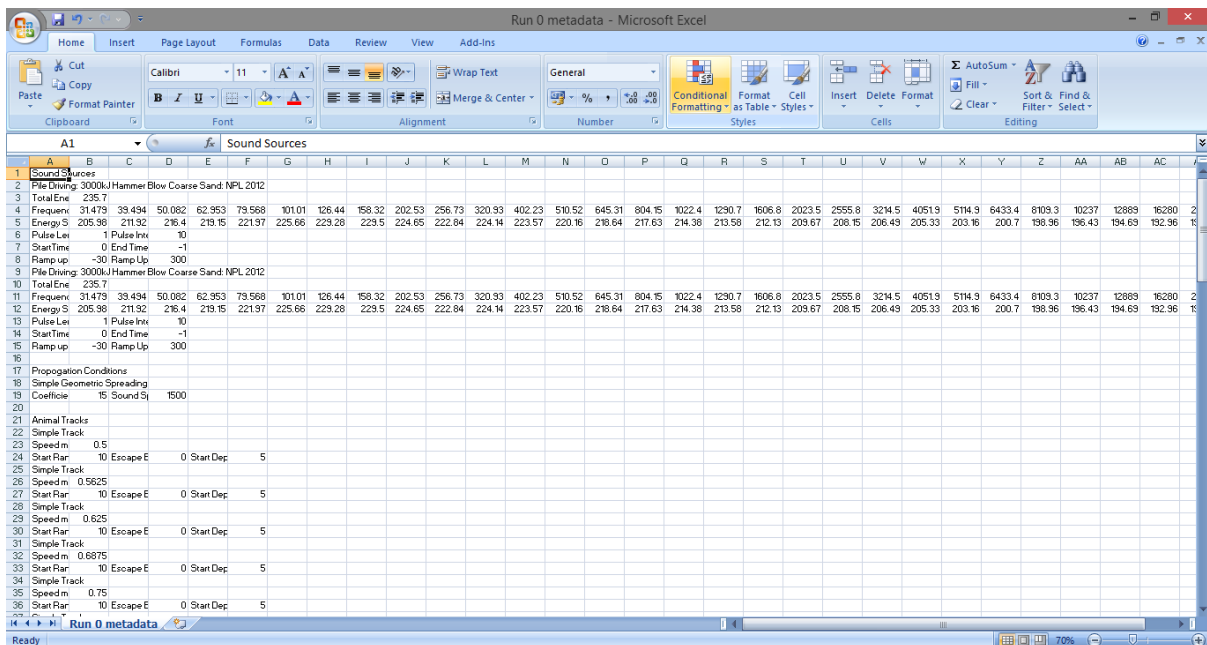

Figure 12. Each run has a metadata file which contains all parameters used for that run. This can also be useful for exporting a sound spectrum, as each sound source spectrum is saved for each run.

4 Envisaged Enhancement and Updates

4.1 Sound sources

More data on sound source characteristics will become available as new measurements are made. Some of these could be incorporated as pre-determined sound sources in the program and/or a library of Excel files could be built up to be imported as required.

4.1.1.1 *Importing future sound sources*

Importing a .wav file or other recording of a pile driving pulse and converting to a spectrum would be convenient for users and allow a lot more flexibility. This might be streamlined by developing code within PAMGuard API.

4.2 Propagation

The existing propagation models are simplistic. We envisage that more sophisticated options might be required in the future

Underwater sound propagation has been extensively researched and good predictions of propagation loss can usually be achieved provided the local sound speed profiles and detailed underwater topography and bottom type data are used in a model which is appropriate for the type of sound being considered. Files of propagation loss predictions from sophisticated propagation loss models could be imported into the SEE to provide improved exposure modelling. Many of these propagation models have been made freely available at sites such as http://cmst.curtin.edu.au/products/actoolbox.cfm.

Another alternative would be to incorporate sound fields measured at the sites of interest.

The structure of the SEE program allows for both of these scenarios.

4.3 Species filters and thresholds

4.3.1.1 *Potential future updates for animal types*

Work on the effects of noise on marine mammals and how to predict safe thresholds for the onset of acoustic impacts is ongoing, especially in the USA. New studies are likely to lead to alternative species sensitivity filters and revised thresholds for the onset of effects such as TTS and PTS. Indeed, NOAA is currently in the process of reviewing its "Damage Criteria" and their draft document suggest that their recommendations for both filers and thresholds will change. New values for these parameters should be added to the sound explorer code as they become available.

4.4 Animal movement

The existing animal movement model, an animal fleeing at a fixed depth, is extremely simple. It is certainly unrealistic to assume that an air breathing animal would stay at a fixed depth and an interesting elaboration would be to "allow" the animals to follow typical dive profiles and explore how this affects sound exposure. Any number of more complicated movement models could be easily coded though at the moment there is no reason to expect any of these to apply. Another future elaboration would be to use tracks of animals measured using telemetry, as yet however, we are unaware of any such data having been collected.

5 Some comments on parameter values

From (Gordon *et al.,*, 2007)

Notes on Escape Speeds

The manner in which animals move in response to pile driving noise and to any AMD signal employed is an important parameter in the model which has a very significant bearing on a subject's cumulative exposure. While it would seem logical that animals should move away from a powerful noise source, there are no reliable data quantifying short term animal movements in response to pile driving noise. However, here we assume that the animals move directly away from the sound source and we use theoretical considerations and field observations to suggest an escape speed.

In many larger swimming animals, oxygen consumption increases rapidly as speed increases beyond the energetic minima for transport, and this has the effect of constraining maximum swim speed for long range movements. In porpoises, Otani *et al.,*(2001) found that during most dives porpoises swam relatively slowly (0.76-0.91 m/s) and the minimum cost of transport occurred at between 1.3 and 1.5m/s. In grey seals Sparling & Fedak (2004) showed that, as predicted, metabolic rate increased with swim speed resulting in shorter dives for higher swim speeds. The maximum swim speed they observed during dives was 1.4 m/s. A range of escape speeds between 0 and 1.5m/s thus seem reasonable to explore in the model.

Additional considerations - porpoise may be accompanies by calves in which case this may limit escape speeds. Same might hold for common seals in close to land.

A seal fleeing from an airgun had an average net displacement of ~.9km hr =0.25 m s -which is very low

6 References

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