Supplemental User Guide for Applying NMFS 2018 Sound Exposure Guidance Alternative Methodology to Geophysical Survey Sources

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BACKGROUND ON REGULATORY ASPECTS OF MANMADE UNDERWATER SOUND

In 2016 and again in 2018, the National Marine Fisheries Service (NMFS), a United States regulatory agency within the Department of Commerce's National Oceanographic and Atmospheric Administration (NOAA), promulgated guidance for estimating hearing risk to marine mammals from manmade sound. As the primary U.S. regulatory agency responsible for administering the Marine Mammal Protection Act (MMPA) (NMFS, 2018a), NMFS is responsible for assessing the potential risk to marine mammals from a variety of activities, including those that emit sound underwater. The guidance is based on an estimation of the range at which a specified sound source might produce a Permanent Threshold Shift (PTS) in hearing (a minor partial permanent hearing loss). The PTS threshold itself is a conservative, precautionary estimate of the potential onset of slight partial hearing loss (Southall et al 2019; NMFS 2018a) and is sometimes used as a surrogate for the regulatory metric of Level A Harassment, though no regulatory or judicial opinion has been rendered on the equivalence of slight partial PTS to Level A Harassment. This should be considered during the process of risk estimation for an activity in which other conservative precautionary assumptions will additionally compound the over-prediction of risk.

Due to the complexity of the initial NMFS guidance (2018a) and the challenges it can present to both expert and non-expert users, NMFS (2018b and 2020) also developed a simplified tool using Microsoft Excel for quickly and easily calculating ranges where the onset of PTS might be of concern (referred to as "isopleths"). NMFS referred to the simplified spreadsheet tool and guidance as an Alternative Methodology (AM) to the NMFS 2018a guidance. In reviewing and updating the NMFS AM User Spreadsheet Tool and Guidance, we have come to the conclusion that the simplified methodology is NOT an acceptable or reasonable "alternative" to the 2018a guidance. However, IAGC recognizes that application of the full NMFS guidance (2018a) may be beyond the capabilities of some users. Therefore, we have provided revised materials consisting of a spreadsheet tool and user guide for that spreadsheet tool, intended to provide a more realistic isopleth calculation. It should be noted that IAGC strongly cautions against the application of the AM spreadsheet tool when possible. We highlight scenarios in which the Alternative Methodology is particularly inappropriate in the body of this document.

The initial aim of the simplified process for deriving PTS isopleths was to provide a less computationally difficult risk estimator without departing too far from the underlying science behind the NMFS 2018a guidance. As this iteration of the User Spreadsheet Tool and Guidance clearly documents, this simplified AM tool should not be treated as equivalent to or even roughly comparable to the 2018a guidance, and should most definitely not be used for MMPA Level A take estimation or regulatory decision making. Unfortunately, the NMFS Alternative Methodology has already figured in at least one MMPA permitting request and authorization (e.g. H.T. Harvey and Associates, 2019) in spite of concerns about the technical utility of the User Spreadsheet Tool. We have done our best to document those concerns and urge users to limit their reliance on the NMFS AM User Spreadsheet Tool to initial, cursory, internal planning activities, intended to lead to a fuller treatment of the produced sound and its potential risk to marine mammal species.

This document is intended to correct some, but not all, of the problematic features of the 2018(b) and 2020 NMFS AM Spreadsheet Tool, most specifically for Tab F as applied to compressed air (CA) sound sources used in geophysical research and exploration surveys. (Indeed, it is not possible to fully analyze the complexities of underwater sound and its interaction with marine mammals using a simplified model.) The aim is to help the user resolve some ambiguities and difficulties associated specifically with the impulsive sound produced by compressed air sound sources or "air guns". For example, the 2018b NOAA Optional User Spreadsheet Tool and User Guidance presents multiple opportunities for the inadvertent entry of incorrect information by the user whereas this Supplemental Spreadsheet Tool and Guidance minimizes the risk of incorrect data entries, and provides more detailed guidance about the choice of values to enter into the spreadsheet tool; all with the goal of reducing the likelihood of user errors in the risk estimation process or misunderstanding by the user of the pre-existing NMFS guidance and associated user tools.

Although this version of the User Spreadsheet Tool offers some improvements over the original NMFS 2018b User Spreadsheet Tool it is probably incorrect to characterize that 2018 (v.2) User Spreadsheet Tool or this proposed supplemental analysis as an "Alternative" to the full NMFS (2018a) Guidance. In this document we highlight some of the as-yet unresolved problems with the AM User Spreadsheet Tool methodology for calculating cumulative SEL isopleths, as well as issues with propagation of sound in shallow water or other special oceanographic conditions, and the problem of chemical absorption of higher frequencies of sound. The issue of chemical absorption of sound at increasing sound frequencies effectively renders all predicted isopleths greatly over-predictive of actual PTS isopleths, most especially for the High Frequency Cetacean (HF) hearing group.

In summary, the User Spreadsheet Tool, even in its currently proposed version, is not a viable alternative to the NMFS 2018a guidance. At best, it can indicate when ranges to PTS are *not* a factor worthy of the time, expense, and effort of fully modeling, or when full ocean acoustic modeling is not only desirable but necessary to facilitate fact-based decision making. Throughout this document we draw the user's attention to physical and biological circumstances that should give the user pause regarding application of the AM User Supplemental Guidance as an alternative to more complete modeling and analysis during regulatory decision-making processes.

EXECUTIVE SUMMARY

This Supplemental User Guide is in three sections:

- New Supplemental Guidance and Tools (Section A) offers amendments to the 2018 NMFS Optional User Spreadsheet Tool, v.2 plus additional tools to help users who may not possess all of the information needed to complete the Optional Spreadsheet Tool, including:
  - A simple conversion tool to help users easily convert sound pressure levels from common geophysical industry units like Bars or Pascals to dB SPL re 1 microPascal[1];
  - A tool to generate hearing-weighted SEL values from default 1/3 octave frequency bands (TOB) replicating the frequency spectrum of a derived Generic Pulse (substitution of user-provided TOB values unique to the user's source is possible, as well); and
  - An Appendix detailing the process by which TOB default values for a Generic Pulse were generated.
- Section B flags those problem areas within the current (v.2) User Guidance and Optional Spreadsheet tool (NMFS 2018b) needing correction or improvement, and provides a rationale for the proposed changes that were addressed in the new User Spreadsheet Tool (Section A);
- Section C provides Background and Context for those desiring more in-depth information about the operational characteristics of compressed air (CA) sound sources ("air guns") and the sound they produce.
- Appendix A provides detailed information about the sources of frequency spectra used to generate a Generic Pulse spectrum for the proposed revised Supplemental Guidance.

[1] A Glossary is provided at the end of this document to help define terms-of-art or abbreviations used in this document.

We recommend that all users, including expert users, read the Background and Context (Section C) to familiarize themselves with the sometimes complex and non-intuitive aspects of the CA sources commonly used in geophysical research and exploration.

Section B describes the potential sources of user errors in the application of the current User Spreadsheet Tool and some of the underlying precautionary assumptions that render predictions of risk from the User Spreadsheet Tool (v.2) much higher than predictions that would result from applying the NMFS 2018a guidance with a more sophisticated modeling approach. Illustrative examples are provided.

Section A provides modifications to the User Spreadsheet Tool and Guidance that will prevent some, but not all, of the most common problems with the current (v. 2) NMFS spreadsheet and guidance. The proposed revisions to the User Spreadsheet Tool and Guidance also provides a Generic Pulse energy spectrum for users who do not possess frequency spectrum data specific to their own CA sound source. The provided Generic Pulse spreadsheet tool is based on the spectra from a variety of array sizes and configurations. Users should substitute their own source level information, pulse duration, vessel speed, pulse repetition rate and pulse frequency spectrum, if known.

Since marine seismic surveys have historically used non-SI (non-metric) units of measure (e.g., cubic inches, pounds per square inch and bars), a simple calculator tool is also provided to convert sound source properties that may have originally been expressed in bar (bar-meter) or an SI unit like Pascals into the decibel metrics used in the NMFS guidance.

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LIST OF ACRONYMS

4D	Four dimensional, meaning spatial change over time. In the context of this document 4D refers to modeling of the propagation of sound, such as CA array sound, through the 3D volume of the ocean over time. Sound may be reflected off the air-water and substrate-water boundaries and may be refracted (bent) by layers of water with different densities and thus different sound speeds. Broadband sounds like CA array sounds, which contain many frequencies, will also be spread in time as they travel, much as light is broken up into its component colors by a prism. Such modeling is computationally intensive, and usually expensive of both time and money, so simpler models like the User Spreadsheet Tool may be used to approximate sound propagation through the water, with decreased realism or accuracy of model predictions relative to a full 4D model.
AM	Alternative Methodology. The term applied by NMFS to a spreadsheet tool and guidance (NMFS, 2018b) offered by NMFS as a simpler alternative to the implementation of their original PTS risk guidance (NMFS, 2018a)
ANSI	American National Standards Institute. For all US standards of acoustic measurement, ANSI is administered by the Acoustical Society of America (ASA).
Bar	is a non-SI unit of pressure often used to express the acoustic output of CA arrays and other geophysical survey sound sources. A bar is equal to 100,000 Pascals or roughly equivalent to the atmospheric (barometric) pressure at sea level.
CA	Compressed air, referring to the most commonly used type of sound source used in marine geophysical survey. Also colloquially known as “air guns”. See Section C.1.
cui	Cubic Inches. The volumes of compressed air sound sources (air guns) are typically expressed in cubic inches rather than SI terms like liters (l) or cubic centimeters (cc).
dB	the decibel (one tenth of a Bel) is a logarithmic ratio expression of acoustic pressure values, and as such it is referenced to a reference value, typically in Pascals (e.g. re 1µPa). The Bel is named after Alexander Graham Bell, and is a logarithmic scale used to express sound pressure levels in smaller numbers than if Pascals were used.
Duty cycle	Duty cycle refers the ratio of sound-on to sound-off for intermittent sound sources such as sonars or geophysical survey sound sources. The typical duty cycle of a CA array is 0.01 or 1 %, since the CA sound, with a duration of less than 0.1 second, occurs approximately every ten seconds (0.1/10 = 0.01).
EARS	Environmental Acoustic Recording System. In this document, EARS refers specifically to a type of underwater sound recording device developed by George Ioup and associates at the University of New Orleans and the Naval Research Laboratory at Stennis, Mississippi for the recording of CA array sound and other marine environmental sounds, including marine mammal sounds.
ESA	Endangered Species Act.
HF	High Frequency, referring specifically to the High Frequency Cetacean Hearing Group, consisting of porpoises and related species of high frequency-hearing specialist marine mammals (also see MF Cetacean Hearing Group).
HRG	High Resolution Geophysical survey, which typically involves a non-CA sound source like a multi-beam sonar. HRG surveys are typically used to resolve more structural detail of the geology at shallower depths than a full CA survey, for the purpose of surface mining of sand or gravel, determining pipeline routes or assessing pile driving sites. But even if CA sources are used, they are fewer in number and not configured like a typical CA array.
Hz	Hertz, the SI unit for sound frequency (1 pressure oscillation or cycle per second = 1 Hz). The normal range of hearing for humans is 20 Hz-20,000 Hz (20 kHz). The normal range of hearing

	for marine mammals varies by group, and can be considerably lower in frequency for LF Cetaceans (7 Hz) or considerably higher for HF cetaceans (up to 180 kHz).
IAGC	International Association of Geophysical Contractors. A non-profit trade association representing the geophysical survey industry.
km	An SI unit of length/distance measurement. 1 km = 1000 meters.
IOGP	International Organization of Oil and Gas Producers.
ISO	International Standards Organization. ISO sets global standards for a variety of physical and engineering terms and measurements. ISO coordinates with ANSI (see) to develop global standards for the expression of acoustic terms and measurements.
Isopleth	Isopleth refers to a line of constant values like topographic lines on a map or depth contours on a navigational chart. In the context of this guidance, Isopleth refers specifically to the radial distance from the CA sound source to the decibel level thresholds for the onset of small, partial PTS (see). The isopleth is the radius of a horizontally circular, and vertically cylindrical volume of water centered at the sound source. The isopleth is assumed to demarcate some unspecified level of risk of PTS in animals within the cylindrical volume of water established by the PTS isopleth.
km	Kilometer, a unit of distance equal to 1000 meters. One kilometer equals approximately 0.6 miles.
LF	Low frequency, referring specifically to the LF Cetacean Hearing Group, consisting of the large baleen whales.
m	Meter, an SI unit of length measurement, as in 30m = 30 meters.
m/s	Meters per second, an SI unit of measure of speed/velocity. A vessel speed of 5 knots is approximately equal to 2.5 m/s.
msec	An SI standard unit of time measurement. A millisecond = 0.001 second.
MF	Mid-frequency, referring to the delphinid cetaceans with high frequency adaptations for biosonar, but lacking the higher hearing range and greater sensitivity of the HF Cetaceans (porpoises and related species).
MMPA	Marine Mammal Protection Act
NEPA	National Environmental Policy Act.
NMFS	National Marine Fisheries Service, a division of the U.S. National Oceanographic and Atmospheric Administration (NOAA) in the Department of Commerce. NMFS Office of Protected Resources (OPR) is charged with implementing regulations and guidance for compliance with the Marine Mammal Protection Act (MMPA), as well as the Endangered Species Act (ESA), where applicable.
OGP	Oil and Gas Producers, original name of the IOGP, a trade association representing oil and gas producers.
OW	Otariid Water – referring specifically to the hearing of otariid pinnipeds (sea lions and fur seals) in water (in comparison to their hearing abilities in air).
Pa	Pascal, the ISO and ANSI standard of measurement of sound pressure, e.g. dB SPL re 1 µPa-m. Sound decibels are typically referenced to microPascals (µPa).
psi	Pounds per square inch. The geophysical industry typically expresses compressed air system pressurization in psi, rather than SI units like Pascals or Newtons per square meter.
PTS	Permanent Threshold Shift refers to a permanent loss of hearing across some or all of an animal's hearing range. The loss may be complete or partial and may range from a narrow frequency notch to loss across the entire hearing range. PTS in the context of this document refers to the first onset of barely noticeable hearing loss across a narrow frequency range of 1/3 octave or less.

PW Phocid Water, referring to the hearing of phocid or true seals (as opposed to otariid seals) in water (as opposed to their hearing abilities measured in air).

SEL Sound Exposure Level, refers to the energy flux or sound pressure over time. A constant sound pressure of 120 dB for ten seconds would yield an SEL of 130 dB SEL. A constant sound pressure of 120 dB for one-tenth of a second would yield an SEL of 110 dB SEL.

SEL_{cum} Cumulative SEL refers to a methodology adopted by NMFS for assessing the hearing risk from multiple CA array sound pulses over a given period of time. The time-separated sounds are summed and treated as one continuous sound for the purpose of simplifying calculations of SEL.

SPL Sound Pressure Level. All SPL units are referenced to 1 microPascal.

SPL_{pp} Peak-to-peak Sound Pressure Level, or the entire pressure change from the peak emitted pressure to the surface-reflected phase-inverted pressure. See Section C.3.4.

SPL_{pk} Peak sound pressure level or zero-to-peak Sound Pressure Level as measured for the initial primary pulse of a CA source. See Section C.3.4.

SPL_{rms} Root Mean Squared Sound Pressure Level. Root mean squared refers to the method of determining the average pressure, since decibel SPL values are on a logarithmic scale and cannot be average arithmetically. Root Mean Squared SPL should carry a metric for the time period over which the averaging occurs. Unless otherwise stated, the reference metric for all SPL_{rms} values is $SPL_{rms0.9}$, or the time over which 90% pf the pulse energy occurs. Other metrics like SPL_{rms125} refer to the time in milliseconds over which sound was averaged.

TOB Third Octave Band, referring to a one-third octave range of frequencies. An octave is a range of frequencies twice the octave below it, and half of the octave above it. Octaves and one-third octaves approximate metrics of human and general mammalian frequency or pitch discrimination.

TTS Temporary Threshold Shift refers to the temporary, fully recovered, loss of hearing across some or all of an individual's hearing range. In the context of this document, TTS refers to the slight temporary loss of hearing that is just barely statistically detectable, and is typically fully recovered in minutes or hours. The NMFS PTS metrics are derived from TTS data (also see Southall et al, 2007 and Southall et al, 2019).

VSP Vertical Seismic Profiling refers to a type of geophysical survey with CA sources that typically does not use a full CA array as a sound source but instead may use a single CA source, cluster of CA sources or a single string of CA sources, and thus produces a sound field and spectrum different than that of a full CA array.

WFA Weighting Factor Adjustment is a value used in the NMFS User Spreadsheet Tool to adjust the absolute SEL level of a specified CA source to its hearing group weighted SEL value, based on how well a particular marine mammal group hears the different frequencies of sound within a CA impulse sound. The hearing-weighting formulae offered in the NMFS (2018a) PTS threshold criteria are very computationally demanding. The WFA was offered as a simplified method for adjusting raw SEL values to hearing-weighted SEL values. The WFA-adjusted SEL will always be less than the raw unadjusted SEL, but the difference between raw and hearing-weighted SEL depends on the hearing abilities of the different marine mammal hearing groups and the frequency structure of the sound of interest.

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LIST OF TABLES

SECTION A: PROPOSED CHANGES TO NMFS SUPPLEMENTAL GUIDANCE V.2

The NMFS 2018b User Spreadsheet Tool and Guidance address a wide range of sound sources. This document focuses solely on revisions to Tab F of the User Spreadsheet Tool. Additional supplemental tools (Tabs F1, F2, F3, F4 and F5) have been added in support of Tab F calculations, and are described below. The revised Spreadsheet Tool Tab F requires fewer user-entered values than the NMFS 2018b Spreadsheet Tool, thus reducing the potential for erroneous entries by users with incomplete understanding of the underlying physical and mathematical principles or with incomplete information about the source of interest. We emphasize, however, that all default values in the Revised Spreadsheet Tool can be modified by the user if so desired.

The same caution is provided to users as was provided for the original NMFS Optional User Spreadsheet Tool (v.2): if modifications are made to the template spreadsheet, then the user should save the modified spreadsheet under a different name to avoid corrupting the template spreadsheet.

Overview

The IAGC spreadsheet contains the following tabs. Inputs are only required in Tab F. Tab F1 contains an optional unit conversion tool. Tab F4 does not require user input, but allows for input of a user-generated spectrum if desired. Tabs F2, F3, and F5 are reference tables that do not allow user inputs, but are included for calculation transparency. As with the NMFS version, all cells that allow for user input are marked in sage green.

- Tab F (Revised Isopleth Calculator): replicates the NMFS Alternative Methodology Spreadsheet Tool, but with some important changes. This guidance walks through the Revised Tab F, from top to bottom, explaining all user entries and calculations, with supporting references as needed.
- Tab F1 (Conversion Tool): enables the user to convert nominal source levels expressed in other units into dB SPL re 1 microPascal
- Tab F2 (wtd SEL Calculator): provides a means of calculating a weighted SEL appropriate to each of the five marine mammal Hearing Groups defined in the NMFS 2018a and 2018b guidance. The resulting Adjustment (dB) is automatically copied to Tab F. Tab F2 takes Generic Spectrum data from Tab F4 and adjusts the 1/3 Octave Band SEL values for Hearing Group weighting factors obtained from Tab 3. There are five tables in Tab F2 (one for each Hearing Group). A graphical representation of the resulting Hearing Weighted spectrum is also provided, as an aid in understanding how the spectrum as perceived by a given Hearing Group may differ from the raw, unweighted spectrum in Tab F4.
- Tab F3 (wtg Values Table): contains a table of weighting functions for each 1/3 octave frequency band center frequency, based on the NMFS 2018a weighting functions. There is no user-entered information required in Tab F3, but if Hearing Group Weighting Functions as set forth in NOAA 2018a change in the future, this tab can be updated without having to change any of the other tabs.
- Tab F4 (TOB Center Frequency Calc): provides data from five representative CA source spectrograms to generate an averaged SEL value for each 1/3 octave band (TOB) center frequency of a Generic Pulse spectrum. The TOB Center Frequency Calculator can be updated if and when additional measured frequency spectra become available in the future. The values

generated in Tab F4 are imported to Tab F2 to generate Hearing Group Weighted SEL values. Users may substitute TOB values from their own CA source in Column O of Tab F4, if desired. A graphical display of the resulting spectrum (in TOB increments) is also provided.

- Tab F5 (TOB Factor Table): contains a list of TOB center frequencies and bandwidths required for internal calculations.

Guidance for completing Tab F

- General Project Information: This section is identical to the current AM User Spreadsheet Tool (v.2). The General Project Information section asks for a Project Title (cell B10) for clarity and consistency during communication about the project, along with a reference to Project Source/Information (cell B11) indicating where a reader might obtain more details about the project (e.g. an Environmental Impact Statement or MMPA Permit Request). A Project Contact (cell B13) such as an individual name, phone number or email provides information about where further queries about the project may be directed.
- The former Step 2 of the User Spreadsheet Tool provided a place for entering a Weighting Factor Adjustment (WFA). This step is now incorporated into the Adjustment values in cells C51 through G51 and the Step 2 WFA component has been eliminated.
- Source Specific Information: The first and only entry required of the user in Step 2 is the Nominal Source Level (see red arrows in Figure 1) into either cell B19 or B21. Cell B21 will automatically calculate SPL_{pk} if a value is entered into cell B19 or the user may enter an SPLpk value into cell B21 if that is the source level information available to the user. This one entry into either call B19 or B21 replaces five user-required entries in v.2 of the User Spreadsheet Tool (see Section B, Figure 8). Using a single required user entry greatly reduces the likelihood of data entry errors or entry of mixed values, some obtained from measured data at range and some obtained from back-calculation to a point source. For example, in several cases encountered by the authors, SPL_{pp} source levels had been entered into cells assigned to $SPL_{pk,}$ SPL_{rms}, and even SEL.
    - The SPL value typically used within the geophysical survey community is SPL_{pp}, or peak-to-peak SPL. If the user enters a value in cell G19, the spreadsheet will then automatically populate the SPL_{pk} in Cell G21 and all other cells requiring source level information. If the provided nominal source level is not clear as to whether the source level is peak-to-peak or zero-to-peak, but a waveform or frequency spectrogram is also provided, then the presence of a negative pressure spike in the waveform (ghost) or notches in the spectrum at approximate 100-150 Hz intervals are indicative of a peak-to-peak source value (see Section C for more about the surface-reflected ghost pressure wave and its effects on the frequency spectrum of the pulse). Otherwise, in the absence of information to the contrary, the provided source level should be assumed to be a peak-to-peak source level (SPL_{pp}).
    - Basis for the relationship between SPL_{pp} and SPL_{pk} values in the User Spreadsheet Tool (cell G20): The adjustment from SPL_{pp} to SPL_{pk} (-6 dB) is related to the reflection of the source sound by the air-water interface, as discussed in Section C (see page 42 et seq.). The user may hand-enter a different adjustment factor in Cell G20 if the actual peak-to-peak gain is known (e.g. imperfect reflectance may only produce -4 or -5 dB gain in SPL_{pp} relative to SPL_{pk}), However, deviation from the -6 dB default is unusual and could be indicative of measurements obtained off the vertical axis of the array, in which case the source level entry and resulting SEL and energy spectrum may not be consistent with

the default assumptions of the spreadsheet tool. Array output at different angles from the array vertical axis is discussed in detail in section C (see page 38 et seq.).

- Tab F section "F1: Method to Calculate PK and SEL_{cum} (using RMS SPL Source Level)" which starts on Row 26 of the NMFS User Spreadsheet Tool v.2 is unnecessary in the revised Spreadsheet Tool, and has been deleted. The RMS source level is approximately 6 dB below SPL_{pk}, although differences as great as 10-12 dB have been recorded (see Section C.); 6 dB is therefore a conservative, precautionary value for the difference between SPL_{pk} and SPL_{rms}. Since SPL_{rms} is only used to predict SEL, and since we know the relationship between SPL_{pk}, SPL_{rms} and SEL we can skip Section F1 of the old Tab F altogether and simply derive an Unadjusted (i.e. unweighted) SEL value from SPL_{pp} (-22 dB) or SPL_{pk} (-16 dB). Again, this is a conservative value, since differences of 20-25 dB between SPL_{pk} and SEL are not uncommon in the literature (e.g.see McPherson et al, 2018).

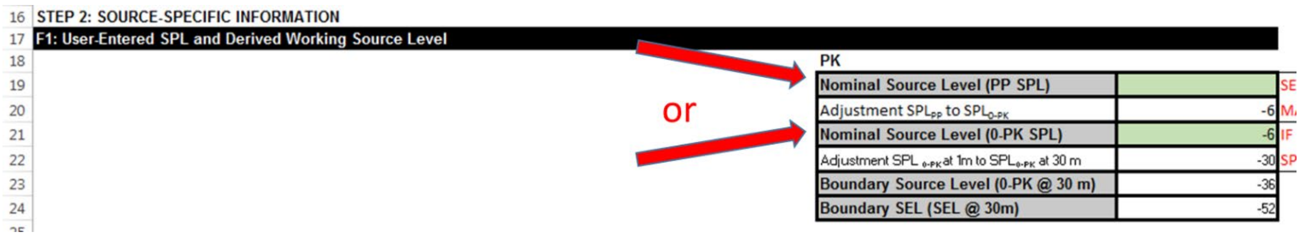


Figure 1. User entered data in Tab F, Step 2 for nominal SPL_{pp} or SPL_{pk} is indicated by the red arrows. Either a peak-to-peak SPL or a zero-to-peak SPL should be entered. All other values will populate automatically.

- Users may replace default spreadsheet values in cells B27-29 if desired, but since the equipment and practices of marine geophysical surveys are very consistent, using the default values is likely to deliver a result near what would be obtained from any one particular survey-specific set of values.

Rationale for Using Array Parameters in the Vertical Direction

The sound field produced by a planar array is complex, and difficulties can arise from using measurements taken at an angle other than directly below the array and applying those values to the source parameters in Tab F, Step 2. The most common source of errors in the use of the NMFS AM User Spreadsheet Tool is combining nominal vertical source level values with pulse durations and frequency spectra obtained at an angle and some distance from the array. In other words, a received level of 200 dB recorded at 1000m and back-calculated to obtain a nominal source level of 245 dB also requires that the user not use the recorded pulse duration of 0.1 s measured at 1000m, but must also back-calculate a pulse duration and spectrum at the source that would have produced the observed duration and spectrum 1000m from the source.

The above properties measured at any angle and distance can be back-calculated by an expert user to generate a nominal source pressure level, duration, and spectrum at any other selected angle (assuming there is good information about the propagating environment). It is important that the user of the simplified spreadsheet tool understand this relationship between the properties of the sound that was emitted and the location at which measurement or modeling was conducted, and to be consistent in the values entered into Tab F.

The default assumptions of the User Spreadsheet Tool (amplitude, duration, spectrum) are for sound emitted in the vertical direction for several reasons. First, because the spreadsheet tool is intended to use conservative, precautionary maximum sound source level for the array, and second, because this is the standard default information provided about the source of interest by an operator in the planning phase of a survey. (See Section C for more detailed discussion.)

Using parameters from the vertical axis of the source array also eliminates the frequency-specific interference patterns between array elements observed in horizontal sound fields around an array. Use of the vertical axis parameters substitutes a smooth circular boundary around the array rather than the more irregular, star-like patterns that would result from off-axis propagated sound (see e.g., BOEM, 2016). The smoother circular isopleth predicted by the vertical data exceeds predictions that would be generated by using data from other angles and is thus a further conservative, precautionary decision point embedded in the simplified Alternative Methodology of the User Spreadsheet Tool (and is just one of several reasons why the User Spreadsheet Tool should not be considered an alternative to full ocean acoustic modeling of the sound field).

Sound Propagation

The default sound propagation value is spherical spreading (Source Level in SPL_{pk} – 20*log(r)), as in the NMFS v.2 version of the User Spreadsheet Tool. This spreading loss formula is most appropriate for resulting isopleth values that are less than 2 times the water depth, or less than 1000-2000 meters horizontal distance in deep water. If the site of interest is in shallow water (less than 200 meters) or other special sound transmission conditions apply, such as occur in partially ice-covered areas, in strongly downward or upward refracting sound speed profiles of the water column, or in sites containing frontal boundaries such as Gulf Stream waters of the Atlantic or freshwater inflow, then the user is ***strongly encouraged not to use*** the predictions of the User Spreadsheet Tool, but instead to proceed directly to full ocean acoustic modeling to more accurately capture the decay of sound levels over distance. Predicted isopleths greater than 1000-2000m are also problematic due to chemical absorption of high frequency sound (see Figure 4). The absence of a correction factor for chemical absorption in the User Spreadsheet Tool can be a major source of error, especially for the High Frequency hearing group.

Minimum Isopleths

Boundary Source Level (cell G23) and Boundary SEL Level (cell G24): Because the nominal peak source level is a function of back-calculation treating the array as a point-source and not a real, measurable sound pressure level from anywhere inside the array, the most appropriate and realistic maximum far-field source value should be a number outside the boundaries of the array itself. Array dimensions are typically 12-20 m on each side, so 30 m from the center of the array was chosen as a range to achieve a realistic coherent far-field array output. Higher frequencies take longer to align than lower frequencies, but rather than set a boundary condition of 100 m or more for all frequencies to enter far-field conditions, we chose 30m as the minimum distance at which most of the acoustic energy from the pulse will become coherent. The Boundary Source Level indicates that if the isopleth value returned by the User Spreadsheet is less than 30 m, then a minimum value of 30 m will be substituted automatically in the Resultant Isopleth cells of the Revised Tab F.

This default conservative, precautionary isopleth value of 30 m means that such 30 m isopleth values ***cannot*** then be used to estimate MMPA Level A takes, since takes would be overestimated by a factor proportional to the ratio of the actual calculated range to threshold versus 30 m (see example in the following section).

Why use 30 m instead of the actual distance from the center of the array when that distance is less than 30 m from the center of the array? Obtaining a calculated PTS isopleth within or very near the edges of the array is not a realistic scenario for two reasons. One is that the array sound field is not evenly distributed at those close ranges, as shown in Section C. For example, an animal could be at a safe range near the front of the array, but not at the back of the array. The exact location of "hotspots" within the array varies with array configuration, i.e., the locations of larger and smaller sources within the array grid. The second reason is that the physical dimensions of the array make it impractical to set a range to threshold that would lie within the box encompassed by the ten to 20 square meter horizontal dimensions of most arrays, including the typical vertical depth of the array at 5-10 m below the surface. For example, for an array with a nominal source level of 245 dB SPL_{pk}, the range at which PTS onset is predicted from SPL_{pk} for a dolphin (MF Cetacean) or sea lion (OW pinniped) is only 5 meters from the center of the array, which is within the actual physical dimensions of the array. This is problematic from a safety perspective as well as a hearing injury perspective: even if an animal might be hearing-safe at 5 m from the center of the array, common sense dictates that it is not safe for animals to be swimming within the physical structure of the array itself. The same logic is applied to the SEL isopleth: a minimum safe range of 30m is applied if the range to the weighted SEL_{cum} is less than 30 meters.

Returned isopleth ranges of 30 m *must not* be used in estimating Level A takes from sound exposure modeling. To do so would result in over-estimation of Level A takes due to the volume of water encompassed by the 30 m minimum isopleth along an entire survey trackline. Even a modest over-estimate of range to PTS of 30 m rather than, for example, a 5 m range to PTS for a 245 dB SPL_{pk} source, would translate to a vastly increased volume of water for an entire trackline of hundreds or thousands of km.

What might superficially appear to be a trivial 25 m increase in the radius from the array out to PTS isopleth could mean a significant over-prediction of takes, both because the Spreadsheet Tool offers an isopleth greater than what was mathematically predicted and because the Spreadsheet Tool assumes that a cylindrical volume of water (all animals exceeding threshold regardless of depth) is ensonified instead of what is actually a hemispherical volume (having vertical as well as horizontal limits).
As a simple example of the over-estimation of ensonified area by using a default minimum 30m radius isopleth versus a 5 m isopleth: a 30 m isopleth creates a 60 m wide swath that over a total trackline of 100 km would encompass an area of 60 m x 100,000 m = 6 km^2, while a 5 m isopleth over the same distance would encompass an area of 1 km^2 (10 m by 100,000 m = 1 km^2). The difference in predicted ensonified area means that any attempt to predict Level A takes based on the 30m default isopleth would also be at least 6 times larger than would have been predicted by the actual, but unrealistic isopleth.

The problem of multiplicative interactions between precautionary variables has been brought to NMFS attention in the past (IAGC, 2017; Zeddies et al., 2017), and should always be considered when making what seem like "simple" precautionary decisions that end up interacting multiplicatively to generate estimates of acoustic exposures or MMPA takes that are thousands or even millions of times higher than the most probable outcome. We endeavored to minimize the number of interactive precautionary assumptions, although the outcome of the User Spreadsheet Tool will still be several orders of magnitude more precautionary than a full ocean acoustic model using the same acoustic threshold criteria and animal distribution data.

Calculating SPL_{pk} and SEL_{cum} Isopleths

The Unadjusted single pulse SEL value (Tab F, cell B27), was a required user-entered value in the User Spreadsheet Tool v.2, but is automatically generated from the user-entered SPL_{pk} or SPL_{pp} in Section F1 of the revised User Spreadsheet Tool (see Figure 2). This value may be overridden by the user if the unadjusted SEL measurement is available, though this is unlikely to be more readily available than SPL values.

Formerly-required user-entered values for source velocity and inter-pulse intervals (1/Repetition rate^(seconds)) are populated automatically in cells B28 and B29 based on the most common values found in most geophysical surveys (Figure 2). However, user-provided values can be substituted. For example, if the source vessel speed was known to be 2.3 m/s instead of the default 2.5m/s or the inter-pulse interval (pulse repetition rate) was known to be 20 seconds instead of 10s, these values can be entered by the user.

26	**F2: CALCULATE SPL PK and SEL_{cum} Isopleths**	
27	**Unadjusted SEL**	-22
28	**Source Velocity (meters/second)**	2.5
29	**1/Repetition rate^ (seconds)**	10
30	**Source Factor**	
31	†Methodology assumes propagation of 20 log R; Activity duration (time) independent	
32	^Time between onset of successive pulses.	

Figure 2. Revised User Spreadsheet Tool cells B27-30, showing Default Unadjusted SEL, Source Velocity, and Repetition Rate.

Pulse duration is no longer a user-entered value since it gives unrealistic estimates of SEL from SPL. The value for Pulse Duration at the source (0.02 s) will give unrealistically low SEL values relative to measured SPL/SEL relationships as documented in Section C. Therefore, a default typical relationship between SEL and SPL_{pk} is used instead of multiplying SPL_{rms} by 0.02s, which would give SEL values more than 25 dB below SPL_{pk}. The selected precautionary relationship between SPL measurements and SEL allows for some spreading in the duration of the pulse as it travels, as well as accounting for energy outside the duration of the primary pulse alone. The adjustment factor between SPL and SEL can be replaced with a user-entered value, but care should be taken to avoid basing the adjustment on a pulse duration from data measured at large distances from the source (>1000 m), since the other parameters in the isopleth calculation are based on the properties of the pulse at its point of origin. The two properties of amplitude and duration are physically linked, and pairing a high SPL at the source with a longer duration at distance will yield incorrect isopleth values. As noted, the selected default SPL to SEL relationship is already highly conservative (by an order of magnitude) relative to the SEL that would be predicted by a primary pulse duration of 0.02 s.

The result is consistent with the NMFS 2018b (Appendix C) default pulse duration of 100 msec, which would also yield an SEL -10 dB below SPL_{rms}. However, we believe our rationale is more robust and is based directly on large amounts of measured data rather than relying on a fictive "typical" pulse duration that is an average of pulse durations obtained at widely varying distances and measurement conditions. Since all other aspects of the model are based on metrics at the source, applying a mix of source values and values at distance creates greater opportunities for errors. We believe that the choice of an empirically derived relationship between SPL and SEL that is robust in free-field propagation out to 1-2 km is preferable to mixing SPL that is back-calculated to the source with other values affected by highly variable propagation metrics dependent on local water depth, seasonal sound speed profiles, azimuth relative to the source and even data recording and measurement factors. Since the outcome is the same for the SPL to SEL relationship in both this proposed revised AM and the NMFS (2018b) User Spreadsheet, this distinction between methods for generating the generic pulse duration may largely be a moot point, but consistency in the methodology for selecting data values is important to user confidence in the model and its output.

System pressurization is an invisible default value, as it was in the original 2018b Spreadsheet Tool and there is no cell for entering system pressurization. For this reason, neither the 2018 Spreadsheet Tool or the proposed Revised Spreadsheet Tool should be used to estimate isopleths for CA sources pressurized to levels other than 1800-2200 psi (nominal 138 bar). Even if the user has a measured or modeled SPL_{pp} or SPL_{pk} value to enter into cell G19 or G21, the emitted frequency spectrum from an under-pressurized or over-pressurized CA source will likely differ from the Generic Pulse spectrum in the Revised Spreadsheet Tool and as a consequence incorrect weighted SEL and cumulative SEL values would be generated by the spreadsheet tool. For example, many CA sources used in laboratory settings are not pressurized to 2000 psi and will exhibit different relationships between SPL_{pk} and SPL_{rms} with resulting differences in the spectrum and weighted SEL.

Resultant Isopleths

The Resultant Isopleths section (rows 35-40) automatically returns isopleth values based on the user-entered source level, combined with the Generic Spectrum in Tab F4 and the Hearing Group weighting functions in Tab F3. The pink highlighted cells convey NMFS 2018a PTS threshold values for each hearing group (C37-G37 for cumulative SEL_{cum} thresholds, and C39-G39 for SPL_{pk} thresholds).

The blue/yellow highlighted cells convey the calculated isopleth for each hearing group: cumulative SEL isopleths in cells C38-G38 and SPL_{pk} isopleths in cells C40-G40. Both the SPL_{pk} isopleth calculation and SEL calculations are the same as in the NMFS 2018b User Spreadsheet Tool. As noted previously, if a calculation returns an isopleth value of less than 30 m, the spreadsheet will automatically return a minimum value of 30 m and the cells will turn yellow to denote the use of the minimum isopleth. Figure 3 shows an example calculation where the isopleth was less than 30 meters for some hearing groups.

35 **RESULTANT ISOPLETHS***

*Impulsive sounds have dual metric thresholds (SELcum & PK). Metric producing largest isopleth should be used.

Row	Hearing Group	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Phocid Pinnipeds	Otariid Pinnipeds
37	SEL_{cum} Threshold	183	185	155	185	203
38	PTS SEL_{cum} Isopleth to threshold (meters)	396.4	30.0	48.5	30.0	30.0
39	PK Threshold	219	230	202	218	232
40	PTS PK Isopleth to threshold (meters)	30.0	30.0	199.5	30.0	30.0

41

Figure 3. An example calculation showing calculated isopleths (blue) and isopleths less than the 30 m minimum in which a value of 30 is automatically returned.

The Cumulative SEL (SEL_{cum}) calculation in the revised User Spreadsheet Tool is the same as the calculation used in the NMFS User Spreadsheet Tool v.2. That said, there are several points of serious concern about the SEL_{cum} calculation that should adversely impact user confidence in the predictions of the AM User Spreadsheet Tool as a substitute for full modelling of exposure using individual-based modeling or similar methods (e.g., BOEM, 2016).

First, the NMFS 2018b methodology for calculating SEL_{cum} assumes that the animals are passing directly through or very near the single pulse SEL isopleth. An animal that only crosses the SEL_{cum} threshold briefly would not in fact accumulate sufficient SEL to exceed PTS. Whether the number of animals that do not in fact achieve the cumulative SEL equals the number which pass inside or near the single pulse SEL and therefore not only meet but exceed the nominal PTS exposure level is unclear. It might be advisable to provide both a single pulse SEL isopleth as well as the multiple pulse SEL_{cum} isopleth as metrics of a gradation of risk probability that occurs between the single pulse PTS isopleth and the cumulative pulse PTS isopleth.

Second, there is no correction for received sound below Effective Quiet levels. Effective Quiet refers to a level of tolerated continuous sound exposure that does not produce TTS or PTS. In other words, all exposures below the threshold of Effective Quiet should not be added to the SEL_{cum} calculation. In humans, Effective Quiet is approximately 70 dB SPL re 20 µPa (Ward et al, 1976), roughly comparable to 132 dB SPL re 1 microPascal in water. We do not yet have directly measured values of Effective Quiet for marine mammals, though values at or slightly higher than 130 dB were recently reported by Jim Finneran at the 2019 Aquatic Noise conference in Den Haag as failing to produce TTS in bottlenose dolphins. Received pulses below the level of Effective Quiet are not factored out of the accumulation of SEL_{cum} in the current NMFS AM. This relationship between TTS, PTS and Effective Quiet should not be confused with thresholds of audibility or the potential for a received sound below Effective Quiet to elicit a behavioral, or Level B response. Effective Quiet refers only to the level of sound that the ear can process continuously without incurring TTS or PTS, and which also allows for recovery from above-TTS exposures even in the presence of sound below the level of Effective Quiet.

Third, no adjustment is provided to the SEL_{cum} calculation for hearing recovery between pulses. At present the energy from all pulses above ambient baseline within a 24-hour period are assumed to accumulate as if they were one continuous sound (e.g., 100 above-ambient received pulses of 0.02 s duration are treated as one pulse of 2 s duration, even though those 100 pulses may have occurred over a span of 25 to 50 minutes, or longer. It is widely understood from the study of humans and other terrestrial mammals that some recovery takes place in the hearing system when exposed to intermittent signals (Finneran et al., 2010). The accumulation of all sound exposures over a 24 hour period as currently applied by NMFS may not be particularly biologically realistic, and is one of several conservative assumptions embedded in the NMFS risk assessment process that contributes to a considerable overprediction of risk from exposure to low duty cycle impulse sources like CA arrays (duty cycle refers to the ratio of time when sound is produced to time when no sound is produced; the duty cycle for CA arrays is lower than for any other intermittent sound source, and is less than 1%).

Fourth, the SEL_{cum} calculation assumes no avoidance response, by which the animal would actively reduce its accumulated sound exposure. We know that some or all individuals of populations tested thus far will avoid the sound source at levels below the PTS threshold (e.g., Stone et al., 2017). Even if only a fraction of animals produced some level of avoidance when exposed to near-threshold PTS values, the predictions of the current SEL_{cum} isopleth would over-estimate incidences of PTS or related Level A take estimates by a considerable percentage.

Fifth, the ability of animals to invoke reflexive or conditioned suppression of loud sound entering the auditory system is not accounted for in the current model of cumulative SEL. Both reflexive mechanisms (e.g., stapedial reflex; Møller, 2012) and anticipatory cognitively mediated mechanisms (Nachtigall and Supin, 2015) are known to exist in marine mammals as well as in humans and common laboratory species. Some level of hearing self-protection could reasonably be expected, especially for populations familiar with CA survey activity in their region. Such self-protective, or “gain control” mechanisms would further reduce the effect of repeated exposures to intermittent and highly predictable impulse sound sources such as sounds from CA arrays. Like behavioral avoidance, the degree of hearing protection invoked by the animals is not directly known, but by assuming that there is no effect from behavioral or physiological hearing protective mechanisms, the cumulative SEL model in the AM User Spreadsheet Tool is adding to a long list of precautionary over-estimating factors.

Important Caveats Regarding Calculated Isopleths

As noted previously, calculated isopleths less than 30 m will return a default value of 30m to the Resultant Isopleths section and these values should not be used in estimating MMPA Level A takes, for reasons described above.

AM spreadsheet isopleths in excess of 2000m should not be used in MMPA Level A take calculations, and are a sign that more sophisticated isopleth calculation methods are necessary. As sound propagates over distances greater than 1-2 km from the source, environmental propagation effects exert an increasing influence on isopleth determination, and these factors are not incorporated into the simple calculations of the AM User Spreadsheet Tool.

The confounding factors involved in long range propagation of seismic survey pulses beyond 2 km include but are not limited to reflection and refraction of sound by the bottom and water column, as well as chemical absorption of sound at high frequencies. Surface and bottom roughness tends to differentially affect shorter wavelengths (higher frequencies) as the sound undergoes multiple interactions with the sea surface and seafloor. Chemical absorption of sound becomes a major cause of declining received levels at distance for frequencies above 1 kHz (Figure 3). For example, sound in the 10 kHz band will be attenuated at the rate of 10 dB/km by chemical attenuation alone, and sound in the 20 kHz band will be attenuated at the rate of 40 dB/km.

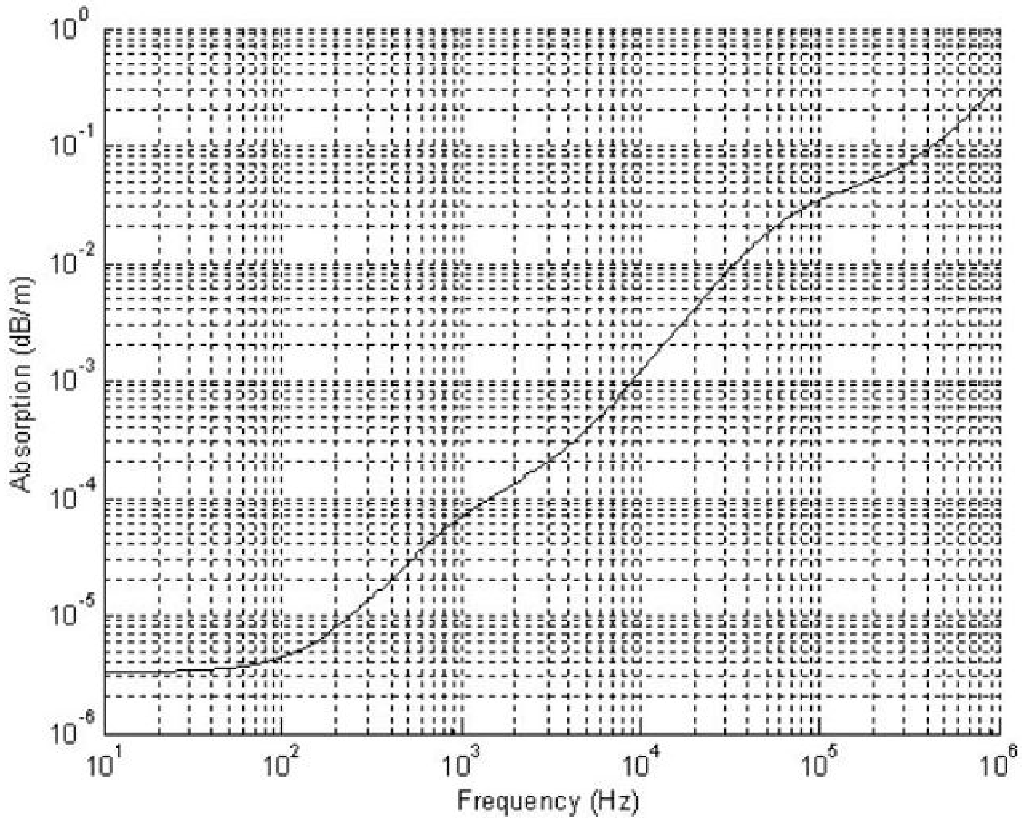


Figure 4. The frequency-specific chemical absorption coefficient for sound in seawater. For example, sound at 1 kHz loses 0.001 dB per m or 1 dB per km, while sound at 20 kHz loses 0.04 dB per m or 40 dB per km from chemical attenuation alone (Richardson et al., 1995).

Calculation Details

The Weighting Functions Calculations section in the spreadsheet (Tab F, rows 45-51; Figure 5) displays the weighting function parameters *a, b,* f_1, f_2, and *C* from NMFS 2018a in cells C46:G50. These numbers are not used in calculating the Adjustment Factors in Tab 4, cells C51-G51, but are provided simply to validate the weighting parameters used to calculate the weighting value for each TOB center frequency in the Weighting Values Table in Tab F3. The weighting values table in Tab F3 is called up by Tab F2 when calculating each Hearing Group's weighted SEL.

WEIGHTING FUNCTION CALCULATIONS

Weighting Function Parameters	260	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Phocid Pinnipeds	Otariid Pinnipeds
a	1	1.6	1.8	1	2
b	2	2	2	2	2
f_1	0.2	8.8	12	1.9	0.94
f_2	19	110	140	30	25
C	0.13	1.2	1.36	0.75	0.64
Adjustment (dB)†	-18.59	-44.37	-34.36	-26.24	-35.02

Figure 5. Weighting function parameters and calculated adjustment (dB) values from NMFS v.2 user spreadsheet tool.

The Adjustment Factors in Tab F, cells C51-G51 are the difference in dB between the unadjusted pulse SEL in tab F cell B27 and the Hearing Group Weighted SEL as calculated in Tab F2.

Tab F1

Tab F1 is a simple user tool to enable users with source levels in bar or Pascals to convert the sources levels to dB SPL re 1 µPa. Similar conversion tables are available on the internet, but we felt it would be more convenient to the user to have such a conversion tool available in the User Spreadsheet Tool bundle. The user will need to either hand enter the resulting and Paste Value the resulting SPL value in cells E11 or E14 or use the Copy and Paste Value tools in Excel to copy the resulting SPL value into Tab F, cell G19 (assuming that the source value is a peak-to-peak measurement). (Note: Using “Paste” instead of “Paste Value” will return an error message in Tab F, since cells E11 and E14 are formulas and not numeric values.)

6	**BAR TO PASCAL**			
7	1 bar = 100000 Pascal			
8	(enter the nominal array SL in bar or Pascal into appropriate sage colored cell)			
9				
10		BAR	Pascal	dB SPL re 1 µPa
11		**63**	6300000	**255.986811**
12				
13			Pascal	dB SPL re 1 µPa
14				**#NUM!**

Figure 6. Tab F1: conversion tool for CA array source levels in bar (bar-m) or Pascals.

Tab F2

Tab F2 is used to calculate the weighted SEL value from the Unadjusted SEL value in Tab F, cell B27. The calculations performed in Tab F2 to generate a hearing weighted SEL are explained column by column, and an example is provided in Figure 6. There are six of these tables in Tab F2, one for each of the five Hearing Groups (Hearing Group is found in the table headers in Rows 1-2), and one unweighted for reference only. Grayed-out rows in each table are frequencies outside the hearing range of that Hearing Group. For example, all frequencies below the 160 Hz TOB band are outside the range of hearing for Mid-Frequency Cetaceans (MF Hearing Group) and are therefore not included in the calculation of the hearing-weighted SEL value (Figure 7). A graphical representation of the pulse with weighting for each hearing group is included below the table (Figure 8).

I	J	K	L	M	N	O
One Third Octave Band Calculator Hearing group: MF						
Frequency (Hz)	Center f SEL	1/3 octave band SEL	Anti-Log of Unweighted SEL in Band	Weighting Function	Weighted SEL	Anti-Log of Weighted SEL in Band
These bands are not included for calculations for this hearing group.						
160	199	215	2.90E+21	-54.49	160	1.03E+16
200	192	209	7.76E+20	-51.39	158	5.63E+15
250	186	204	2.44E+20	-48.30	156	3.61E+15
315	183	201	1.41E+20	-45.09	156	4.37E+15
400	176	196	3.89E+19	-41.77	154	2.59E+15
500	172	193	1.88E+19	-38.68	154	2.55E+15
630	171	193	1.86E+19	-35.48	157	5.27E+15
800	168	190	1.08E+19	-32.18	158	6.53E+15
1000	166	190	1.00E+19	-29.11	161	1.23E+16
1250	162	186	4.42E+18	-26.06	160	1.10E+16
1600	159	185	3.16E+18	-22.72	162	1.69E+16
2000	157	184	2.53E+18	-19.74	164	2.68E+16
2500	154	182	1.54E+18	-16.83	165	3.20E+16
3150	155	183	2.18E+18	-13.92	169	8.84E+16
4000	152	181	1.34E+18	-11.07	170	1.05E+17
5000	149	180	9.15E+17	-8.62	171	1.26E+17
6300	150	182	1.58E+18	-6.35	176	3.66E+17
8000	151	184	2.29E+18	-4.36	179	8.40E+17
10000	143	176	4.32E+17	-2.86	173	2.23E+17
12500	141	176	3.67E+17	-1.71	174	2.47E+17
16000	138	174	2.56E+17	-0.82	173	2.12E+17
20000	137	174	2.34E+17	-0.31	173	2.18E+17
		Summed SEL	4.17E+21		Wtd summed SEL	2.57E+18
		SEL per pulse	232		Weighted SEL per pulse	184

Figure 7. Hearing-weighted SEL calculation for the MF Cetacean Hearing Group.

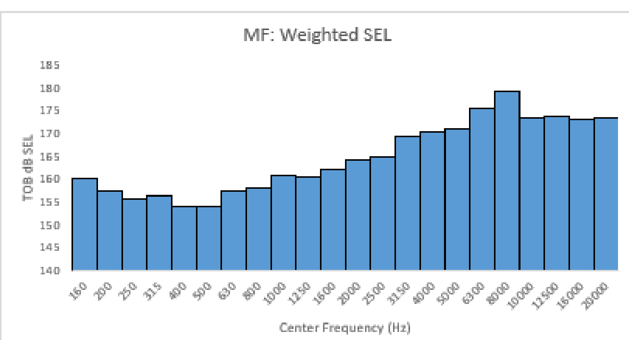


Figure 8. Graphical representation of weighted pulse for MF cetaceans.

The first column in each table contains the center frequency value for each TOB. These are the ISO and ANSI standard center frequencies for 1/3 octave bands. In the second column, the 1/3 octave band (TOB) center frequency SEL values are imported automatically from Tab F4, column O.

Note that not all cells are populated in the tables for the different hearing groups in Tab F2. Frequencies outside of the nominal hearing range of the Hearing Group (NMFS 2018a) are not included in the Weighted SEL calculation and these cells are grayed out in the appropriate Hearing Group tables in Tab F2. Frequencies above 20 kHz are also not included in the calculation of the weighted SEL value because they are a very small fraction of the total pulse SEL. For example, the TOB SEL for the 20 kHz band would be 179 dB for a total pulse SEL of 238 dB, or about 60 dB below the total pulse SEL; that is, the 20 kHz band contributes about 0.1 per cent of the total pulse energy. The third column in each table performs a bandwidth adjustment to the center frequency SEL: *[=IF(B45>0,B45+(10*LOG(bandwidth))," ")]*. Note that as bandwidth increases, the adjustment factor applied to the center frequency SEL gets larger. The fourth column converts the bandwidth-adjusted SEL for each band into its anti-log so that the numbers can be added arithmetically at the bottom of the column (row 46). This number is then re-converted back its log (dB) value in row 48. (The anti-log conversion is necessary because the dB values from each TOB cannot be added directly because the decibel scale is logarithmic.) The resulting sum at the bottom of each Hearing Group table is the unweighted pulse SEL within the hearing range of the selected hearing group. The fifth column applies the appropriate Hearing Group weighting adjustment to each TOB SEL from the third column. The weighting adjustments are drawn from Tab F3. Since weighting functions change smoothly from frequency to frequency, applying the weighting correction for the center frequency of each TOB is equal to the average weighting for the entire band and saves the effort of calculating the weighted SEL for each single frequency. The sixth column displays the weighted SEL values for each TOB. The seventh column converts the weighted TOB SEL to its anti-log so that the numbers can be added arithmetically, as was done for the unweighted TOB SEL values in the fourth column. The anti-log values are summed at the bottom of the column (row 46) and then converted back to a decibel value on row 48, which is the weighted total pulse SEL within the hearing range of that Hearing Group.

The results in the sixth column are displayed graphically in a bar graph below the table (Figure 8 above). While both single frequency and 1/3 octave spectra are often displayed as line graphs, with lines connecting the SEL value at the center of the band, we believe that the more appropriate way to present these data is with a bar graph, since the SEL value actually represents the summed sound energy across a range of frequencies within the band.

Generation of the Adjustment parameter for Tab F

The hearing-weighted SEL value in row 48 of Tab F2 is then subtracted from the unweighted SEL in Tab F, cell B27 to produce the Adjustment (dB) parameter on line 51 of Tab F. The adjustments on Tab F, line 51 are subsequently used in the formulae in row 38 of Tab F to calculate the cumulative SEL isopleth

Tab F3

Tab F3 is a look-up table of calculated weighting values for each TOB in Tab F2. The information in Tab F3 is called-up by Tab F2 during the calculation of the Hearing Group weighted SEL values that are then used to calculate SEL_{cum} isopleths in Tab F. The weighting function look-up table uses the Hearing Group Weighting Function parameters *a, b,* f_1, f_2, and *C*.

Tab F4

Tab F4 documents the derivation of a Generic Pulse Spectrum. Tab F4 enables any total pulse value obtained from Tab F, cell B27 to generate the relative energy per TOB based on the Generic Pulse Spectrum, which is then exported to Tab F2 (the user would enter a peak-to-peak SPL for the source in Tab F and an SEL 22 dB lower than that value would automatically be populated into cell R3 of Tab F4). Alternatively, if the user substitutes their own Unadjusted SEL in Tab F, cell B27, then both Tab F4 and Tab F2 will automatically generate TOB SEL values and hearing-weighted isopleths based on the entered SEL value and the Generic Pulse Spectrum (Figure 9 and 10). If the user also wishes to substitute a different spectrum than the generic spectrum, those TOB values may be entered directly into the sage cells in column O of Tab F4. The user would need to provide data and calculations to support the alternative spectrum and verify that the summed TOB SEL values are consistent with the nominal source total SPL and SEL also provided by the user.

Tab F4 also creates a graphical representation of the values in column O (Figure 10). The plotted points create a smoothed pulse spectrum, without the peaks and valleys of an off-axis or peak-to-peak spectrum. The smoothing is a product of the spectrogram sampling method described in Appendix A and the averaging of multiple sample spectra as described below. The result is another conservative, precautionary step in the isopleth calculation process, because the choice of TOB SEL relative to the total pulse SEL slightly increases the sum of TOB SEL values relative to the original pulse SEL. This is done to capture energy from outside the primary pulse itself and to elevate higher frequency values in particular. This “inflation” of the summed TOB SEL values is necessary in order to account for the contribution of energy from bubble oscillations and cavitation bubbles following the primary pulse.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
One Third Octave Band Calculator														
Center Frequency (Hz)	SEL in Band							Nominal SEL - SEL in Band					Geometric Mean SEL Difference	Calculated Values from Nominal SEL
	Caldwell 2005	Gardline TOB	Gardline Center f SEL	Blees et al. 2010	MacGillivray 2018, Pa	MacGillivray 2018, SEL	Sidorovskaia	Caldwell 2005	Gardline Center f SEL	Blees et al. 2010	MacGillivray 2018	Sidorovskaia		
1.25				134	397	172				58	65		62	170
1.6				138	685	177				54	60		57	175
2				141	1128	181				51	56		54	178
3.15				153	3377	191				39	46		43	189
4				158	6773	197	188			34	40	42	39	193
5				160	11956	202	197			32	35	33	34	198
6.3				166	27874	209	200			26	28	30	28	204
8	148			170	32433	210	202	29		22	27	28	26	206
10	149			171	29578	209	202	29		21	28	28	26	206
12.5	150			167	25768	208	204	27		25	29	26	27	205
16	151			171	29294	209	205	26		21	28	26	25	207
20	152			168	32725	210	206	25		24	27	24	25	207
25	153			163	37419	211	207	24		29	26	23	25	207
31.5	155			168	40612	212	207	22		24	25	23	23	209
40	156		212	167	44851	213	208	21	35	25	24	22	25	207
50	158		217	162	41629	212	208	20	30	30	25	22	26	206
63	158	213	201	166	40711	212	206	19	29	26	25	24	24	208
80	157	217	204	166	28784	209	203	20	25	26	28	27	25	207
100	151	212	198	166	13027	202	199	26	30	26	35	31	29	203
125	145	207	192	169	10646	201	191	33	36	23	36	39	33	199
160	144	203	187	170	14234	203	189	33	40	22	34	41	33	199
200	136	200	183	157	10005	200	188	41	44	35	37	42	40	192
250	126	196	178	149	6084	196	184	52	47	43	41	46	46	186
315	124	192	174	145	3315	190	182	53	51	47	47	48	49	183
400	119	189	169	133	1400	183	177	58	55	59	54	53	56	176
500	118	183	162	132	368	171	176	59	61	60	66	54	60	172
630	117	184	162	132	251	168	174	60	61	60	69	56	61	171
800	111	184	161	126	184	165	171	66	61	66	72	59	64	168
1000	109	182	158	126	215	167	169	68	63	66	70	61	66	166
1250	105	173	148	120	187	165	167	73	72	72	72	63	70	162
1600	103	171	145	119	120	162	164	74	74	73	75	67	73	159
2000	101	169	142	118	84	159	161	76	77	74	78	69	75	157
2500	100	165	137	115	41	152	160	77	81	77	85	71	78	154
3150	98	167	138	117	57	155	158	79	79	75	82	72	77	155
4000	96	167	137	114	19	145	157	81	79	78	92	74	80	152
5000	89	168	137	111	16	144	155	88	78	82	93	75	83	149
6300	89	168	136	118	15	144	154	88	78	75	93	76	82	150
8000	87	161	128	132	8	138	153	90	85	60	99	77	81	151
10000	85	156	122	107	5	134	152	92	90	85	103	78	89	143
12500	86	168	133	101	4	131	151	91	90	91	106	79	91	141
16000	84	158	122	96	2	128	149	94	90	96	109	81	94	138
20000	83	155	118	93	2	124	149	94	90	99	113	82	95	137
NOMINAL SEL	177	231	231	192	237	237	230							

Figure 9. Tab F4 generates TOB center frequency SEL values based on a Generic Spectrum derived from the geometric mean of the five spectra cited in the table.

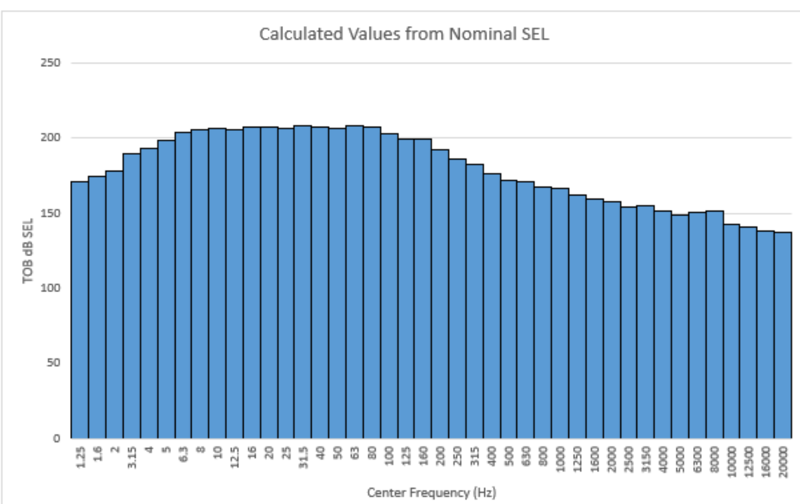


Figure 10. Graphical representation of TOB dB SEL from Tab F4.

The Generic Pulse Spectrum is derived from five sample data sets, detailed in Appendix A and listed in Columns B through H of Tab F4. In two cases, Gardline (2004) and MacGillivray (2018), the obtained values were not in dB/Hz and a second step converts the original TOB SEL to a center frequency SEL (Gardline, 2004) or, for MacGillivray (2018), the conversion of a spectrum scaled in Pascals to a spectrum scaled in dB re 1 µPa.

In columns I-M of Tab F4 the directly measured TOB SEL values are scaled relative to the total pulse SEL of each spectrum. The relative scale values in columns I-M of Tab F4 are generated by subtracting the TOB center frequency SEL from the total pulse SEL for each sample data set. This calculation effectively produces the relative proportion or percentage of the total pulse energy per TOB when adjusted for bandwidth in Tab F2. The relative scale values for each sample pulse in cells I-M are then subjected to a geometric mean calculation in Column N to produce a Generic Pulse TOB center frequency SEL for each TOB. A geometric mean method of averaging is required because the dB scale is not linear, but logarithmic.

In column O of Tab F4, the relative TOB scaling factor in Column N is subtracted from the total pulse SEL in cell R3 to produce a relative SEL value for each TOB. The resulting TOB center frequency SEL values are then exported to Tab F2. The total pulse SEL in Tab F4 cell R3 is imported from Tab F, cell B27.

User-entered values may be entered into Column O in place of the geometric mean of the five sample data sets. The user-entered value would be the difference of the measured TOB center frequency SEL from the total pulse SEL entered into cell B27 of Tab F. The same caveat applies as for any user-entered substitution for default values in Tab F: the spreadsheet should be saved under a different name to avoid corrupting the template spreadsheet, and the user should archive supporting materials justifying the user-entered substitution(s).

As more spectra become available and standards of practice in recording and presenting the data are improved, spectra are likely to become more consistent. Updating the Generic Spectrum every few years would likely be a useful and worthwhile undertaking. (See Appendix A for a more in-depth discussion of currently available spectrum data from CA arrays.)

Tab F5

Tab F5 is a list of ISO/ANSI standard 1/3 octave band center frequencies and bandwidths, used in calculating the unweighted TOB SEL values in Tab F2. Because most tables of standard 1/3 octave center frequencies and bandwidths only cover the frequencies of human hearing (20 Hz to 20 kHz), we felt a look-up table for the frequency bands used in SEL-based isopleth calculations might be useful to the user, and the values in the table are needed in calculations.

Precautionary Simplifying Assumptions

Multiplicative interaction between the many precautionary assumptions in the User Spreadsheet Tool leads to over-prediction of risk by several orders of magnitude (IAGC, 2017; Zeddies et al., 2017). The simplicity of using the Spreadsheet Tool instead of a full modeled sound field comes with a price: the Spreadsheet Tool contains at least nine simplifying assumptions, all erring on the conservative or precautionary side (detailed below). The resulting prediction of range to threshold (isopleths) and related risk expressed in MMPA take or other metrics will be orders of magnitude greater than the actual likely outcome (in other words, not double or triple, but more than 100, 1000, or even 10,000 times higher than the best available data-based risk analysis).

Few non-expert users of multivariate models like this acoustic exposure model fully appreciate the multiplicative effects of interaction between multiple precautionary assumptions. But in fact, interactions between precautionary assumptions within the User Spreadsheet Tool generate a highly elevated estimate of risk. The multiplicative interactions between model variables mean that the precautions do not add up, but multiply.

That said, the User Spreadsheet Tool can give the user some confidence regarding some very basic decisions:

- Isopleth predictions below or around 500m from the source indicate that risk can be effectively mitigated by the application of current commonly-employed risk mitigation practices;
- Isopleth predictions below or around 30 m are predictions of near-zero risk, since above-threshold exposures may not exist at all or exist only at small spots within the actual physical boundaries of the sound source itself. Since we know that the Spreadsheet Tool is over-predicting risk already, assuming zero risk inside 30 m is a reasonable metric of risk; and
- Predictions of isopleths exceeding 2 km, most often encountered for the HF cetacean hearing group, should signal that full-scale modeling is required, since factors like chemical attenuation of high frequency sound and long-range ocean propagation effects make the actual range-to-threshold unpredictable by use of the User Spreadsheet Tool alone.

For these and other reasons detailed below, the User Spreadsheet Tool should not be considered an “Alternate Methodology” to fully-realized modeling of sound exposure, but can only appropriately be considered an initial “rough” tool as an aid to decisions about the scope of additional effort needed to clarify points of concern that might be raised by the Spreadsheet Tool.

There are, at minimum, nine conservative, precautionary assumptions built into the User Spreadsheet Tool:

- The Permanent Threshold Shift (PTS) criteria themselves are precautionary, conservative estimates of the level of sound exposure likely to produce small losses of hearing ability across a narrow frequency range (NMFS 2018a; Southall et al 2007; Southall et al 2019). Actual range to PTS is likely several dB higher than the values used by NMFS and therefore 10s to 100s of meters nearer the source than predicted by the current PTS threshold criteria.
- The relationship between SPL_{pk} and SPL_{rms} is assumed to be -6 dB. Actual measured SPL_{rms} values 15-25 dB lower than SPL_{pk} have been reported (e.g. McPherson et al, 2019). The relationship is affected by whether recordings are made off the vertical axis of the array, whether the pulse has spread in time during propagation away from the source, and the measurement time window used by the data analyst. Ten dB is a conservative, precautionary relationship between SPL_{pk} and SPL_{rms} with larger adjustment factors being within the realm of reported values.
- The relationship between SPL_{pk} and SEL is similarly conservatively assumed to be –16 dB. Impulse sound sources like CA arrays produce very short duration sound waves, << 1 second in duration, but SEL is a measure of energy flux over time and the standard reference for SEL is 1 second. Therefore, the energy required to produce a pressure pulse much less than 1 second long is also much less than the stated SPL_{pk} or SPL_{rms}. Near the source, the pulse is only 0.02 s in duration, which would predict an SEL 56 dB lower than the SPL_{pk}. Use of an SEL value only 16 dB

lower than the SPL_{pk} is highly conservative, and was based on measured relationships between SPL_{pk}, SPL_{rms}, and SEL at a distance from the source, and which includes sound energy produced by the array outside of the actual primary pulse, as well as differential propagation effects for different frequencies in different environmental conditions.

- The maximum source level (directly below the source) is used to calculate the range to effect rather than a lower source level obtained from measurement at other angles. It is hard to predict which aspect of the array will contribute most to the observed far-field pulse properties at distance. Propagation factors like shallow water and refraction (bending) of the spectrum by the sound speed properties of different layers of water can all affect what the "horizontal" pulse looks like. Since all angles other than vertical are lower in amplitude than the vertical pulse, use of the vertical pulse properties is a conservative, precautionary assumption of the User Spreadsheet Tool.
- Because the User Spreadsheet Tool can return unrealistic isopleth values shorter than the actual dimensions of the array itself, a precautionary conservative minimum distance of 30 meters is returned by the Spreadsheet Tool. This conservative assumption also means that isopleth values at or near 30 m should not be used to estimate MMPA takes, in combination with a related conservative precautionary assumption:
- The Spreadsheet Tool only uses a horizontal isopleth dimension, meaning that all animals within the specified cylindrical volume of water are ensonified equally. In fact, the sound field around the source in deep waters is hemispherical and animals less that the isopleth distance horizontally may be beyond the isopleth distance vertically. This is especially true for deep divers like elephant seals, sperm whales, beaked whales and others. The amount of precautionary overestimation of MMPA takes based on the predicted isopleths would depend on the species, water depth at the site, and other variables not accounted for in the simplified Spreadsheet Tool.
- The Spreadsheet tool uses a simplified metric of sound propagation (-20 dB per doubling of distance) that is only true for short ranges in deep water. Shallow water sites, sites with sound ducts or frontal boundaries can offer propagation constants ranging from -10 to -30 dB per doubling of distance. Points at multiples of the water depth can offer interactions between the wavefront and its reflection that can produce sound levels several dB higher or lower than predicted by simple straight-line propagation. For high frequencies above approximately 1 kHz, chemical absorption of sound by dissolved salts in sea water further reduces propagation distance. For 20 kHz sound, the absorption coefficient alone is -40 dB per km. Because of the simple assumptions of the propagation formula used in the Spreadsheet Tool, users are advised to use additional modeling tools for User Spreadsheet Tool predictions of isopleths > 1-2 km, especially for HF cetaceans because the frequencies to which they are most sensitive are highly attenuated by chemical attenuation.
- The weighting functions for some hearing groups are based on little or no directly measured data. Weighting functions for PW Pinnipeds (phocid seals) and for LF Cetaceans in particular are unusually broad and offer reduced weighting compared to most other marine and terrestrial mammals for which the weighting functions are backed by good supporting data. It is likely that the LF Cetacean weighting function in particular will be found to be less broad and with greater drop-off in hearing ability at both the low and high frequency limits, relative to the current conservative, precautionary weighting function.
- The derivation of SEL_{cum}, the cumulative SEL from exposure to multiple pulses as the paths of the vessel and animal cross, contains multiple precautionary conservative assumptions. The difficulties are detailed in Section A (see page 6 et seq.) and again, in Section B (see page 26),

but the amount of precautionary conservatism in the SEL_{cum} calculation is high, especially when compounded with the other conservative assumptions of the User Spreadsheet Tool, listed above.

Summary of Caveats Associated with the Use of the User Spreadsheet Tool

- This Guidance and associated revised User Spreadsheet Tool are applicable to only a limited set of geophysical survey methods using arrays of compressed air sound sources ("air guns"):
  - Use of the Alternative Methodology Tab F may not be appropriate for smaller specialty arrays and clusters used in applications such as Vertical Seismic Profiling (VSP) or High-Resolution Geophysical Surveys (HRG) (e.g., see Crocker and Fratantonio, 2016).
  - Non-standard survey methods, such as distributed or "popcorn" sources (Wu et al., 2015; Abma and Ross, 2013) would also not be conformable to the worksheet.
  - Tonal sound sources such as multibeam sonars or Marine Vibrators should not use Tab F.
  - Other commonly used impulse sources for geophysical surveys such as electro-mechanical sources (e.g., sparkers, boomers,) will not present the same amplitude, pulse duration and pulse spectrum as a typical CA array and should not use the spreadsheet.
- Total array volume alone is not a reliable or consistent predictor of array source level or frequency spectrum.
- While animals may be exposed to seismic array output at various angles, it is difficult to know what angle represents the best, most appropriate, or average exposure scenario. The vertical output, as the highest amplitude output of the array, is widely used as the precautionary default source level, duration and spectrum, even though this will result in an over-prediction of exposures when using the simple assumptions of the Alternative Methodology and User Spreadsheet Tool.
  - The term "horizontal" sound field is often used (e.g. BOEM, 2016) to refer to measurements made laterally from the array, but these measurements do not represent the true straight-line horizontal field of the upper 10 m of the water column where the source is located, but are instead laterally measured refracted or multi-path arrivals, measured at depths greater than 10 meters, but at distances where the angular difference between receiver depth and true horizontal direct propagation is small (e.g., McPherson et al. 2019).
  - Care must be taken to not mix back-calculated point-source values of the array (SPL, SEL, and pulse duration) with measured values at some distance where propagation effects have modified the SPL, the frequency structure of the pulse, and the duration of the pulse. The User Spreadsheet Tool should only be used with measured or back-calculated source parameters. If values measured at some distance from the array are used, then an appropriate ocean acoustic model is needed to project forward or backward from the measurement point to the SPL_{pk} and hearing-weighted SEL at appropriate PTS isopleth distances.
- Certain environmental sound propagating conditions may affect received levels as much or more than the source properties. At short ranges, where most of the PTS isopleth estimates will occur, the spherical spreading propagation model of the Alternative Methodology is appropriate. But for longer ranges, in shallow water, and/or under other unusual propagating conditions, the simple assumptions of the Alternate Methodology and User Spreadsheet may

give incorrect ranges to the PTS threshold. Any of the following conditions should trigger a full propagation model and abandonment of the Alternate Methodology:

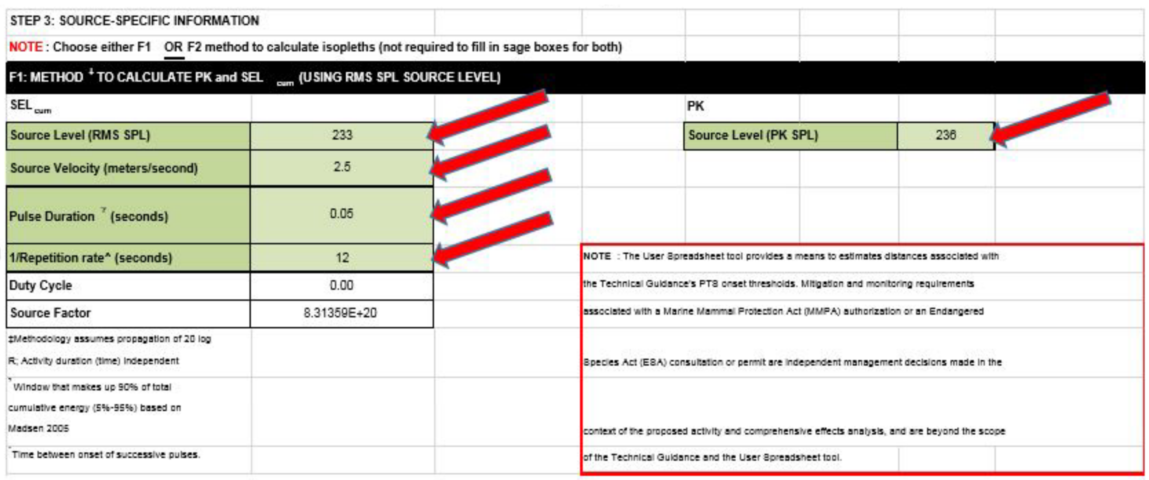
   - Shallow water depths of 10-100 meters
   - Predicted PTS isopleth ranges greater than 1000 meters
   - Potential for unusual propagating conditions, such as surface ducts, polar water conditions or mixing of water masses of different temperature and salinity such as freshwater intrusions, frontal boundaries between currents or upwelling conditions
   - Care should also be taken when propagating the higher frequency component of the pulse (above 5 kHz) due to attenuation of those higher frequencies by seawater.

- Based on data from a variety of sources (see Section C) made at 70-1000+ m from the source, we consider -6 dB to be a conservative, precautionary factor for deriving SPL_{rms} from SPL_{pk} and -16 dB to be a similarly conservative and precautionary relationship between SPL_{pk} and SEL. At greater ranges or under the limiting propagation conditions mentioned earlier, SPL_{pk} and SPL_{rms} will approach equality, as will SEL, but it is also true that as SPL_{pk}, SPL_{rms}, and SEL approach equality the total energy within the pulse will have spread, dissipated and been absorbed to a considerable degree.
- A conservative pulse duration at the source of 0.1 s is recommended as the default in the current AM User Spreadsheet model, even though multiple data sources indicate actual primary pulse durations of 0.01 to 0.03 s at the coherent boundary of the array output. A small fraction of the total acoustic output of the array comes after the primary pulse, due to oscillations of the air bubbles and cavitation bubbles created by interaction of the pulse with the surface reflected pulse. This energy is factored into the spreadsheet SEL and spectrum by using conservative values for SPL_{pk} to SEL scaling (-16dB), and by adding relative value to the high frequency bands of the pulse spectrum.
- The simplifying use of 1/3 octave SEL values to generate weighted pulse SEL values carries two important caveats:
   - The selected center-frequency SEL value for the 1/3 octave band should be representative of the average SEL across the band (smoothing peaks and nulls in the spectrum), and
   - A correction for bandwidth must be applied, since bandwidth increases with increasing frequency.
- The spreadsheet tools should not be applied to systems pressurized to more than or less than 1800-2200 psi (138 bar).
- The methodology for deriving cumulative SEL isopleths involves a number of conservative and precautionary assumptions that lead to overestimation of above-threshold acoustic exposures and thus MMPA Level A take estimates. However, the task of developing an alternative to the current User Spreadsheet v. 2 methodology is beyond the scope of this current proposed revision of the NMFS AM and will require further effort by a larger expert community. As with the other caveats in this list, users should consider using a full ocean-acoustic, individual-based model to produce more realistic estimates of SEL_{cum}.

SECTION B: COMPARATIVE OVERVIEW OF THE NMFS v.2 USER SPREADSHEET TOOL

User Inputs

First and foremost, the current NMFS AM User Spreadsheet Tool (v.2) (2018b) requires far too many user-entered values. Requiring the user to enter information they may not possess or fully understand offers the potential for possible errors in the user-required entries (highlighted in red in Figure 23). Because a considerable level of subject matter expertise is needed by the user to ensure correct entries in the proper cells of the Spreadsheet Tool, the current User Spreadsheet Tool is not as "user-friendly" as it should be for non-expert users (Figure 11).



STEP 3: SOURCE-SPECIFIC INFORMATION

NOTE : Choose either F1 OR F2 method to calculate isopleths (not required to fill in sage boxes for both)

F1: METHOD ‡ TO CALCULATE PK and SEL cum (USING RMS SPL SOURCE LEVEL)

SEL cum		PK	
Source Level (RMS SPL)	233	Source Level (PK SPL)	236
Source Velocity (meters/second)	2.5		
Pulse Duration ˀ (seconds)	0.05		
1/Repetition rate^ (seconds)	12		
Duty Cycle	0.00		
Source Factor	8.31359E+20		

‡Methodology assumes propagation of 20 log R; Activity duration (time) independent

ˀWindow that makes up 90% of total cumulative energy (5%-95%) based on Madsen 2005

^Time between onset of successive pulses.

NOTE : The User Spreadsheet tool provides a means to estimates distances associated with the Technical Guidance's PTS onset thresholds. Mitigation and monitoring requirements associated with a Marine Mammal Protection Act (MMPA) authorization or an Endangered Species Act (ESA) consultation or permit are independent management decisions made in the context of the proposed activity and comprehensive effects analysis, and are beyond the scope of the Technical Guidance and the User Spreadsheet tool.

Figure 11. A snapshot of the NMFS v.2 Spreadsheet Tool with required user-entered values flagged by red arrows.

The user is required to enter no fewer than five separate values (indicated by red arrows), most of which would not typically be available from current permit application materials or survey planning documents used in environmental risk assessments. The most common problem encountered thus far arises from the user incorrectly entering the nominal peak-to-peak source level (SPL_{pp}) into the data boxes for SPL_{pk} (or even in some cases for SPL_{rms} or SEL). Depending on user expertise and the information available to that user, the user may not be able to derive other user-entered values such as RMS SPL or single pulse SEL from the available nominal source level.

Understanding the difference between SPLpp and SPLpk

The TTS/PTS metrics from which impulse sound thresholds were derived in the NMFS 2018 guidance are based on SPL_{pk} data, so it is very important to distinguish between impulse sound metrics that are derived from peak-to-peak measurements versus zero-to-peak measurements. The default standard-of-practice in the geophysical industry is to report SPL_{pp}, but this can lead to a 6 dB over-prediction of the source level of regulatory interest, SPL_{pk}. The reader is referred to figures 25 and 26 and the discussion of the relationship between SPL_{pp} and SPL_{pk} in Section C. In the proposed revised Alternative Methodology (section A), the SPL_{pp} to SPL_{pk} conversion is performed automatically to prevent this potential source of errors.

System pressurization, source velocity

Aside from the crucial value of SPL_{pk}, all the other user entries (source velocity, pulse duration, and pulse interval, along with system pressurization) are highly standardized for seismic surveys because the equipment is designed with those parameters in mind for optimal data collection. For example, system air pressure is an important part of array performance, but that is standardized at **2000 psi (138 bar)**. That may be the reason why NMFS 2018b, v.2 of the User Spreadsheet Tool omits that system parameter from the data entries requested of the user. Research sources and some specialized surveys may employ lower system air pressures, which would result in a lower SPL_{pk} than one might expect from the same array volume operated at 2000 psi.

The vessel speed for almost all surveys is typically 4.5 to 5.0 knots or **2.3 to 2.5 m/s.** The speed of travel is crucial to the spacing of the data samples, which in turn is crucial to subsequent geophysical data processing. This is made a default value in the proposed Revised User Tool spreadsheet using the higher, or precautionary, velocity of 2.5 m/s, but the value can be changed by the user if needed.

Pulse Duration

The typical pulse duration is 0.02 s, as described in Section C, but the user may not possess this information or may only have pulse duration information at some distance from the array when propagation effects have increased the spread of acoustic energy over time. Since the calculations in the spreadsheet depend on metrics at the source (source level, pulse duration, etc.) it is important to be consistent and not apply durations measured at several hundred meters from the source in combination with modeled or back-calculated SPL values at the source. In the 2018 Optional User Spreadsheet Tool v.2, this is a user-entered value and the subsequent calculation of SEL_{cum} is very sensitive to variations in duration. The Revised IAGC User Spreadsheet Tool does not require entry of a pulse duration value, but instead offers a conservative relationship between SPL and SEL that is more consistent with a pulse duration of 0.1s instead of 0.02s.

Users who offer a different relationship between SPL and SEL should be prepared to justify the basis for their selection in terms of pulse duration and how it was derived. The standard metric for pulse duration is 90% of the pulse energy, to avoid including ambient noise in the derivation of SPL_{rms} and SEL. The duration of the primary pulse at or near the source is very short; 0.02s, which would make the SEL values derived from that duration about 10-20 dB lower than the relationship offered in the revised Spreadsheet Tool. However, small contributions of sound from the array come from bubble oscillations following the primary pulse and from cavitation bubbles created by the interaction of the primary pulse with its surface-reflected “ghost”. For this reason, the default duration was altered to account for the mostly high frequency energy emitted after the primary pulse. Alternatively, a pulse duration obtained 2 km from the source in shallow water might be as long as 1 s, making SEL equal to SPL_{rms}. But it would not be appropriate to apply that relationship between SPL_{pk} and SEL to the SPL/SEL relationship at the source.

Pulse Repetition Rate and Derived Duty Cycle

The user-entered value of “1/repetition rate^seconds” may not be immediately clear but the 1/repetition rate^seconds data entry is simply asking for the time, in seconds, between pulses. This value typically ranges between 10-20 seconds, but intervals as short as 6 seconds may be found, and longer intervals >20 seconds have also been used. A default of 10 seconds is provided in the proposed Revised User Spreadsheet, but a user-entered value may be substituted.

Estimation of SEL

The NOAA Spreadsheet Tool asks the user to enter a value for SPL_{rms} and SEL, but these are difficult values to estimate if measured values are not available, which is most often the case. And, as noted earlier, mixing measured values at distance from the array with source values back-calculated to the center of the array will produce incorrect isopleth distances. Fortunately, measured SEL, SPL_{RMS} and SPL_{pk} values are available from a number of arrays (see Section C). Therefore, SPL_{RMS} and SEL are automatically populated in the revised User Spreadsheet Tool discussed in Section C of this guidance document, reducing the risk of user-entered values not consistent with the known SPL-SEL relationships for CA arrays.

The SPL_{rms} is an average sound pressure over some period of time, and as such, the reference time period must be clear. The standard for impulse sounds like explosions, piling strikes and CA arrays is $SPL_{rms0.9}$ which refers to the time over which 90% of the pulse energy is emitted. This is a useful standard since pulse durations vary with the impulse source (explosions are shorter in time than piling strikes, and piling strikes are shorter in duration that CA pulses). However, other time metrics for calculating SPL_{rms} may be used in different situations. For example, McPherson et al. (2018), in measuring CA pulses in shallow water at distance from the source used an $SPL_{rms\text{-}125msec}$, or a sliding time window of 125 milliseconds intended to replicate the approximate energy integration time of the mammalian ear. The absence of a clearly stated standard for measuring SPL_{rms} is another argument for not making SPL_{rms} a user-entered value. Just as source SPL often omits whether it is zero-to-peak (omitting the surface-reflected ghost) or peak-to-peak (including the surface-reflected ghost), SPL_{rms} without specifying units should be assumed to be the industry default of $SPL_{rms0.9}$.

Weighting Factor Adjustment (WFA)

Once project information is entered in Step 1 of the User Spreadsheet v.2, the user must also enter a Weighting Factor Adjustment in Step 2. One can either create a source-specific WFA oneself, obtained from an information source outside of the Spreadsheet Tool, or use the NMFS-recommended default value obtained from the Introduction tab of the NMFS 2018b v.2 Spreadsheet Tool (Figure 12).

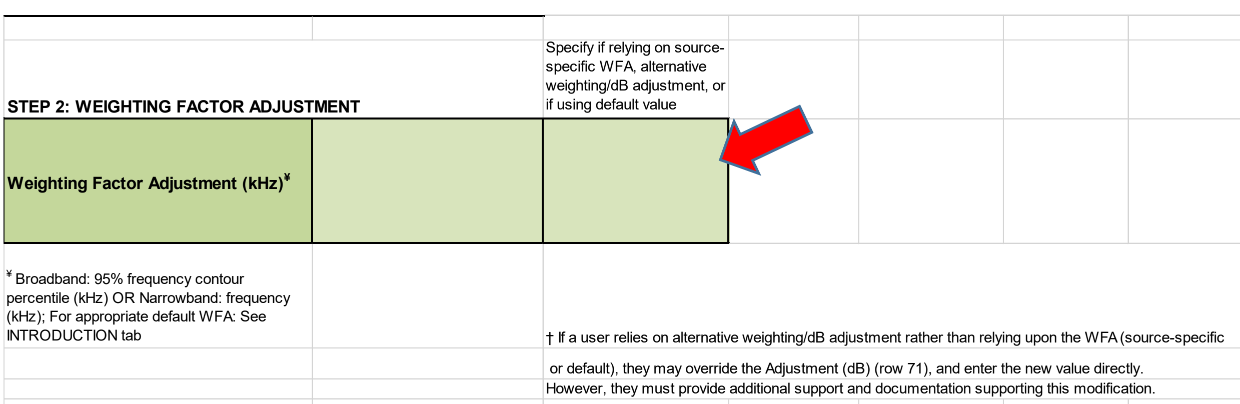


Figure 12. User-entered value in the NMFS Spreadsheet Tool: Weighting Factor Adjustment (WFA).

The default value for seismic sources, obtained from the Introduction tab of the NMFS Spreadsheet Tool, is the weighting function for 1 kHz, and will vary with marine mammal hearing group (LF cetacean, HF cetacean, OW pinniped, etc.). For LF Cetaceans, 1 kHz is within their range of best hearing and there is essentially no weighting applied at any frequency when using the Default WFA. For HF Cetaceans, 1 kHz is outside their range of best hearing and some weighting is applied, although not as much as the signal should be given, since more than 99% of the energy in a seismic pulse is below 1 kHz. The default WFA value therefore tends to under-weight the signal and thus over-predict the range to threshold. In the NMFS User Guidance for the Spreadsheet Tool (NMFS 2018b), Table 4 on page 13 indicates how much of a penalty the user pays by using the default WFA versus using the actual weighted spectrum from a real seismic source. We have further quantified the default WFA penalty to impress upon the user the degree of conservatism embedded in the default WFA for risk estimates derived from the NMFS Supplemental User Guide and Spreadsheet Tool.

Quantifying the Over-Prediction of Take Due to Use of the Default WFA Value

To illustrate the difference between isopleths to PTS that would be predicted by the default WFA versus a WFA based on the one-third octave spectrum from a seismic array, Table 2 (below) compares the outcomes obtained by applying either the default WFA or a one-third octave-based weighting value based on the example provided in the NMFS 2018(b) Supplemental User Guide. Although the spectrum offered in NMFS 2018b is a modeled spectrum from a hypothetical CA array not used in research or industrial applications, the sample spectrum offered by NMFS (2018b) is useful for illustrating the magnitude of difference in outcome obtained by using the default WFA rather than a spectrum-weighted WFA. All other variables in the comparison offered in Table 1, below, were set the same in both examples (source level, duration, source velocity, pulse repetition rate, etc.). The last line of Table 1, Increase in Exposure Area, was obtained by deriving the area, in meters^2, for the Range to Threshold isopleths and then subtracting the smaller exposure area predicted by the frequency weighted WFA from the area obtained by using the default WFA. Thus, using LF cetaceans as an example, an area of 53,100 m^2 (or 0. 053 km^2) was ensonified using a weighted frequency spectrum, whereas the area ensonified was increased to 978,179 m^2 (0.98 km^2) by using the default WFA, an 18-fold increase in area ensonified if the default WFA is used, with a corresponding 18-fold increase in resulting predicted Level A takes, all other variables being equal (animal distribution, density and behavior). This is clearly not within the realm of reasonable precaution, especially when considered in combination with the nine or more other precautions detailed in Section A.

Hearing Group	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Phocid Pinnipeds	Otariid Pinnipeds	
NMFS Threshold	183.00	185.00	155.00	185.00	203.00	
Source (SEL) no weighting	238.00	238.00	238.00	238.00	238.00	
WFA default weighting	-0.06	-29.11	-37.55	-5.90	-4.87	
NMFS 1/3 octave weighting	-12.7	-57.4	-65.7	-28.7	-33.6	
Difference in weighting (dB)	-12.64	-28.29	-28.15	-22.80	-28.73	
Range to threshold (single pulse), unweighted	562.34	446.68	14,125.38	446.68	56.23	10^((NMFS Threshold - SEL)/-20)
Range to threshold (single pulse), WFA default	558.19	15.64	187.39	226.55	32.09	
Range to threshold (single pulse), 1/3 octave wtg	130.32	0.60	7.33	16.41	1.17	
Increase in exposure area (default/calc)^2	925,492.81	767.67	110,148.47	160,398.73	3,229.99	Default Penalty (area/takes)

Table 1. A comparison of the resulting range to threshold ("isopleth") and corresponding area ensonified (as an indicator of relative MMPA takes): default WFA versus frequency-weighted WFA based on the BOEM 8000 cubic inch array example in the NMFS Guide to Users.

Caveats when using alternatives to the default WFA.

It should be noted that the value that the user enters in cell B16 of the v.2 Spreadsheet Tool for default weighting (1 kHz in the case of seismic sources) is then used in an "invisible" set of calculations in cells C73 to G76 which produce the weighting functions subsequently displayed in C71-G71. Care needs to be taken not to inadvertently delete or write over the calculations hidden in cells C73-G76.

As the NMFS User Guide notes, if the spreadsheet is used with something other than the default WFA, then the contents of cells C71 through G71 need to be cleared, and values for cells C71 through G71 must be hand-entered from another sheet of calculations (in the above example the values come from Table 4, p. 13 of the NMFS User Guide). A spreadsheet that is thus altered by using hand-entered values for cells C71-G71 will then need to be saved under a different name than the original spreadsheet template ("Acoustic Guidance 2018 BLANK USER SPREADSHEET (508)") in order to prevent the blank spreadsheet from being rendered unusable as a default master spreadsheet for subsequent calculations.
B.3. Calculation of Cumulative SEL (SEL_{cum}).

The User Spreadsheet (v.2) employs a mathematical model originally developed by Sivle et al. (2014) for behavioral disturbance of a schooling fish (herring) by sonar, adapting the Sivle (2014) formula to derive a cumulative SEL value. Several aspects of the model offer considerable opportunities for overestimating the likelihood of inducing PTS through repeated exposures to a moving seismic array.

How Much Does the SEL_{cum} calculation over-estimate the range-to-exposure and resulting number of Level A takes?

Calculation of the magnitude of over-estimation of PTS exposures using the SEL_{cum} method based on Sivle et al. (2014) is beyond the scope of this exercise, and would likely require many iterations of a randomized individual-based model to approximate (with confidence limits) the likely overestimates for different marine mammal species with different movement and diving patterns. However, like the default WFA, the SEL_{cum} calculator probably adds, at minimum, one or two orders of magnitude (10 – 100+ times) to the conservatism of the User Spreadsheet Tool predictions. In other words, a simple model that already overpredicts risk by several orders of magnitude due to other conservative assumptions (source level, onset of PTS, default weighting function) is pushed even further away from the best available science estimate by conservative assumptions in the estimation of cumulative sound exposure. As such, the User Spreadsheet Tool v.2 (NMFS, 2018b) cannot reasonably be treated as an "Alternative" Methodology to the full modeling of sound exposure in a 4D ocean acoustic model.

Summary of Problems with the current Supplement User Guide and Spreadsheet Tool (v.2):

Requiring multiple user-entered values creates more opportunities for incorrect data entries. When using Version 2 of the Spreadsheet Tool, care must be taken to avoid incorrect user-entered values. Section C of this Supplemental Guidance offers a data-based rationale for default entries used in the proposed revised Spreadsheet Tool in Section A. All default values in the revised Spreadsheet Tool offer the option of substituting user-entered values for default values.

The Default WFA used to generate weighted SEL values greatly over-estimates the range to PTS threshold and thus, potentially, MMPA Level A takes. Users of the current NMFS "Alternative Methodology" (2018b) are strongly advised to NOT use the default WFA. A simple one-third octave (TOB) weighting tool is provided in the revised Spreadsheet Tool and is described in Section A of this document.

The methodology for deriving cumulative SEL isopleths involves a number of conservative assumptions that will lead to overestimation of isopleths and associated MMPA Level A take estimates. This problem is not corrected in the proposed revised Supplement User Spreadsheet Tool.

SECTION C: TECHNICAL AND ACOUSTIC ASPECTS OF THE CA SOUND SOURCE

How does a Compressed Air (CA) source work?

The CA source is filled with air drawn from the atmosphere and compressed, typically to 2000 pounds of pressure per square inch (psi) (ambient air pressure is about 14.7 psi). Upon activation of an electronic release, the reservoir of air within the CA source is released through ports spaced equidistantly around the perimeter of the cylindrical device to create a spherical acoustic pressure front (not to be mistaken for the escaping air bubble itself, which expands more slowly than the speed of sound). A typical CA source is shown in Figure 13.

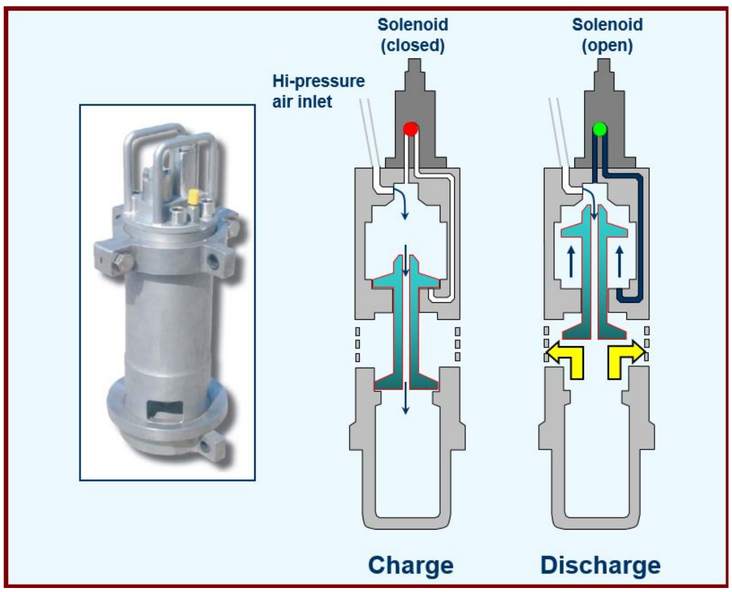


Figure 14 illustrates the rapid time sequence of the creation of the primary acoustic pulse. Maximum pressure is reached within about 10 milliseconds of the opening of the ports, during the initial push of the escaping compressed air on the surrounding water. A second, smaller acoustic pressure pulse occurs as the air bubble itself grows to its maximum expansion. The elastic properties of water then exert a pressure rebound of the surrounding water on the air bubble, re-compressing the air bubble, which then produces more sound as the bubble partially rebounds a second time. During this time, the air bubble is rising to the surface and will typically reach the surface after the third or fourth oscillation, where the air bubble and the force it exerted on the surrounding water are dissipated into the atmosphere.

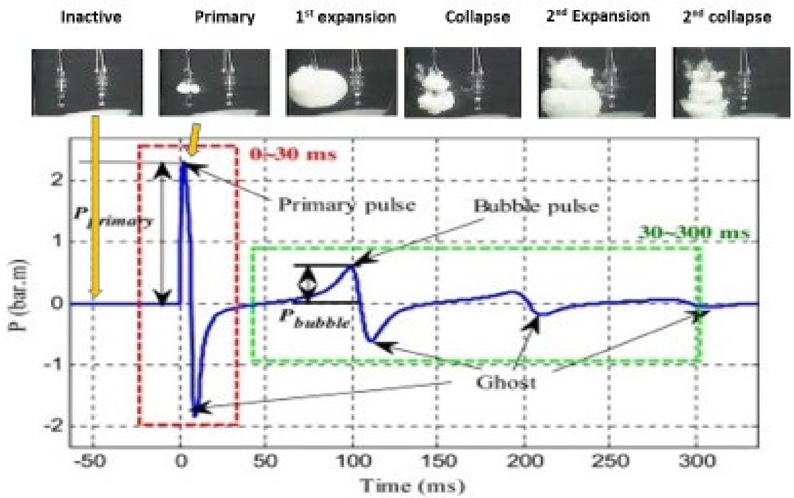


Figure 14. Chronology of the acoustic output of a single CA source. The primary pulse, which contains more than 90% of the energy produced by the release of the compressed air, occurs within 10-20 milliseconds (msec) of the opening of the ports as the air is just starting to escape. A second, much smaller pressure pulse is created by the expansion of the air bubble, which takes about 100 msec and again with the second re-expansion from about 150-200 msec, etc. The time period of bubble expansion is correlated to the volume of air released: larger CA sources create pressure traces with longer periods between the bubble pulses because a larger bubble takes longer to fully expand. Using different sized CA sources in an array thus helps reduce the contribution of sound from the bubble oscillations, due to interference effects between the timing of the different sized bubbles from multiple CA sources of different sizes (though this effect is strongest perpendicular to the plane of the array, or in the vertical direction).

Individual sources can be placed in close proximity to each other (about 1 m apart) in what is called a cluster. Clustered sources are used to create a pulse and combined bubble volume comparable to a single source having the same volume as the combined sources. For example, a cluster of three 90 cubic inch CA sources would have the same output as a single 270 cubic inch source.

Why are CA sources combined in arrays?

The acoustic output of an individual CA source or a cluster of sources increases as the cube root of the source volume, meaning that volumes much above 2000 cubic inches (32 liters) do not significantly increase acoustic output (doubling the pressure amplitude of a 2000 cubic inch source from, say, 225 dB SPL_{pk} to 231 dB, would require a CA source with an 8000 cubic inch or 128-liter internal volume). Instead, multiple smaller CA sources can be arranged in a geometrical array like the ones pictured below in Figure 15-16 in order to achieve the desired nominal source level and to optimize the shape and frequency content of the sound field for geophysical imaging.

While a single string of two or more elements is technically an ‘array’, optimal array gain and concentration of the array output directly below the array is most commonly achieved by an array of two, three or more parallel rows, with each row containing a series of four or more elements, made up of either a single CA source or a cluster of 2-3 sources (Figure 16). In Figure 15, the ship is towing two such arrays of three strings each. During a geophysical survey, the vessel will alternate the release of air (and therefore production of sound) between the two sets of three strings, so that one set of three is refilling with air while the other is discharged. The arrays are activated alternately, with one discharged every 10-20 seconds, typically. (There is a tremendous variety to the number of elements in an array and their arrangement: another array configuration is illustrated in Figure 17.)

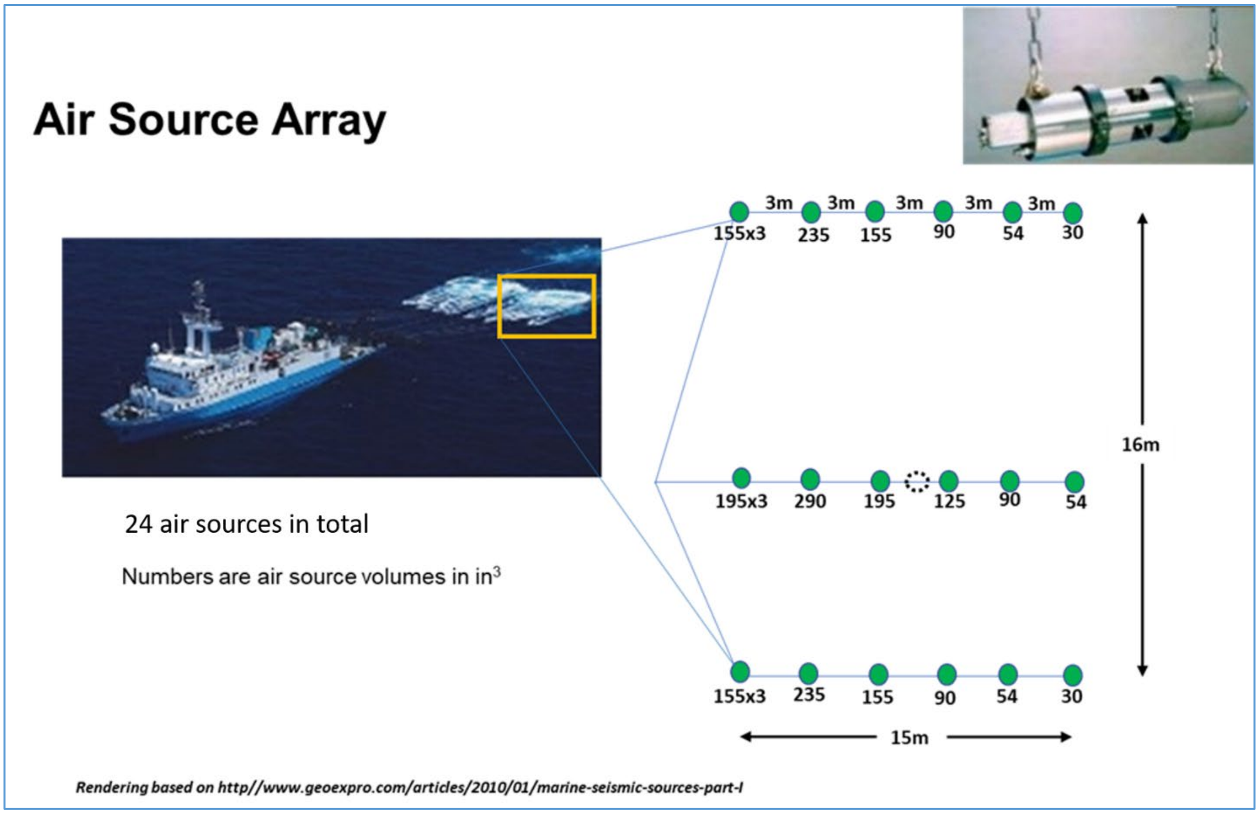


Figure 15. A typical array shown as it would be towed (the photo at upper left) illustrates the standard seismic survey operating procedure with two side-by-side identical arrays of 18 elements, activated alternately every 10-20 seconds in an A-B-A-B pattern). The photo at the upper right show a typical single compressed air source or array element. The geometry of the three strings in a typical array is shown schematically at center right, with each element or cluster of elements spaced at 3 m intervals, and each string separated from its neighbor by 6-8 meters, forming a rectangular or 'planar' array that may range from 10 to 20 m on a side, depending on the number of strings and the number of elements in a string.

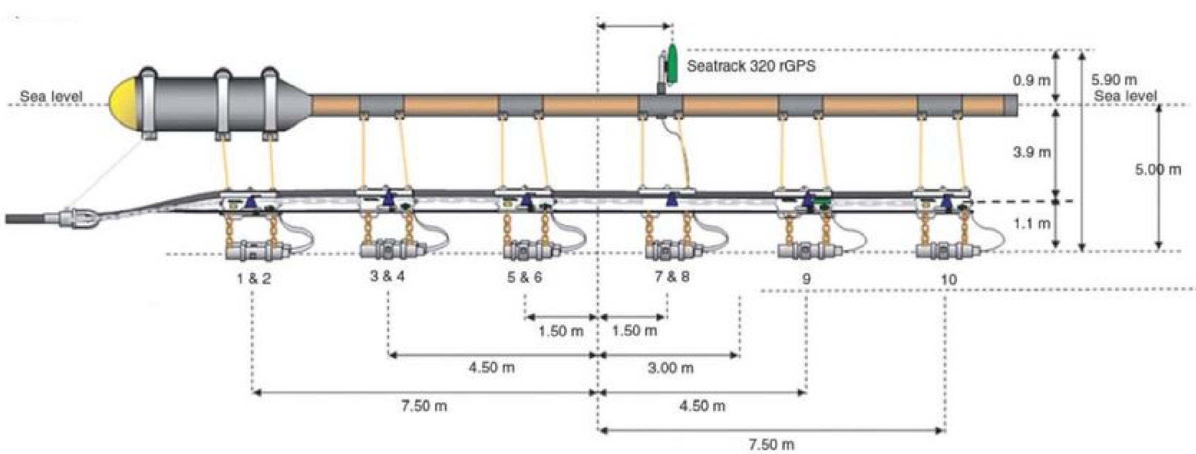


Figure 16. A single string of sources is shown, as it would look suspended below its float, with the elements usually hanging 5-10 m below the float. (Llandro et al., 2013). In this example, from left to right there are four clusters of two CA sources each (1&2, 3&4, 5&6, 7&8) and then two single CA sources (9, 10). The total length of this string is 15 meters, with 3m spacing between each source or cluster (the sources in a cluster are typically separated by 1 m).

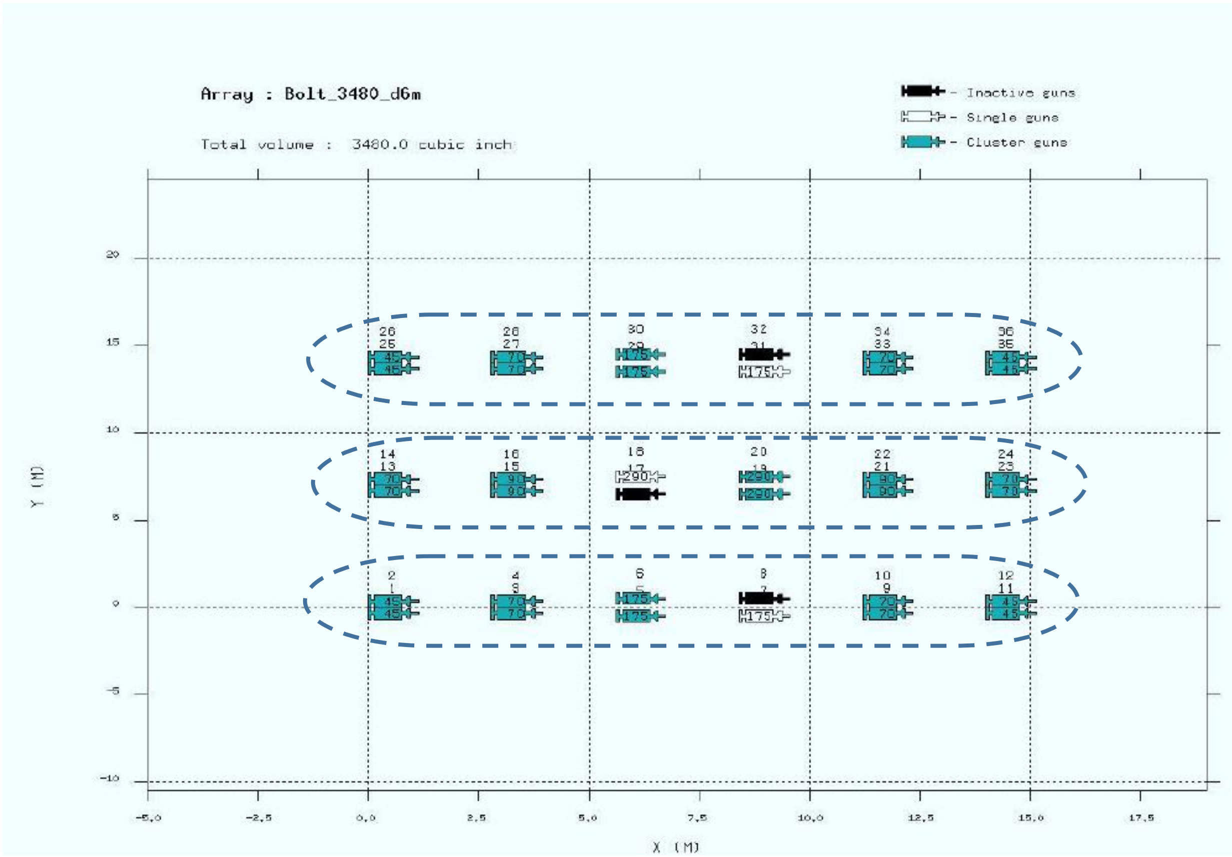


Figure 17. A schematic diagram of a different array than the one shown in Figure 14, (above). The sources shown in green are "clusters" or groups of 2 or 3 sources that can be treated as a single source equal to the summed volume of the individual elements in the cluster (e.g., a cluster of two 45 cubic inch sources acts as a single 90 cubic inch source). The pairings of black and white elements indicate that only one source is activated and the other is a spare. The use of spares is quite common, and enables the spare source to be activated when the source previously in use fails, allowing for fewer interruptions in the survey for repairs and replacements. The sources in this example are arranged in three strings, with each string having six evenly spaced single or clustered elements. The floats (dashed outline) are generally spaced 5 meters apart, with the single or clustered elements separated by 3 m along each string. The dimensions of this array are therefore 15 x 18 m.

NOTE: Use of the Alternative Methodology Tab F may not be appropriate for smaller specialty arrays and clusters used in applications such as Vertical Seismic Profiling (VSP) or High-Resolution Geophysical Surveys (HRG) (e.g. see Crocker and Fratantonio, 2016). These arrays do not achieve the suppression of high frequency energy obtained from a full array, and thus the Generic Spectrum described in Section A and Appendix A may not predict the correct hearing-weighted SEL. On the other hand, VSP and HRG sources typically do not achieve as much signal gain in the vertical direction, so nominal source level values are more-or-less omnidirectional, unlike the challenges offered by two and three string arrays. Operators of tonal sound sources used in geophysical research and surveying, such as Multibeam sonars or Marine Vibrators should also not employ Tab F to estimate ranges to PTS. Other commonly used impulse sources for geophysical surveys such as explosive or electromechanical sources (e.g., sparkers, boomers) will not present the same amplitude, pulse duration and pulse spectrum as a typical CA array, and the assumptions embedded in the supplemental tools presented in Section A of this guidance should not be applied to those non-CA sources.

While this introduction to CA source arrays uses examples of the most common array configurations, there are numerous variations on this theme, far beyond what can be explored in this brief introduction, though the general principles are consistent. A single float ("string") may carry four to eight sources each to create arrays of anywhere from 12 to over 40 individual sources (some in clusters). Some surveys may employ simultaneous activation of both the port and starboard (A and B) arrays to double the source level of the output signal (+6 dB SPL). Given the tremendous variety in array configurations and the technological ingenuity that is part of marine geophysical survey technology, it is not possible to predict a nominal array source level based on simple metrics like total array volume or the number of elements in an array.

NOTE: The possibility of using total array volume to predict an approximate array source level was explored during development of this guidance, but proved to not be a good predictor of array source level.

Acoustic Properties of CA Arrays

Single element acoustics

As described previously, a single CA source produces an omnidirectional expanding spherical "shell" of sound (or wave front) when the compressed air is released into the surrounding water. The sound produced by the primary pulse of the CA source should not be confused with the visible presence of the air bubble itself. The air bubble oscillations after the primary pulse do produce sound, but they produce so little sound relative to the primary pulse that less than 10% of the total acoustic energy produced by the release of air from a single CA source occurs after the primary pulse. In the next section on CA array acoustics, we will see that the arrangement of multiple CA sources of different sizes causes interference between the sound fronts generated by the individual source elements, thus reducing the contribution of the bubble oscillations to about 1% or less of the total acoustic output of the array, most of which would not be discernable above the ambient background noise (which is not included in the "noise free" example in Figure 18).

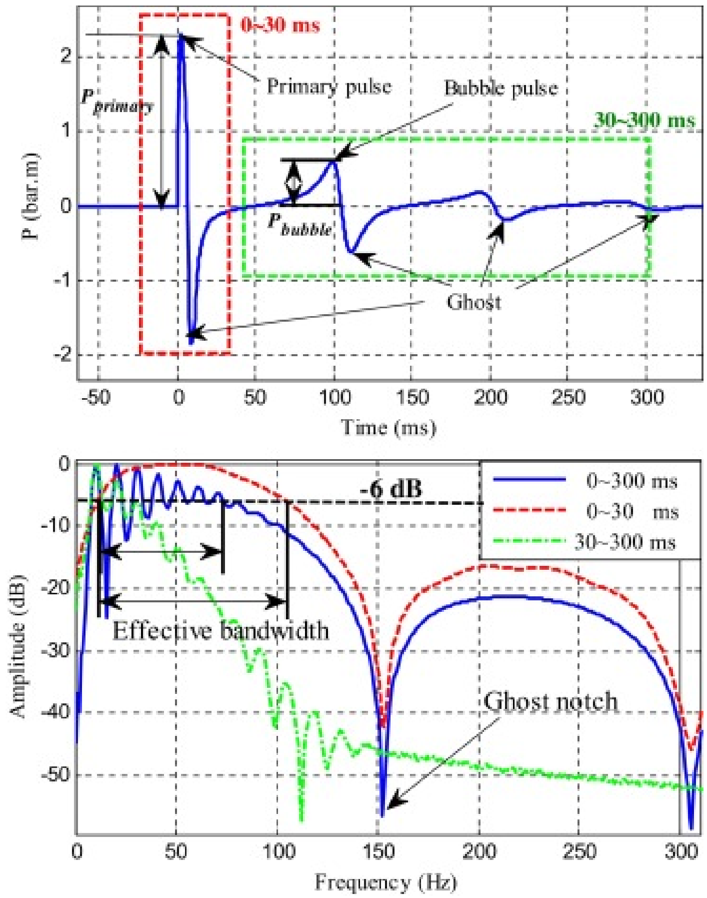


Figure 18. Graphical representation of the time/amplitude structure (top graphic) of sound produced by a single compressed air source with the resulting frequency spectrum (lower graphic) (Zhang et al., 2017).

Figure 18 shows that most of the acoustic energy (more than 90%) produced by a CA source is contained in the primary pulse, which has a pressure rise time of less than 10 msec and a total duration of less than 30 msec. This aspect of CA source sound production is important, because expressions of pulse duration in the literature often vary, depending on the reference time window used. For the standard impulse integration time of 90% of the total energy, the pulse duration is around 0.2 to 0.3 s (within the 0-30 msec segment of Figure 16, shown in red).

A small amount of additional energy comes from the oscillation of the air bubble during the time period of 30-300 msec (in green dashed box), as well as from interactions of the pulse and its surface-reflected inverse pressure pulse or “ghost”. The horizontal dashed black line at -6 dB illustrates the contribution of the surface-reflected pulse: the surface reflected pulse increases the peak-to-peak amplitude of the pulse by 6 dB, but also creates frequency-specific interference patterns based on the two-way travel distance of the surface-reflected pulse. The surface reflected acoustic pressure front is commonly referred to as the “ghost” because it is the almost-perfect inverse or reflection of the pulse emitted by the CA source. In Figure 18 above, we can deduce that the array was at 5 m depth, since the two-way distance (10 m) is the wavelength of a 150 Hz tone and that is where the interference effects from the ghost appear in the frequency spectrum.

The term “effective bandwidth” in Figure 18 refers to the frequency range most useful for deep geophysical imaging (about 2-100 Hz): the individual CA sources, and the arrays of those CA sources, are designed to reduce as much as possible sound in frequencies outside the effective bandwidth. One of the challenges in constructing the Generic Pulse in the revised User Spreadsheet Tool was that frequencies above 200-300 Hz are not of interest for geophysical research and surveying, and were therefore seldom included in historical models or recorded data sets prior to about 2010.

Array acoustics versus single element acoustics

Compared to the output of a single source, the sound from an array shows suppressed contributions from oscillations of the air bubbles following the primary pulse and a smoother distribution of energy across the frequencies used in geophysical imaging (around 2 to 100 Hz) (Figure 19). Note too that the cumulative energy in the pulse (blue line in the figure on the right) reaches 90% around 200 Hz and energy above 1 kHz contributes less than 1% of the total pulse energy.

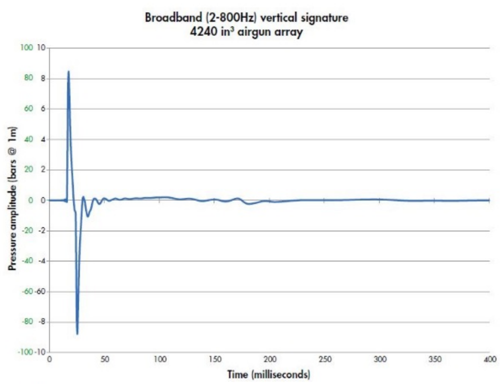


Figure 19a *(credit: Polarcus)*

This shows the time-series (amplitude versus time) display of an airgun signal from a 4450 in³ array that has 33 active guns. The green numbers are the theoretical back-calculated values for this array if one could measure the full output at 1m from the center, thus the units bars at 1m. The black numbers are the actual maximum values in bar-meters that one would measure given the array dimensions of about 14m by 14m.

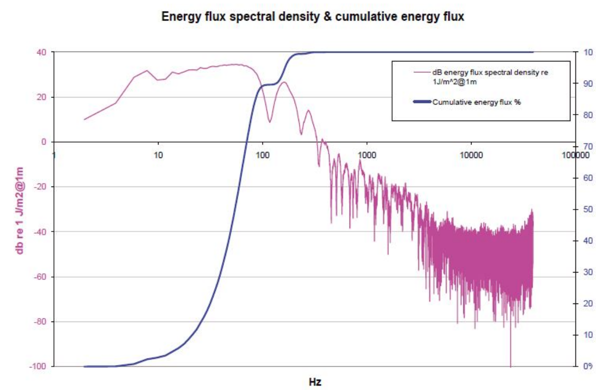


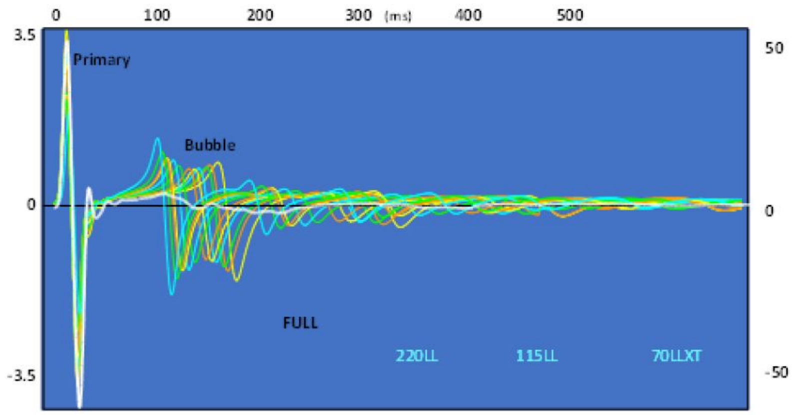
Figure 25 (*credit: Gary Hampson, Chevron*)

Broadband spectrum of the energy flux (proportional to the square of the amplitude) indicated by the vertical axis on the right. The main point from this figure is that 99.9% of the energy is contained in frequencies below 305Hz. These data are for the 3397 cubic-inch array that has 24 guns.

Figure 19. A measured pulse from a 3397 cubic inch array, as measured in the vertical direction (below the array). The surface-reflected "ghost" is included, but the sound from bubble oscillations following the primary pulse is suppressed due to interference between bubbles of different size produced by larger or smaller elements in the array. The spectrum of the array pulse shows the "ghost" notches at multiples of the depth of the sound source (6m depth = notches at multiples of 125 Hz) (OGP/IAGC, 2011).

Figure 20 illustrates how the amplitude fluctuations over time from the different sized elements in the array interact to create a stronger, sharper initial primary pulse (array gain) while suppressing sound production following the initial primary pulse. Figure 20 also illustrates how the nominal source level can simply derived from the combined source levels of the individual elements (shown in bar rather than decibels so that the source levels can be added arithmetically). The table on the right of the figure shows actual measured data obtained from hydrophones mounted 1 m from each of the individual array elements, as well as the measured sound pressure at a hydrophone suspended 33 m below the array (Fontana, 2018). The sum of the individual source levels from each element provides the nominal point source level of 66.9 bar or 256.5 SPL_{pk}. The actual measured value obtained at 33 m below the array was 226 dB SPL_{pk}, or about the same as if we had projected a nominal source level from a single point at the geometric center of the array to 33 m below the array, using simple spherical spreading:

$$SL - 20 * \log(r) = 256.5 - 20 * \log(33) = 226.13\ dB$$



	3090 in³ Array	
Element	Volume	0-P (bar-m)
1	45+45	4.8
2	70+70	5.1
3	230+230	7.3
4	230	4.4
5	70+70	5.1
6	45+45	4.8
7	90+90	5.4
8	110+110	5.6
9	380	5.0
10	380+380	8.4
11	110+110	5.6
12	90+90	5.4
	Max 0-P	66.9
		256.5 dB re 1uPa

At a far- field distance of 33m 0-P = 2.03 bars = 226.1 dB re 1uPa

Figure 20. Measured source levels for each source element in the array, expressed as peak pressure in bar at one meter (table on the right side of the figure). The nominal source level can then be derived by simply adding the source levels of the individual elements, expressed in bar-m in this case) and converting the summed bar-m value to dB re 1 µPa-m. A far-field measurement was made by a hydrophone placed 33 m below the array, and conforms well with 20 log r (spherical) spreading of a point source of 256.5 dB located at the center of the array (even though there was no actual sound source at the geometric center of the array). The image on the left of the figure is the modeled individual time/amplitude fluctuations of the individual elements superimposed on each other. The resulting interference between the wavefronts from each individual element in the array produces the white composite time/amplitude signature of the array in the far field (as seen in the vertical direction, directly below the array) (Fontana, 2018).

An important and difficult concept about the acoustics of the array is that there is no actual physical location within the array where the nominal (single point) source level is achieved. We say that the nominal source level expresses what the source level *would be, if* the sound came from a single point, but in terms of actual measurable achieved sound pressure levels at points within the array itself, the nominal source level cannot be found. This geometrical effect of the CA array not being a point source becomes important when ranges to PTS thresholds are smaller than the range at which the signals from the separate elements in the array come together, which is a function of sound frequency as well as array dimensions.

Predicted thresholds less than 30 to 100 m from the center of the array should be treated with caution, since the actual received sound pressure level at such close ranges is likely lower than predicted by a model that treats the entire array as a single point source. At greater distances of 100-plus meters from the array the array can be treated as a point source for most calculations, although the effect of receiver angle from the array must also be considered, and will be discussed in more detail below.

The physical geometry of the CA array also means that the array achieves its increased nominal source level only at some distance from the array where pressure wavefronts from multiple physically separated sources come together (recall the array geometry shown previously). Because the alignment between the separate acoustic wavefronts can only take place at some distance from the individual point sources, the energy of the expanding wavefront from each source is spread thinner and the sound pressure level decreases in proportion to the doubling of distance, even before the wavefronts come together.

As illustrated in Figure 21, this near-field distance (variable ‘a’ in the equation) where the pulses have not yet aligned in space and time, is a distance equivalent to the longest horizontal dimensions of the array. For example, for an array that is 15 m by 15 m, the wavefronts from the separate elements would not align and behave as a single unified pressure front (and produce array gain in amplitude) until the sound had traveled at least 15 m (in this case). There is a frequency/wavelength dependent aspect of the far-field array gain (variable ‘f’), but for the purposes of this discussion, almost all of the pulse energy, being at lower frequencies (longer wavelengths), has aligned and behaves like a single acoustic wavefront coming from a point source at ranges that are just a little larger than the array dimensions ‘a’.

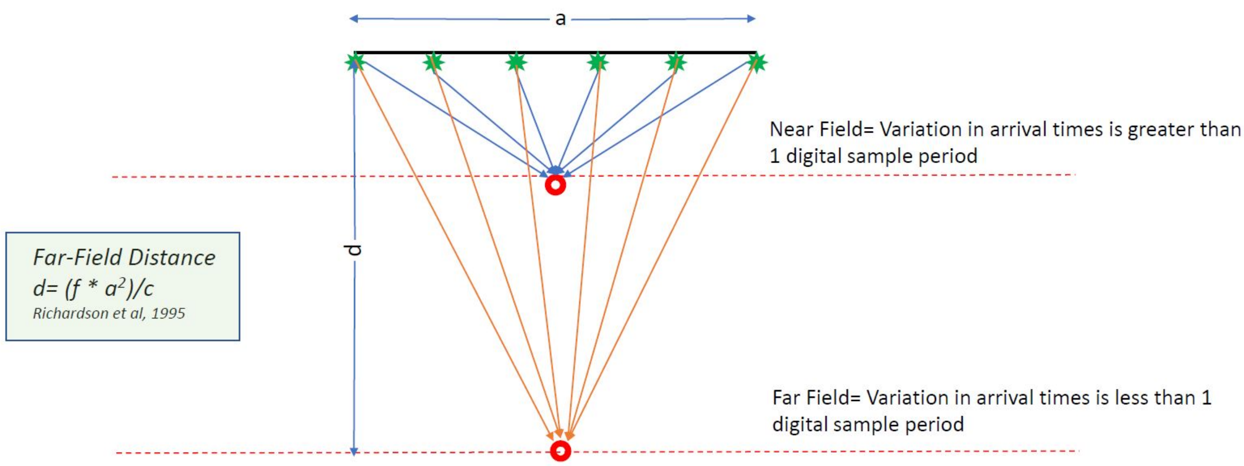


Figure 21. Measurements in the near field will necessarily contain arrivals that are not simultaneous (i.e., greater than 1 digital sample period). Note that the far-field distance (d) is dependent on array dimensions (a), and that any measurement at a distance less than the dimensions of the array will not produce a received SPL consistent with the nominal point source SL due to unequal contributions from the array elements (Fontana, 2018).

Keep in mind, too, that the expanding acoustic “shells” are not to be confused with the visible expression of the expelled air bubbles, and that the acoustic wavefronts (the acoustic “shells”) are expanding at 1500 m/s or almost a mile per second; much faster than the physical expansion of the actual air bubbles themselves.

The acoustic space within the array is not uniform

As we noted earlier, the individual elements in the array are not all the same size (volume). Not only do they have different periodicities of bubble oscillation, but their different volumes mean that some are of higher amplitude than others. As a result, the acoustic space within the array is very uneven: a given point near a small source might yield a relatively low received level, while another point within the bounds of the array might be near a larger source and therefore receive a relatively higher peak SPL. This point is illustrated in Figure 22, showing a modeled fine-scale sound field as seen from above and from the side. In this particular example, the largest element(s) are at and behind the center front of the array (at 0,0 and 0, -5), but different array geometries will have different “topographies” of relatively higher and lower sound energy levels within the array. Again, there is no point in the center of the array where the pressure equals the nominal array source level. In fact, there is typically no actual sound source at the geometric center of the array, and the largest sound source may be before or behind or to the left or right of the geometric center of the array.

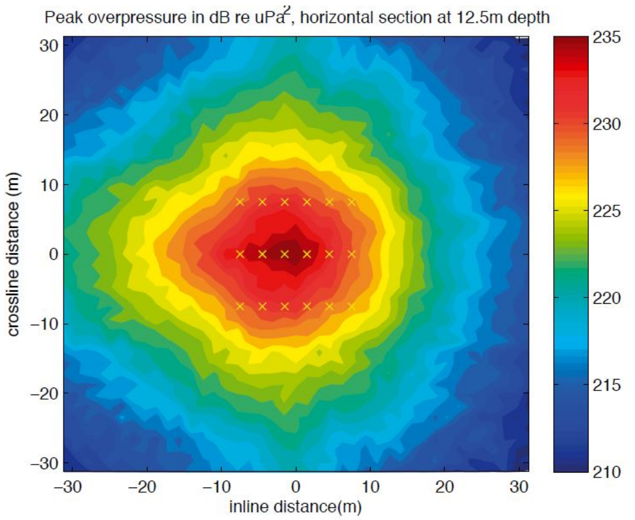


Figure 23a *(courtesy IAGC)*

This shows the modeled sound pressure (zero-to-peak) on a horizontal slice at a depth of 12.5 metres. The depth of the array is 7.5 metres, and the total frequency band used is 0-400 Hz. It has 18 elements arranged in three subarrays each 15 metres long and separated by 7.5 metres. It has a total volume of 5205 cubic inches and is charged to 2000 psi. The elements at the front (left) of the array are larger and this accounts for the inline asymmetry. The yellow crosses indicate positions of the source elements. Contours are shown from 210dB re μPa^2 upwards.

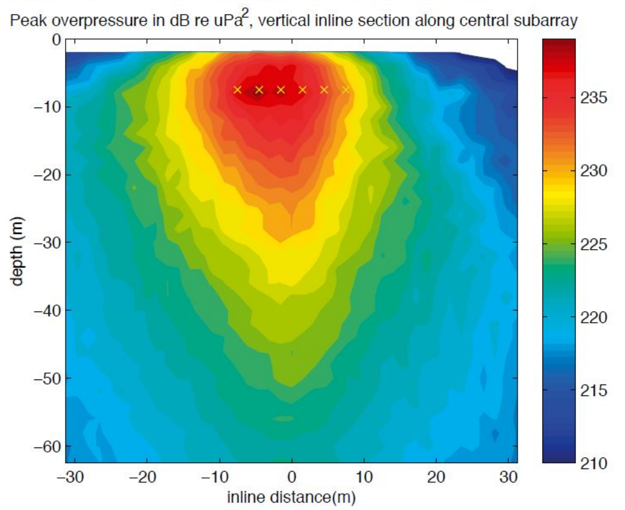


Figure 23b *(courtesy IAGC)*

This shows the modeled sound pressure (zero-to-peak) on an inline vertical slice through the centre of the array. The depth of the array is 7.5 metres, and the total frequency band used is 0-400 Hz. It has 18 elements arranged in three subarrays each 15 metres long and separated by 7.5 metres. It has a total volume of 5205 cubic inches and is charged to 2000 psi. The elements at the front (left) of the array are larger and this accounts for the inline asymmetry. The yellow crosses indicate positions of the source elements. Contours are shown from 210dB re μPa^2 upwards.

Figure 22. Inhomogeneities within the dimensions of the array, from the horizontal view (a, above) and vertical (b, from the side). One can see that the highest amplitude source is not always at the center of the array and that the familiar downward projected gain from the interaction of the individual elements is not achieved until about 20 meters, or outside the dimensions of the array (the figures from the IOGP/IAGC 2011 document were originally generated by Dr. Robert Laws for Schlumberger).

How is the nominal source level derived?

In addition to adding up the sound levels produced by each individual element in the array, the nominal source level of the array can be derived by back-calculating from measurements at different distances from the array. Back-calculation of source levels can be problematic, however, because a) we may not always be confident about the transmission loss during propagation through the water, and b) the shape of the array, a rectangular plane, means that the interaction between the elements in the array will differ with the slant angle between the receiver (animal or hydrophone) and the array.

The model below (Figure 23) illustrates how measurements at different distances in the far-field are used to back-calculate the nominal source level. Inside the near field of the array (at 10m or less from the center of the array), some rays show achieved levels of as much as 242-243 dB, corresponding to sound from the single largest single source within the array, but those sound pressure levels are still far short of the nominal 256 dB point source level we obtain in Figure 18 by adding up the contributions of the individual elements in the array.

Interaction effects with the other nearby CA sources within the near-field will also affect the received sound level from the array in the far-field, leading to the differing predictions of array source level, depending on the angle between the array and receiver. At near-horizontal angles (e.g. 70 degrees) the far-field received levels would predict a nominal point source level for the array that would seem to be 10 dB lower than the source level back-calculated on the vertical axis (252 dB SPL_{pp} versus 262 dB SPL_{pp}).

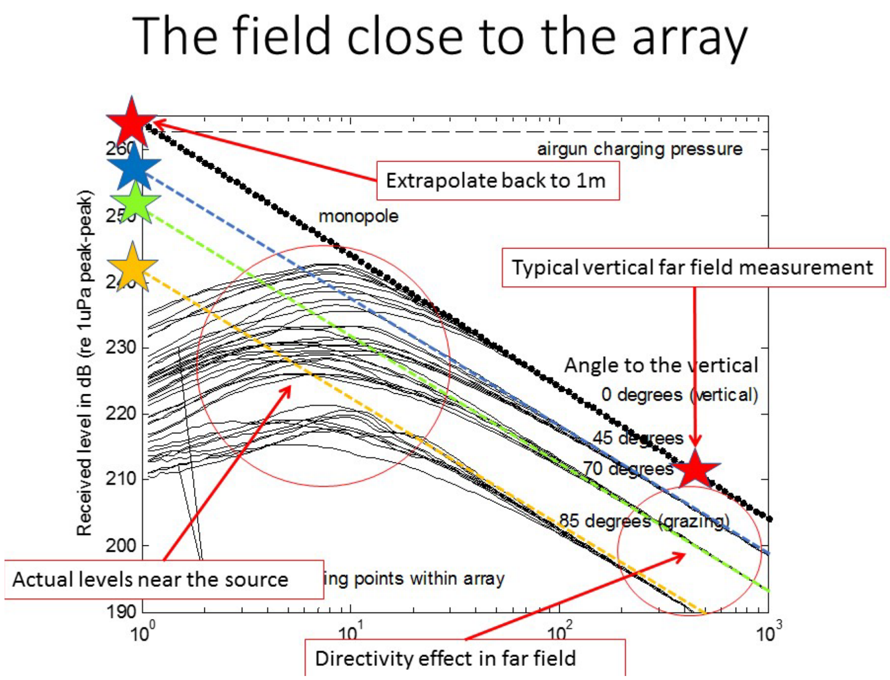


Figure 23. Modeled computations of received peak-to-peak sound pressure levels at different ranges and angles from a full seismic array. The figure illustrates how the nominal point source level is derived by back-calculating from far-field measurements, whereas the actual measurable values in the near-field fall some 20 dB or more below the nominal source level. At angles other than vertical (0 degrees) the acoustic wavefronts from the different elements in the array are not time-synchronous and the achieved peak or peak-to-peak SPL levels are thus considerably lower than they are on the vertical axis. (Courtesy of Robert Laws, with modifications.)

Another way of conceptualizing the somewhat conical downward focused sound field produced by the array is to view the received levels recorded by receivers at three depths (100m, 200m and 400m) as the array approaches the receivers (Martin et al. 2017; their Figure 11, reproduced as our Figure 24, below). The figure is best explained by the original wording in Martin et al. (2017):

"Seismic arrays concentrate sound in the vertical direction with an angular beam width that depends on frequency (Fig. S-9). As the vessel approached within 1 km of the recording station, the deepest hydrophone "entered" the beam first, and therefore as the vessel approached the received sound level at 400m depth rose before the levels at the 200 and 100m depths (Fig. 11). At the closest point of approach, all three hydrophones were almost entirely in the main lobe of the seismic array, so that the 100m deep

hydrophone had the highest sound levels since it was closest to the array and had the lowest geometric spreading loss."

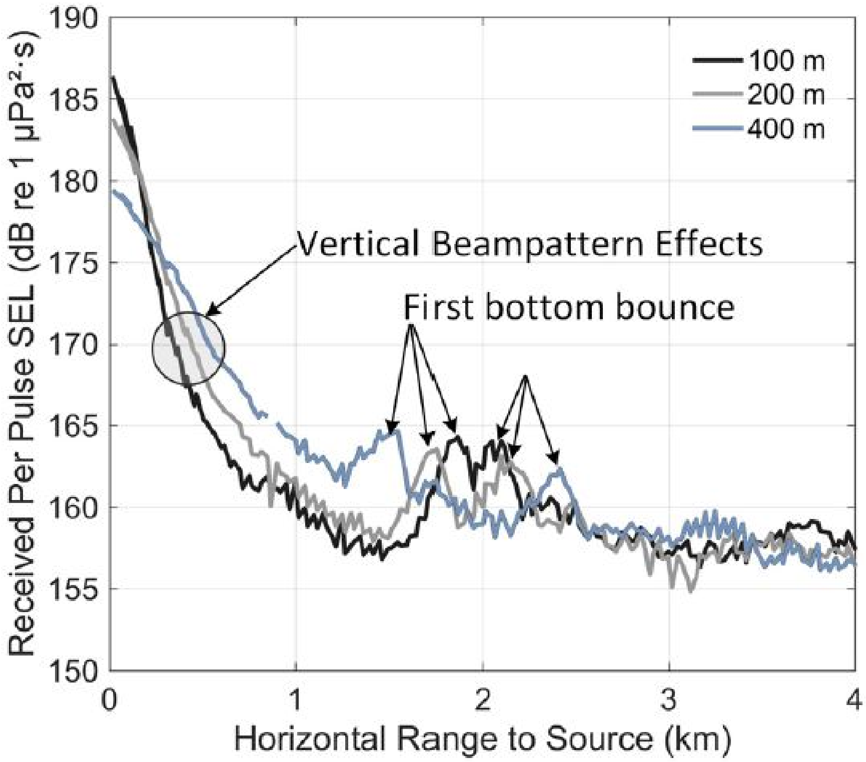


FIG. 11. (Color online) Per-pulse SEL for 125 ms impulses detected at Station BB3 hydrophones from the 3480 in.^{3} seismic source as it passed the station on 18 September 2012. Differences in received sound levels were primarily within the first 3 km from the source.

Figure 24. An illustration of the downward-looking conical shape of a CA array's output. As noted by the authors, the receiver at the greatest depth "sees" the outer edge of the conical sound field first and the receivers closest to the array do not generate higher received levels until the source is nearly overhead within about 100 meters horizontal distance from the array.

Source Level on the Vertical Axis is the Most Conservative, Precautionary Source Level

Since the User Spreadsheet Tool makes the most conservative, precautionary assumption that all animals are exposed to a "worst case scenario" equivalent to being directly below the array, estimates of range to threshold isopleths and corresponding MMPA takes will be higher than actual results for animals distributed normally around the array at different distances and depths. Alternatives of using the source level as propagated at some angle other than vertical mean that the source level will be lower, but also that the time course of the sound pulse and the resulting spectrum will also be different.

"Horizontal" Source Properties are not Truly Horizontal

The alternative option, as employed in BOEM (2016) and others, has been to use the source level and pulse spectrum from some angle between source and receiver other than the vertical, an angle that might better express what the majority of animals would experience since most marine mammals, even deep divers, spend the majority of their time in the upper 10-20 m of the water column. However, a different set of complexities arise when seeking a “more typical” angle at which to express array output. The term “horizontal” is often used to refer to pulse metrics that might better capture the exposures experienced by the majority of animals. However, the “horizontal” source metrics offered by BOEM (2016) and others are not truly horizontal, since the source and receiver would need to be very close to the surface: typically, less than 10 m depth. As seen above in Figure 23, truly horizontal pathways at 80-90 degrees from vertical produce a powerful reduction of received sound near the surface (around -40 dB) due to surface release phenomena (change of sound energy from pressure to particle motion near the air-water interface), Lloyd’s mirror effects in which surface-reflected sound interferes with incoming sound from below, scattering by air bubbles and biological structures in near-surface waters, and other propagation effects. This 40-plus dB reduction in apparent source level near the surface of the water is believed to be why dolphins are often seen bow-riding on the vessel and even the towed array floats themselves while the sound sources are active.

This problem with truly horizontal propagation pathways is also why recording instruments are almost never placed in the upper 10-20m of the water column, especially when recording low frequency sources like CA sources, where the majority of the sound occurs at wavelengths greater than the depth of the source (10-20 m corresponds to the wavelength of frequencies around 150-300 Hz). For frequencies lower than 150-300 Hz the upper 10-20 m of the water column is a kind of “shadow zone” where particle motion exceeds sound pressure. Since both marine mammals and hydrophones are pressure transducers and do not detect the particle motion component of sound, the perceived sound level is greatly reduced for low frequencies in the upper portion of the water column near the surface. Thus, reference to “horizontal” measurements of CA array output are not true horizontal sound measurements, but are most often a reference to complex multipath sound recordings made at distances several times the water depth and therefore seemingly “horizontal” because the depth of the receiver (e.g., at 100 m) seems nearly horizontal to the source when the source is 10,000 m away. At that point the sound is not a horizontal direct path product of the array, but the product of sound that has bounced off the surface and bottom multiple times, has entered the underlying geology and been re-introduced into the water and has been bent or refracted by the sound speed profile of the water. The received “horizontal” sound is actually made up of arriving sound from many pathways between source and receiver, and can only be unraveled to a nominal point source by complex ocean acoustic modeling.

Thus, the recommended option for simplified modeling without full animal movement and ocean propagation modeling, is a “worst case” prediction based on the vertical properties of the acoustic output. This choice of which alternative angle from the array other than vertical is a topic that clearly deserves careful consideration, but that discussion would need to involve complex and site-specific propagation factors like water depth, bottom type, seasonal sound speed profiles and proximity of recording devices to the surface or bottom, all of which cannot be fully explored in the context of the simple mathematics of the User Spreadsheet Tool.

Data from different distances and angles should not be mixed

One of the reasons why the revised User Spreadsheet Tool reduces the number of required user-entered values is to minimize the risk of users inadvertently mixing duration, source level, or spectrum values for different angles between source and receiver. Animals encountering the acoustic output of the array at angles other than directly below the array will receive a lower SPL_{pk}, but the receiver will also experience a different pulse duration (since the wavefronts from the different elements will be arriving at different times), and thus a different frequency structure, resulting in a different SPL_{pk} and hearing-weighted SEL.

Figure 25 illustrates how reduced alignment between the spatially separated sound sources in an array affects the time-amplitude signature of the array at angles departing from the vertical even before the confounding variable of propagation effects is introduced. For the vertical signature all sources are aligned in time, producing a single clear pulse. At a more horizontal angle, the contributions from the individual sources are not aligned in time (some are closer to the receiver, others are farther away) and this results in a "messier" series of smaller peaks, as well as a smaller reflected component ("ghost").

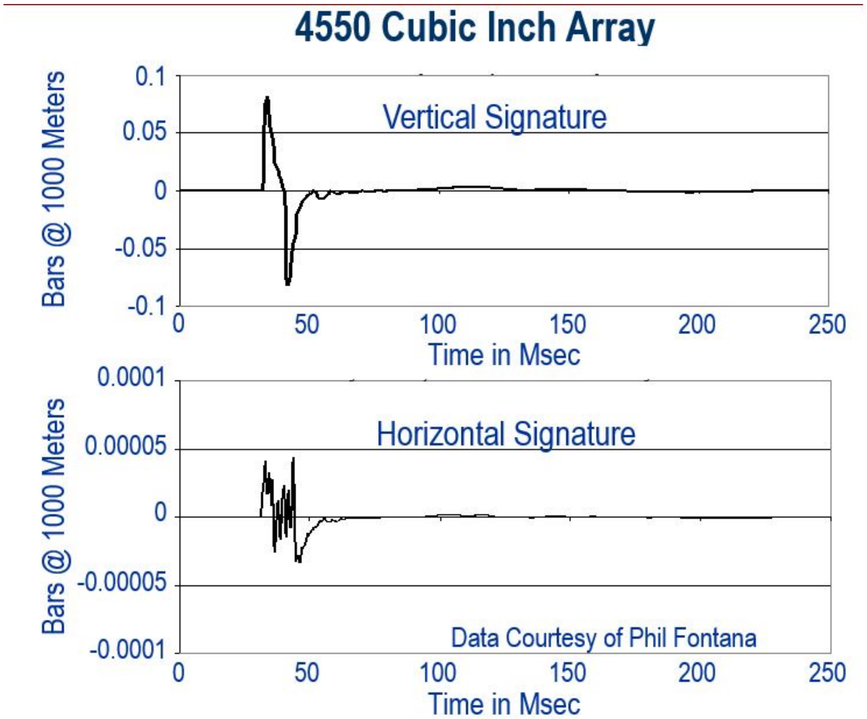


Figure 25. A recorded pulse from a 4550 cubic inch array used in the Gulf of Mexico EARS Buoy Study (SWSS), courtesy of Jack Caldwell, GeoSpace Engineering Resources International and obtained originally from Tashmukhambetov et al. (2004). The recording of the waveform in the upper figure was made at 1000 meters range directly below the array (Vertical Signature, above) while the recording in the lower figure was made at a similar distance, but at an angle near horizontal (about 60-70 degrees from vertical) in the lower graph. The x-axis, or time in ms is the same for both figures, but note that the signal amplitude on the Y-axis is different, with the lower scale being three orders of magnitude less for the horizontal signature relative to the vertical signature (+0.1 bar vs +0.0001 bar). Leaving the same scale on the Y-axis of both graphs would have produced a pulse of such small amplitude on the lower graph as to be nearly invisible at the scale used for the vertical pulse in the upper graph.

This complex aspect of a geometrical array like the standard seismic array can be illustrated in several ways that are relevant to considering how a biological receiver would be perceiving and processing the sound from the array at different angles. These are shown in Figure 26, below. Note that the low grazing angle received sound (at 70-80 degrees from vertical) is some 18-20 dB lower than the signal on the vertical axis (0-10 degrees), consistent with the data shown earlier. As we shall see in Appendix A for the derivation of a generic pulse spectrum, measurements at angles other than vertical may include more *relative* energy at higher frequencies, but the absolute levels are still so low (some 10-20 dB lower) that the decreased source level counters any potential increase in the hearing-weighted SEL that might be anticipated due to there being relatively more high frequency energy at more horizontal angles.

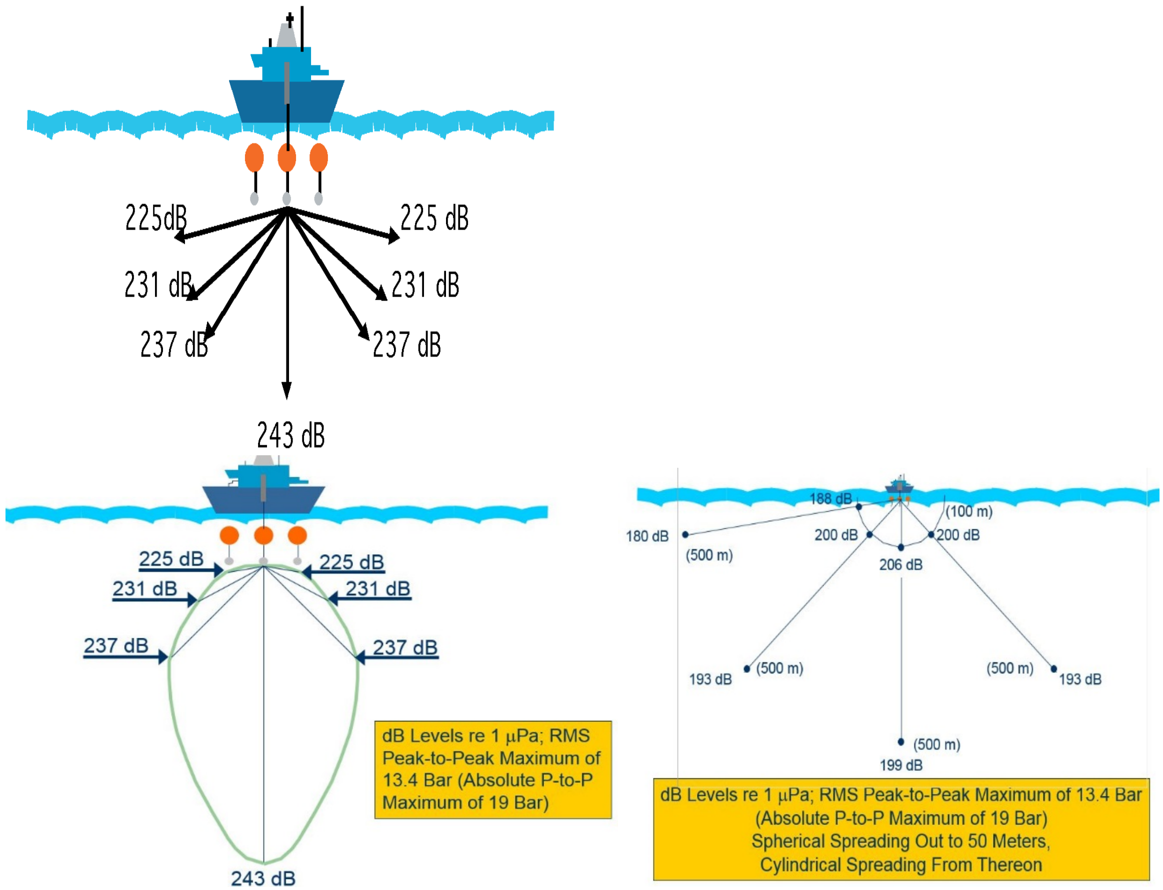


Figure 26. The difference in array gain obtained at representative angles from the vertical is illustrated in different ways from these three figures. The figure at upper left illustrates the maximum achievable received level for a receiver at different angles relative to the array. The figure at lower left illustrates the distance from the center of the array at which these levels are achieved. Since there is no appreciable array gain at horizontal angles, the maximum RL is achieved very near the array, whereas maximum amplitude below the array occurs at a great distance after the output of the spatially separated elements has aligned. And, finally, the figure at lower right illustrates that the direct path to a given regulatory range (in this case 500 m) yields received levels differing by as much as 19 dB from each other, depending on what angle the receiver is from the array at 500 m distance. In this example the values are dB SPL_{rms} re 1 µPa for the full peak-to-peak pulse (the primary pulse plus surface-reflected "ghost").

Propagation Effects of the Environment

Certain sound propagating conditions in the ocean environment may affect received levels as much or more than the source properties. At short ranges (less than 1 km), where most of the PTS isopleth estimates will fall, the spherical spreading propagation model is usually appropriate for deep water environments. But for longer ranges, and/or in shallow water, or under other unusual propagating conditions, the simple assumptions of the Alternate Methodology and User Spreadsheet may give inaccurate ranges to the PTS threshold. Among the conditions that should trigger a full propagation model and abandonment of the User Spreadsheet Tool are:

- Shallow water depths of less than 100 meters;
- Predicted PTS isopleth ranges greater than 1000 meters;
- Potential for unusual propagating conditions; including but not limited to warm unmixed surface water layers (surface ducts), ice covered waters, or mixing of water masses of different

temperature and salinity such as freshwater intrusions, frontal boundaries between currents or upwelling conditions at shelf edges; and

- When propagating the higher frequency component of the pulse (above 5 kHz) more than 1 km, propagation should be reduced due to attenuation of those higher frequencies by the molecular properties of dissolved salts in seawater.

Relationships Between Sound Pressure Level (SPL) Metrics: Peak-to-Peak SPL (SPL_{pp}), Zero-to-Peak SPL (SPL_{pk}) and Root-Mean-Squared Average SPL (SPL_{rms}) in the Output of a CA Source Array

The relationship between the most commonly presented metric for array amplitude, Sound Pressure Level (SPL), either peak-to-peak, zero-to-peak, or averaged (rms), is referenced to 1 microPascal (μPa) and other metrics of acoustic properties such as SEL (Sound Exposure Level) are highly consistent for CA array acoustics, due to the highly standardized academic and industry process for interpreting the geophysical data produced by the CA sound pulses.

Peak-to-peak SPL (SPL_{pp}) is typically 6 dB higher than (i.e., double) zero-to-peak SPL (SPL_{pk}), due to the nearly perfect reflection of the source energy in the vertical direction by the sea surface above the array, as illustrated in Figures 17, 18, and 23, as well as in another way in Figure 25, below. Surface roughness due to wind, waves, or other causes might reduce the contribution of reflected high frequency energy in some cases: for example, McPherson et al. (2019) obtained measured differences between SPL_{pp} and peak SPL_{pk} in the range of 5.3 to 5.7 dB for shallow water measurements and Sidorovskaya et al. (2019) obtained measured SPL_{pk} values that were 5.1 dB lower than SPL_{pp}. But for the wavelengths that comprise most of the energy in the pulse (e.g., 150 m wavelength for 10 Hz, 15 m for 100 Hz), the sea surface is a nearly perfect reflector, regardless of roughness created by wind and ocean swells.

Since the most common practice in the geophysical industry is to include the surface reflected energy in their source description, *the user should assume that the operator-provided nominal source level is the peak-to-peak SPL (SPL_{pp}) unless otherwise stated.* Inclusion of a time-amplitude waveform showing the characteristic inverse pressure pulse following the primary positive pulse is also an indicator that the nominal source level is a peak-to-peak value.

Peak pressure or zero-to-peak pressure (SPL_{pk}) refers to the energy directly produced by the array itself, without inclusion of the surface-reflected pulse. Since the start and finish of the pulse is difficult to pick out against the ambient background noise, the standard of practice is to define the peak amplitude of the pulse in terms of the time over which 90% of the total pulse energy is produced ($SPL_{0.9}$). Some practitioners, most notably JASCO (e.g., in BOEM, 2016 and McPherson et al., 2018), omit the reflected energy as a propagation effect and not a source property, as seen in Figure 28, which does not include an SPL_{pp} value.

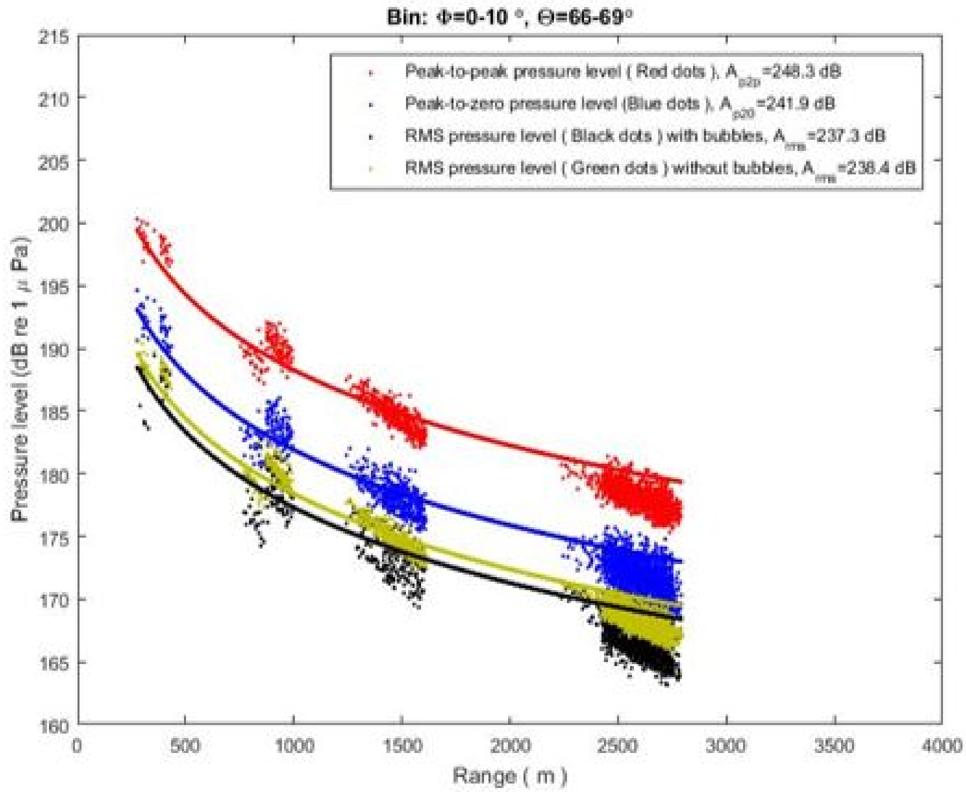


Figure 27. Relationship of SPL_{pp} (red), SPL_{pk} (blue), and SPL_{rms} (green and black) (Sidorovskaia, 2019 JIP 3D array project GOM).

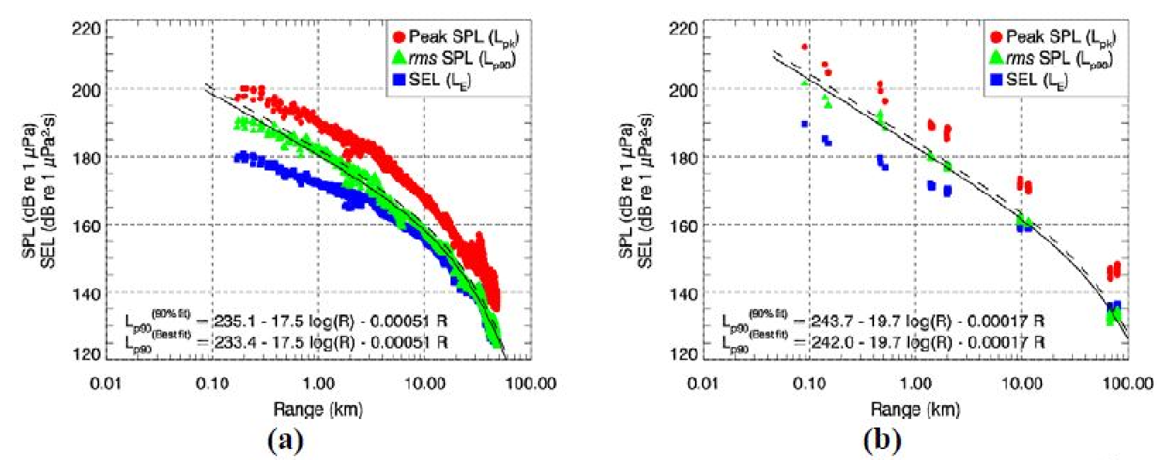


FIGURE 3.5. Peak SPL, *rms* SPL, and sound exposure level (SEL) versus range for 3000 in^3 array airgun pulses at the SSV site: (a) endfire on OBH A1, and (b) broadside on OBH A1, B, and C. Solid line is best fit of the empirical function to SPL_{rms90} values. Dashed line is the best-fit adjusted to exceed 90% of the SPL_{rms90} values.

Figure 28. Measured SPL_{pk}, SPL_{rms} and SEL for a 3000 cubic inch array. Measurements began at 200 m for passage of the source over a receiver and continued out to 50 km from the source (a; endfire); and for a series of sensors perpendicular to the source at 100, 200, 800, 1100 meters, as well as 10 and 70 km (Blees et al. 2010).

Root-mean squared Sound Pressure Level or SPL_{rms} is the averaged pressure over a given time span. Root mean square refers to the fact that sound pressure levels in decibels are on a logarithmic scale and cannot be simply added up to obtain an average, but must first be squared, before being divided by the number of samples. The RMS average pressure is the square root of the resulting number. This is a calculation that will not be familiar or easy for the non-expert user, making the revised Supplemental Guidance and User Tool a handy way to quickly generate an approximation of the relationship between SPL_{pp}, SPL_{pk}, SEL, and SPL_{rms}.

The current NMFS v.2 Spreadsheet Tool (see Section B) provides a place for the user to enter a value for SPL_{rms}, but since SPL_{rms} is not used directly in the NOAA 2018 threshold criteria for impulse sound, it is not directly relevant to the isopleth calculation for impulse sound sources and has therefore been omitted from the revised AM User Spreadsheet Tool. SPL_{rms} does bear a direct relationship with SEL, which is also a function of the averaged pressure over a given surface area (typically one square meter) during a reference timespan, typically one second of time. Since SPL_{rms} and SEL are both functions of SPL_{pk} together with pulse duration, we actually only need to provide either SPL_{pp}, or SPL_{pk}, to generate both SPL_{rms} and SEL. While the standard practice for presenting SPL_{rms} for an impulse is to use the 5% and 95% boundaries (90% of the signal energy), or SPL_{rms90}, some authors (e.g., McPherson et al. 2018) may use different averaging methods like averaging across a 125 msec window that they assumed to roughly approximate the integration time of the mammalian ear. The fact that SPL_{rms} measurement practices may vary among authors is another reason for not using SPL_{rms} as a data entry in the User Spreadsheet Tool.

Figures 27 and 28 above illustrate the consistent empirical relationships between peak-to-peak SPL, zero-to-peak SPL, average or RMS SPL, and SEL. Just as SPL_{pk} is almost always -6 dB lower than SPL_{pp}, so SPL_{rms} tends to fall another 6 dB or more below SPL_{pk}, depending on the breadth of that peak in time. This difference between SPL_{pk} and SPL_{rms} can vary between -6 to -12 dB, depending on how well-aligned the pulses are and how far the signal has propagated from the source, since both alignment in time and distance traveled tend to broaden the pulse and thus reduce the difference between SPL_{pk} and SPL_{rms}. Based on measurements made at 70-1000m from the source, we consider -6 dB to be a conservative, precautionary factor for deriving SPL_{rms} from SPL_{pk}. At greater ranges or in limiting oceanographic conditions mentioned earlier, SPL_{pk} and SPL_{rms} will become equal. This relationship is reinforced by the analysis by McCauley et al. (2016) (Figure 29), which compiled 49 data sets obtained from 24 different seismic arrays. SEL approximately follows SPL_{pp} -22 dB, or the sum of the – 6 dB difference between SPL_{pp} and SPL_{pk}, the -6 dB difference between SPL_{pk} and SPL_{rms}, and the -10 dB difference between SPL_{rms} and SEL.

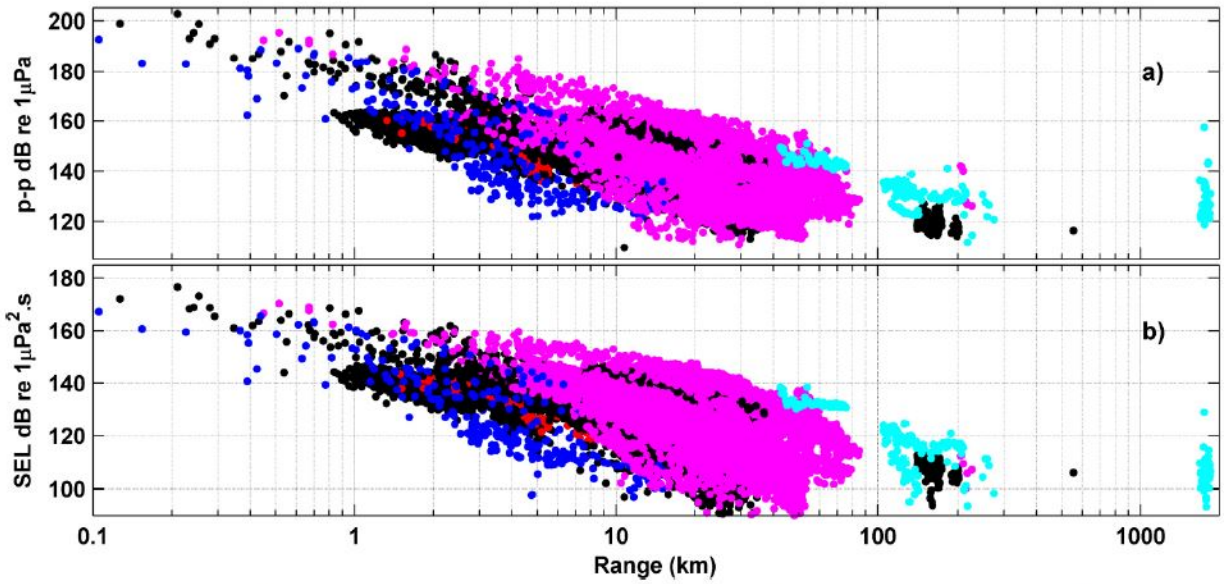


Figure 2: **Transmission decay curves** for all sets of air gun signals analysed in peak to peak (a) and SEL (b) units over ranges of 10 m to 1850 km. For clarity only every 25th air gun signal is displayed. Data sets are colour coded as: 0 to 1000 cui blue; 1000 to 2000 cui red; 2000 to 3000 cui black; 3000 to 4000 cui magenta; 4000 to 5000 cui cyan.

Figure 29. McCauley et al. (2016) provided synthesized measurements from 49 separate data sets for 24 different source arrays. Only SPLpp and SEL are shown, but they exhibit the same relationships illustrated by Blees et al. (2010) and Sidorovskaia et al., (2019). SEL is approximately 22 dB lower than SPL_{pp}. Note the different scales on the Y-axis for peak-to-peak SPL (top) and SEL (bottom).

Sound Exposure Level (SEL) Metrics: Pulse Duration and SEL; Cumulative SEL (SEL_{cum})

Sound Exposure Level (SEL) is a function of SPL and pulse duration, as a measure of the energy over time required to maintain a specified sound pressure level. In ISO and ANSI standard terminology SEL is standardized relative to a 1 second constant, and SPL_{rms} = SEL for a one second duration sound. We therefore need to adjust SEL relative to SPL_{rms} for sounds shorter than 1 second, since less energy is required to produce the specified SPL_{rms} for a duration less than 1 second. At short ranges (less than 500-1000 m in most cases) measured SEL tends to fall between 16-20 dB below SPL_{pk}, or 10-14 dB below SPL_{rms}. Based on the short duration of the primary pulse (see following section) we might expect, and sometimes observe, differences between SPL_{rms} and SEL of -20 dB or more. However, the small contribution of acoustic energy from bubble oscillations following the primary pulse, along with spreading of the pulse in time as it propagates, combined with other factors such as imperfect array alignment, all argue for -10 dB as the more conservative and precautionary relationship to apply when generating nominal source SEL from SPL. This conservative approach (-10 dB) has been confirmed by three large independent high-quality data sets illustrated above.

Fortunately, we have a large data set of very precise measurements of pulse durations at short range from a real operational 3D survey array (Figure 30, Sidorovskaia et al., in prep. – these data are not published yet but are part of a contract project by JIP and will be available to support the uptake of the revised guidance in a timely manner when needed).

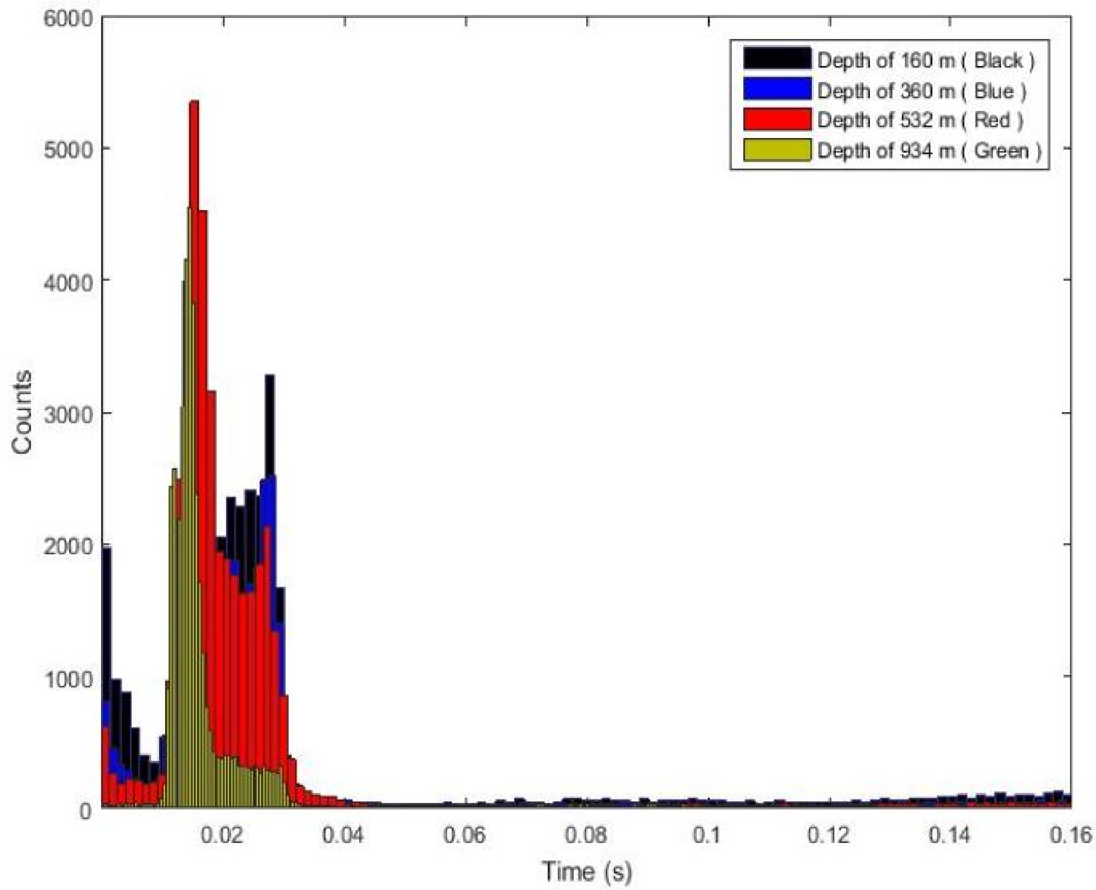


Figure 30. Durations of recorded pulses from a full 3D array. Pulse durations below 0.01 s in this figure are most likely include misfires and ambient noise spikes that triggered the data recorders (Sidorovskaia, in prep).

Similar results were obtained by JASCO Applied Sciences (Austin et al., 2016); see Figure 31 below. Note that the pulse duration near the source is between 0.01 s and 0.02 s, then at a range of about 500 m in this shallow water environment, the sensor begins to pick up multiple peak arrivals from surface or bottom-reflections and gets "confused" about the pulse duration before settling into a consistent pattern of increasing pulse duration from around 2 km (pulse duration = 0.2 s) to 20 km (pulse duration = 3.0 s). Note too, however, that the SPL_{rms} at 500m is about 175 dB and that therefore most, if not all NOAA 2018 (a) PTS threshold values would likely occur at ranges less than 500 m in this example.

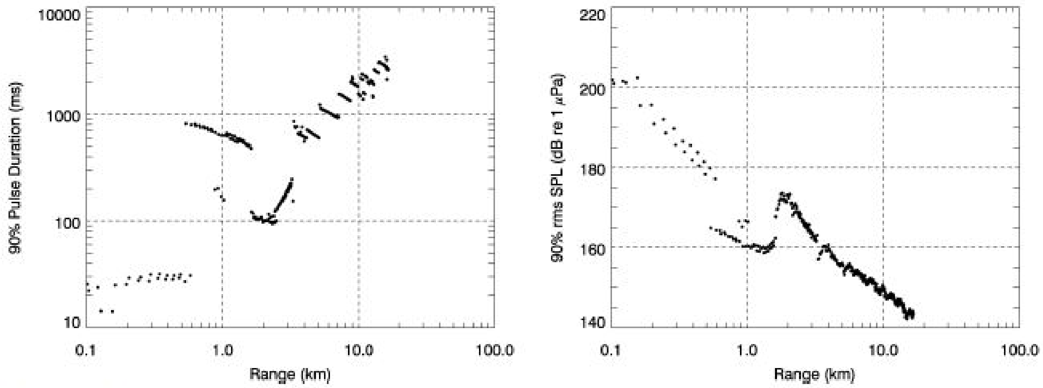


Figure 13. *Amani* airgun array 90% energy pulse duration and root-mean-square (rms) sound pressure leve (SPL) as a function of range at Station BB3 Top for Track 5.

Figure 31. Measurements of SPL_{rms} and pulse duration from Austin et al, 2016. Measurements are from a shallow water environment in the Chukchi Sea.

For our purposes in this discussion, and as a default for the User Spreadsheet Tool, we adopt 0.1 s as the typical pulse duration near the array, which is highly conservative and precautionary, since the median values actually fall closer to 0.02 s.

That said, reported pulse durations in the literature vary considerably, due to differences in the range from the source at which the pulse is recorded and the methodology used to determine pulse length (e.g. compare Hildebrand et al. (2009) to Zhang et al. (2017). As we saw earlier in Section C, small contributions to the total acoustic output of the array occur up to 300 msec after the primary, and even at longer delays after the primary pulse for array output sampled at near-horizontal angles, where sound from array elements furthest from the receiver may arrive 300-800 msec after the sound from the array elements closest to the receiver, depending on the dimensions of the array and position of the receiver.

Acoustic Energy outside of the Primary Pulse

The energy from the late arriving bubble oscillations described above, as well as from cavitation bubbles created by interaction between the pulse and its reflected "ghost" all collectively comprise only a tiny fraction of the total acoustic output. These smaller contributions are separated from the >90% of energy in the primary pulse by 100-200 msec periods dominated by ambient noise. This means that a non-trivial amount of ambient noise will also be incorporated into pulse SPL and SEL metrics if longer pulse durations are employed. For that reason, we recommend that the default pulse duration should only include the primary pulse, recognizing that a small percentage of the total acoustic energy (less than ten per cent) is not included in the duration of the primary pulse, but is more than compensated in the precautionary assumptions applied to the SPL and derived SEL and frequency spectrum. A correction factor, described below, is applied to prevent the data from the primary pulse alone producing underestimates of high frequency energy (above 300 Hz) produced by bubble oscillations following the primary pulse.

For example, if SEL is calculated only from the primary pulse, the relationship between SPL_{pk} and SEL would not be SEL = SPL_{pk}-16 dB (pulse duration 0.1 s), but closer to SPL_{pk} - 26 dB (pulse duration ≈ 0.01 s) at the source. But empirical measurements of SPL_{pk} and SEL even at short distances of a few hundred m show that the relationship between SPL_{pk} and SEL includes energy after the primary pulse and therefore

SPL_{pk} -16 dB is the more conservative, precautionary relationship to apply in the simplified calculations of the Alternative Methodology.

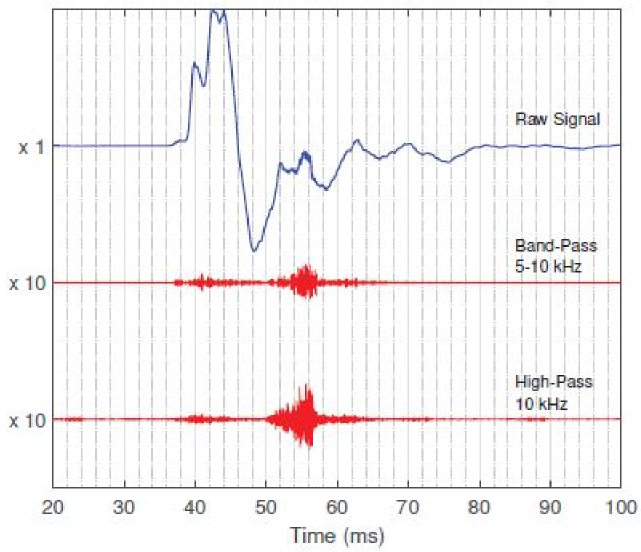


Figure 1.7: recorded signal from a full air-gun array and its frequency contents in 5-10 kHz and >10 kHz bands are plotted after amplification by a factor of 10.

It is seen that the majority of high-frequency energies appear with around 8 ms time delay after the main peak (direct arrival). This time delay roughly corresponds to the ghost pressure wave to reach 2-3 meters above the mid-array. Landrø et al. (2011) hypothesized that these high-frequencies are due to the cavitation phenomena and called it ghost cavitation. That is the reflected pressure waves from the sea surface (i.e. ghost) drop the hydrostatic pressure below the water vapor pressure which can induce cavitation.

Figure 32. Khodabandeleroo (2016) band-pass filtered the high frequency energy from an array pulse to illustrate where in time most of the high frequency energy in an array impulse occurs. As Khodabandeleroo notes, most of the high frequency energy is due to tiny cavitation bubbles generated within the array space due to the interaction of the source pressure pulse and the reflected pulse that is 180 degrees out of phase with the source pressure pulse, resulting in points where the negative pressure is great enough to produce cavitation (tiny voids or vacuums within the volume of the water). The cavitation bubbles are very small and therefore produce high frequency sound as a result.

Use of the primary pulse alone would not convey the added high frequency energy from the pulse that occurs 8 to 300 msec after the primary pulse. As a consequence, the relative proportion of high frequency 1/3 octave bands in the received pulse is greater than would be predicted by the Fast Fourier Transform of the primary pulse alone. The proposed generic spectrum applies a lower-than-predicted difference between SPL_{rms} and SEL, which also provides higher-than-predicted values for higher frequency bands, thus allowing for the small but non-trivial contributions from higher frequency bands generated by bubble oscillations and cavitation interactions following the primary pulse. This is one of several conservative, precautionary assumptions of the revised User Spreadsheet Tool that contribute to the likely over-prediction of risk, especially for the HF Cetacean Hearing Group that is most sensitive to high frequency sound.

An alternative rationale to that provided by Khodabandelaroo (2016) (Figure 32) is offered in an analysis by Carr et al. (2010), which also arrives at a simplified -10 dB relationship between SPL_{rms} and SEL.

"For in situ measurements the SEL, pulse duration, and 90% rms SPL can all be measured, and SPL is related to SEL via a simple relation that depends only on the rms integration period T:

SPL_{rms90} = SEL – 10log(T) – 0.458

Here the last term accounts for the fact that only 90% of the acoustic pulse energy is delivered over the standard integration period. In the absence of in situ measurements, however, the integration period is difficult to predict with any reasonable degree of accuracy, for the reasons outlined above. The best that can be done is to use a heuristic value of T, based on field measurements in similar environments, to estimate a rms level from the modeled SEL. Safety radii estimated in this way are approximate since the true time spreading of the pulse has not actually been modeled. For this study, the integration period T has been assumed equal to a pulse width of ~0.1 s resulting in the following approximate relationship between rms SPL and SEL: SPLrms90 = SEL + 10

In various studies where the SPLrms90, SEL, and duration have been determined for individual airgun pulses, the average offset between SPL and SEL has been found to be 5 to 15 dB, with considerable variation dependent on water depth and geo-acoustic environment (Greene et al. 1997; Austin et al. 2003; Blackwell et al. 2007; MacGillivray and Hannay 2007)."

The same relationship is applied between SPL_{rms} and SEL by Blees et al. (2010) in a slightly different formulation:

$$L_E = L_{P90} + 10\log(T_{90}) + 0.458.$$

For example, a measured SPL_{pk} of 260 dB for a primary pulse duration of 0.02 s, would yield an SPL_{rms} of 254 dB and an SEL of 254 +10*log(0.02) = 237 dB if we used primary pulse duration alone. But, as noted, the chosen convention for the revised Alternative Methodology is to simply use SPL_{rms} – 10 dB = SEL, yielding an estimated SEL of 244 dB, which is more conservative (precautionary) than calculating SEL using the primary pulse duration (0.02sec). This conservative relationship between SPL and SEL is consistent with a large body of measured data cited earlier in this section and carries the added advantage of providing conservative precautionary over-estimates of SEL in the high frequency bands contributed by events after the primary pulse (bubble oscillations and cavitation bubbles produced by the interaction of the primary pulse and surface-reflected pulse or "ghost").

Frequency Spectrum of The Pulse and Hearing Weighting Functions.

How do we get frequency structure out of an impulse sound?

One of the most difficult concepts for non-acousticians to grasp about impulse sound is how an impulse sound, which has only one or a very few pressure oscillations over a very short time, can have frequency or pitch as we understand those terms. Pitch and frequency refer to the number of pressure oscillations per second in a sound, like the Middle C on a piano, which is produced by a sound frequency of 262 Hz or 262 pressure oscillations in a second. So how can a seismic sound with only one pressure oscillation that takes place over a tiny fraction of a second have frequency content as we understand that term? The answer is that the pulse can be mathematically transformed into a set of oscillations of different rates of pressure fluctuation (frequency) that, when combined, would produce the pressure time course we see in a brief impulse sound. Even an introductory text can be daunting (e.g., Cohen, 1995), so we take the unusual step of also referring to a basic Wikipedia definition in the hope that this will help the non-expert reader gain some basic understanding of spectral analysis and the tools used for transforming an impulse into a frequency structure like the Fast Fourier Transform (FFT): https://en.wikipedia.org/wiki/Time%E2%80%93frequency_analysis

There is also a practical reason for going to the trouble of performing a frequency transform on an impulse sound: the ear also transforms the pulse into "component frequencies" just like a mathematical transform; apportioning the signal energy differentially to different parts of the hearing structures of the ear. In other words, our ears hear the same mix of frequencies in an impulse sound that a mathematical transform of the pulse, like a Fast Fourier Transform (FFT), would produce.

For that reason, a pulse that is mathematically transformed into its "component frequencies" is the foundation of the weighted SEL criteria in the NMFS (2018a) guidance, and is intended to replicate the auditory experience of the impulse sound by the ears of a particular marine mammal hearing group (e.g., otariid pinnipeds, or low frequency cetaceans). As explained in NMFS 2018a, the use of dual criteria, both SPL_{pk} and SEL, is intended to capture both the mechanical effects on the structural anatomy of the ear (the SPL_{pk} threshold) as well as the neurosensory fatiguing effects from stimulation of the cochlea and auditory nerve (the weighted SEL threshold).

The differential calculus required to generate an FFT from an impulse sound, and the tens of thousands of calculations required to apply frequency-specific weighting functions across the more than 20,000 single Hz frequency values in a CA array pulse would require the user to know how to use software that can perform an FFT (MatLab is just one of many examples of such software toolkits[2]) and to then apply the appropriate weighting function calculation to each frequency. Software such as MatLab or the statistics software R can be used to create an automated process for running these calculations, but that implies a level of expertise in the use of such software that many concerned stakeholders and regulatory agencies may not possess, and for which the User Spreadsheet Tool may be a helpful means of obtaining a rough, preliminary idea of the potential risk posed by a given sound source, and the further effort needed, including more expert modeling, in order to make sound, science-based decisions about a given manmade sound source.

Example of a CA array frequency spectrum & proposed way forward

In its User Guidance for the Optional User Spreadsheet Tool v.2, NMFS (2018b) offers an example of one-third octave (TOB) integration of the energy spectrum of the pulse as a means of reducing the calculations required to generate a weighted SEL. The spectrum is taken from the CA array specifications used in the BOEM PEIS for the Gulf of Mexico (BOEM, 2016). However, NOAA did not offer a tool to enable the user to apply this one-third octave methodology in their initial 2018b User Spreadsheet Tool. The proposed revised User Spreadsheet Tool (see Section A) enables users to calculate a hearing-weighted SEL threshold that is either based on the user's specific source of interest, or a default Generic Spectrum derived from several examples of CA array spectra from the literature (see Appendix A for details of the process by which a generic pulse spectrum was derived).

[2] Mention of a specific commercial product does not imply endorsement.

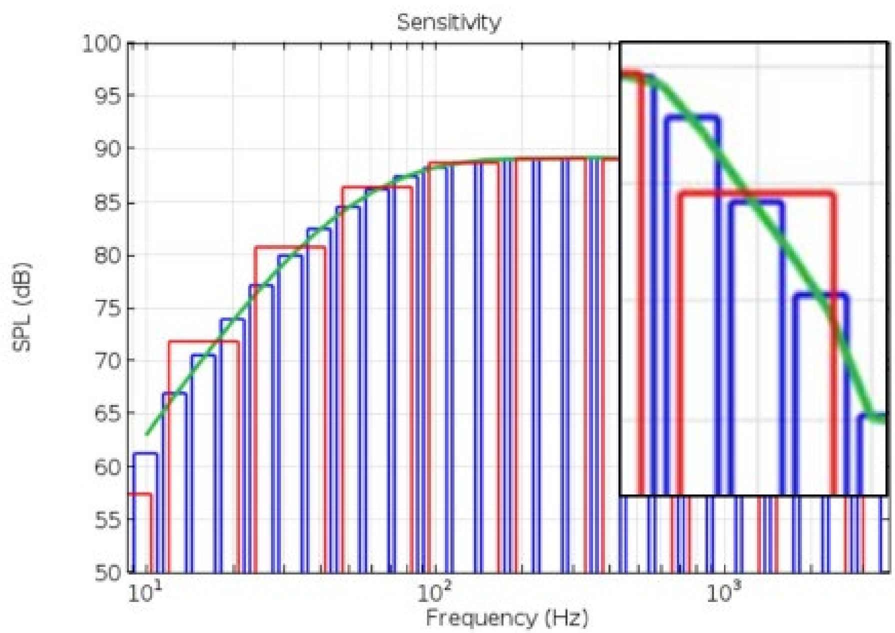


Figure 33. When using 1/3 octave bands (blue) the SPL or SEL at the center frequency of the band should represent an average of the SPLs or SELs of the individual frequencies in the band (green line). That is, the pressure or energy values above and below those at the center of the band should be equal, as in this example. (https://www.comsol.com/blogs/new-octave-band-plot-for-acoustics-simulations-in-version-5-2/)

One-Third Octave Bands

One-third octave bands are used not only for simplifying the burden of calculations, but also because 1/3 octave bands are more biologically relevant than single frequency SPL or SEL values, since the mammalian ear tends to also process the incoming acoustic energy in approximate one-third octave bands[3].

There are a couple of assumptions in using 1/3 octave bands instead of single frequency weighting. One assumption is that the amplitude differences between the single frequencies within a band are such that the SPL or SEL at the center of the band closely corresponds to the average across all frequencies within the band (e.g., Figure 33). The default spectrum offered in Appendix A is a smoothed spectrum composed of the averages of multiple measured spectra, thus eliminating the potential for selection of a non-representative value for a given band (e.g., selection of the SEL at a "ghost notch"). Users providing their own one-third octave values must be aware of this issue. An example of this "smoothing" is shown in Figure 34.

[3] A more recently proposed alternative decimal band system, the deci-decade (ISO, 2016), also closely aligns with the one-third octave banding structure (within 0.08%).

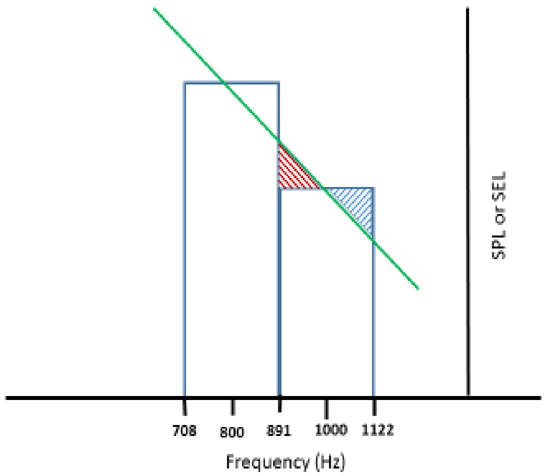


Figure 34. The bars outlined in blue represent standard 1/3 octave band and their center frequencies. The green line tracks the actual single frequency spectrum. This simplified illustration highlights the need for the center frequency of the band (in this example 1000 Hz) to be representative of an average of the band (i.e., the area of the red triangle, SEL values above that of the center frequency) should equal the area of the blue triangle (SEL values below that of the center frequency). Selecting a value to be representative of the band as a whole should include an equal number or area of values over the representative value and under the representative value. This is especially important for a complex impulse sound output as from a CA array, due to the peaks and valleys of constructive and destructive interference between the different elements and between the direct downward signal and the surface-reflected signal.

The second consideration is that the SEL metric is an energy metric and not a pressure metric, and therefore the amount of energy in a one-third octave band is a function of the band's width or its range of included frequencies. To calculate the one-third octave SEL, the center frequency SEL must be corrected for bandwidth, using the formula:

$$SEL_{Center\ Freq.} + 10 * \log{(bandwidth)}$$

In other words, an SEL value of 200 dB SEL at the center of the band (1000 Hz) would need to be adjusted for the sum of single-frequency energy values across the width of the band (891 Hz to 1122 Hz) by the addition of 23.6 dB (=10*log(1122-891)), and not the 200 dB SEL value for the center frequency alone. The result, as one can see in Figures 35 and 36, is that a TOB spectrum should present larger SEL values than a single frequency spectrum, especially at higher frequencies, where the 1/3 octave bandwidth is broader than at lower frequencies (i.e., there are more single frequency SEL values being added together within the TOB at 2000 Hz than there would be at 20 Hz). Figure 35 illustrates the increase in 1/3 octave band SEL relative to the single frequency SEL values.

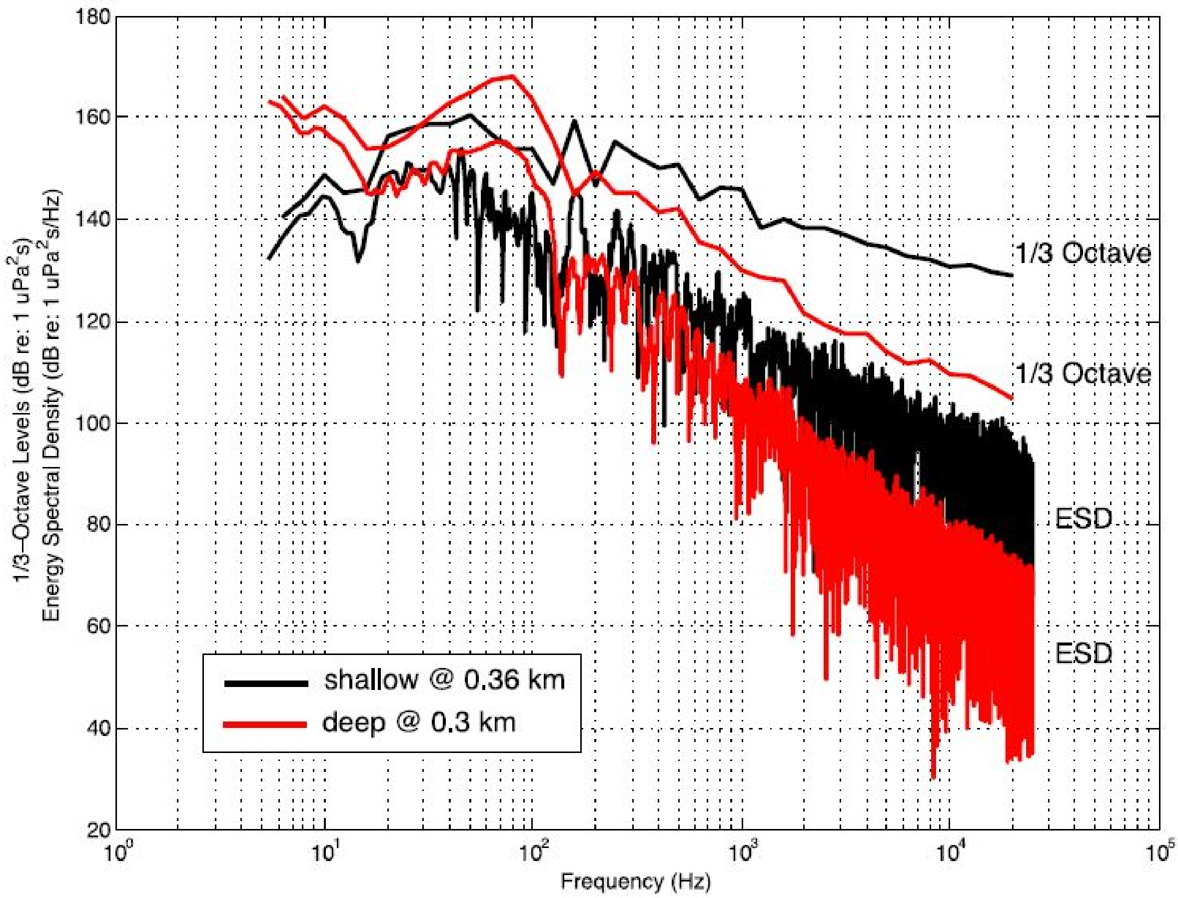


Figure 35. Example of the difference in single-frequency SEL levels (ESD) and one-third octave band SEL values. The one-third octave band levels are higher than the single frequency values because there is energy from more than one frequency within each band. This is especially true at higher frequencies where the bandwidths are wider and therefore sum up the energy from more frequencies. (Tolstoy et al., 2009).

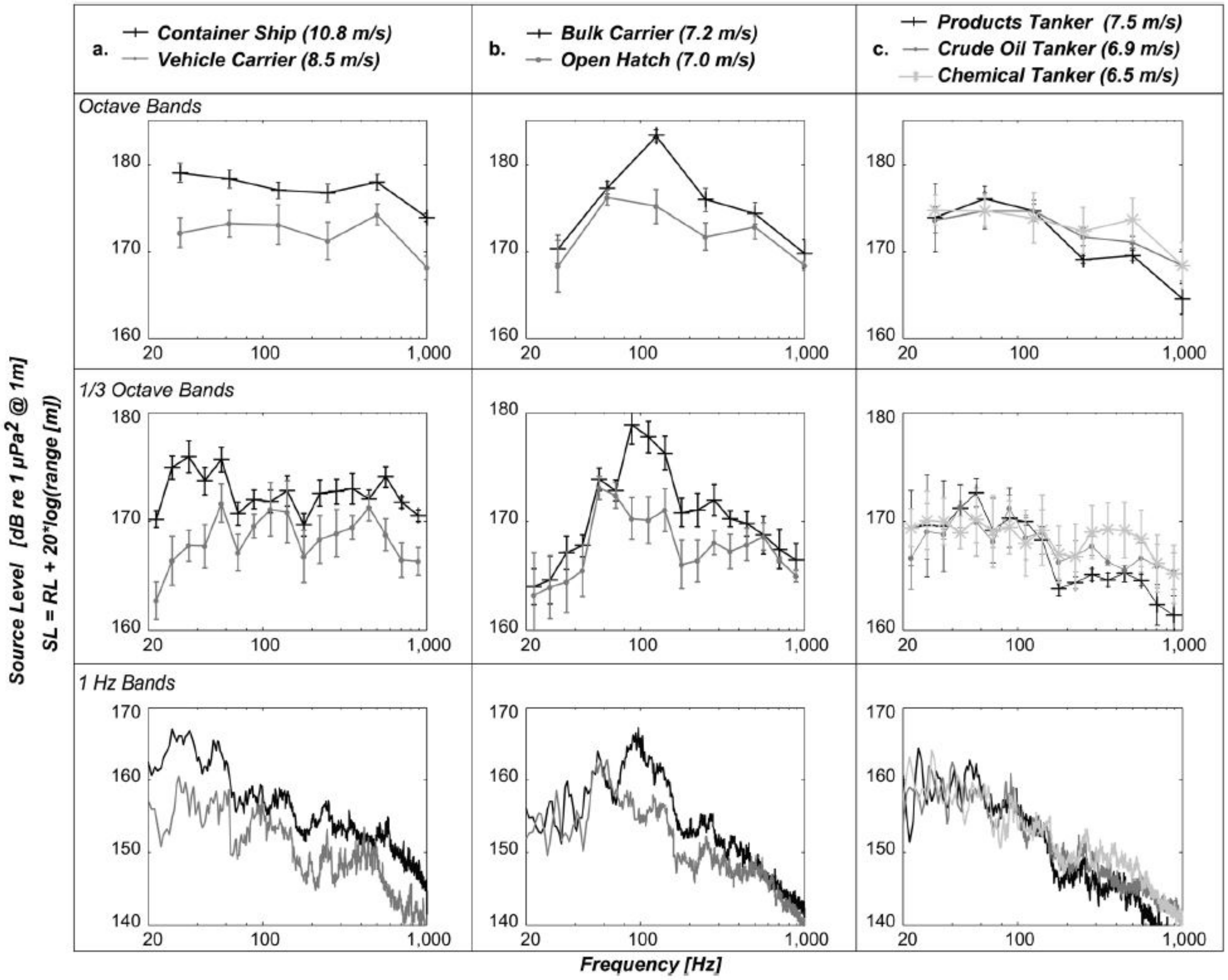


Figure 36. In this comparison of broadband ship noise displayed in 1 Hz (single frequency) bands (bottom row), 1/3 octave bands (middle row) and 1 octave bands (top row) from McKenna et al (2012), the effect of broader bandwidths at higher frequencies can be seen. Note that the 1/3 octave values at the far right (for frequencies above 500 Hz) are elevated relative to the single frequency values. Ideally, the one third and full octave band figures would be presented as bar graphs and not line graphs, since each point actually represents a range of frequencies. Also note that the scales on the Y axes are not the same, with the 1/3 octave band scale being 160-180 while the single frequency scale is 140-170 (McKenna et al., 2012).

In Section A of this document, we explain how to use an accessory tool, the Generic Pulse tool (Tab F4), to enable the user to input their own 1/3 octave SEL values to generate a weighted SEL for each Hearing Group in the NMFS guidance or to use a default generic spectrum derived from multiple sources. Because all seismic arrays are designed for a very similar purpose there is actually relatively little variation in the pulse spectrum for different CA arrays, especially when parsed into 1/3 octave bands, which tend to smooth out minor fluctuations in individual array spectra.

Resources for Additional Background Information

For further information on the basics of seismic sound sources the interested reader is encouraged to consult the website of the International Association of Geophysical Contractors (www.iagc.org) or experts in the commercial and academic marine geophysics community such as the Lamont-Doherty Earth Observatory (LDEO) (https://www.ldeo.columbia.edu/), and the Society for Exploration Geophysics (SEG) (https://seg.org/).

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SECTION E: ACKNOWLEDGEMENTS

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APPENDIX A: DERIVATION OF THE GENERIC CA SPECTRUM

Methods

Capturing Data Points from a Spectrogram

Spectra of geophysical signals are rarely available in numeric formats, but are sometimes published in visual form. Accordingly, we utilized a graph digitization program to translate these figures into numeric data suitable for compilation into a generic spectrum.

To generate the parameters of a generic CA array spectrum, we digitized openly available spectrograms using the free software GetData Graph Digitizer[4] (http://getdata-graph-digitizer.com/). The digitized files used to generate the amplitude of the 1/3 octave center frequencies have been archived for inspection if desired, but will need to be opened using the GetData software. GetData allows the user to use a variety of standard image formats (e.g., JPEG or similar), to set the locations of the axes and the ranges, and then to manually select points. If a 1/3 octave center frequency falls on a ghost notch or peak, a point intermediate between the two surrounding center frequencies was used, essentially smoothing the frequency spectrum.

Images saved as .jpg, .tf, .bmp, or .pcx files may all be used with the GetData software, either directly (i.e., downloaded as an image online) or by taking a screenshot of the image of interest. To import the image into GetData, the user selects the 'file open' icon (circled in green) and then browsing to the location where the file is saved. This example (Figure 37) uses a published spectrogram from Tolstoy et al. (2009).

[4] Mention of a commercial software product does not imply endorsement.

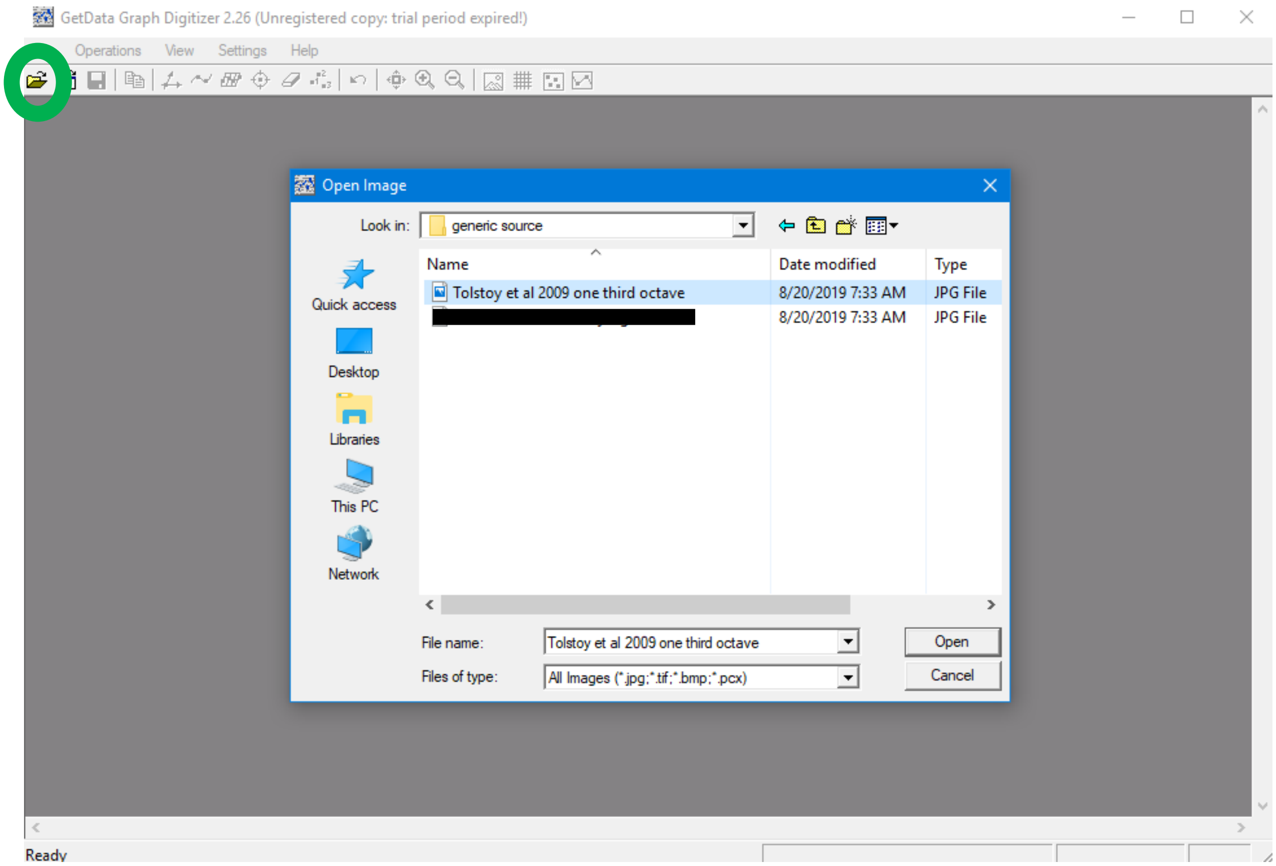


Figure 37. Screenshot of the GetData file import screen.

Once the spectrogram is opened, the axes are designated using the “set the scale” button, circled in green in Figure 38. To set the lower limit of the x-axis, use the cursor to hover over the general area of the point. The box in the lower right provides a magnified view (indicated in the purple box in Figure 38). Once the cursor is in the general vicinity, holding the Ctrl key allows for precise positioning. Click to set the point, and then enter the appropriate value (in this case “1”) in the pop-up box. Repeat for the upper limit of the x-axis, and the upper and lower limits of the y-axis. Once complete, a pop-up window will show the entered values, where the axes values can be corrected if necessary. Tick the box to indicate a logarithmic scale as appropriate, and then click “OK” (Figure 39).

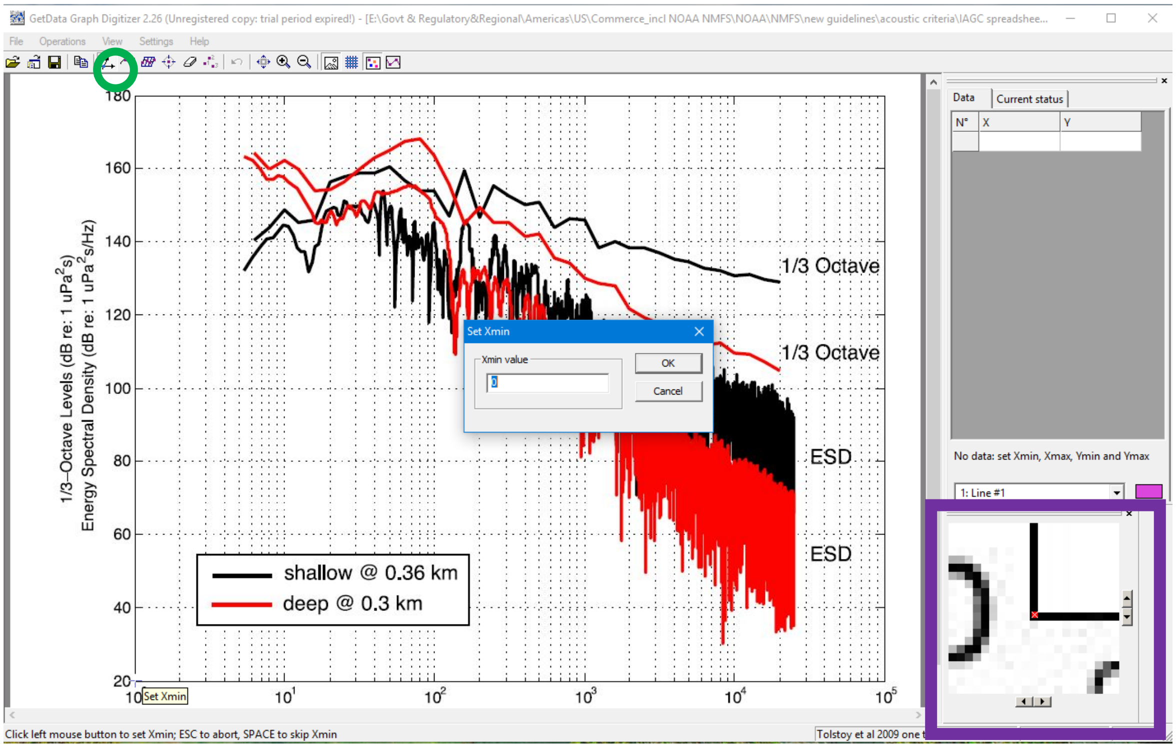


Figure 38. Screenshot of the GetData tool for setting X and Y axis value scales.

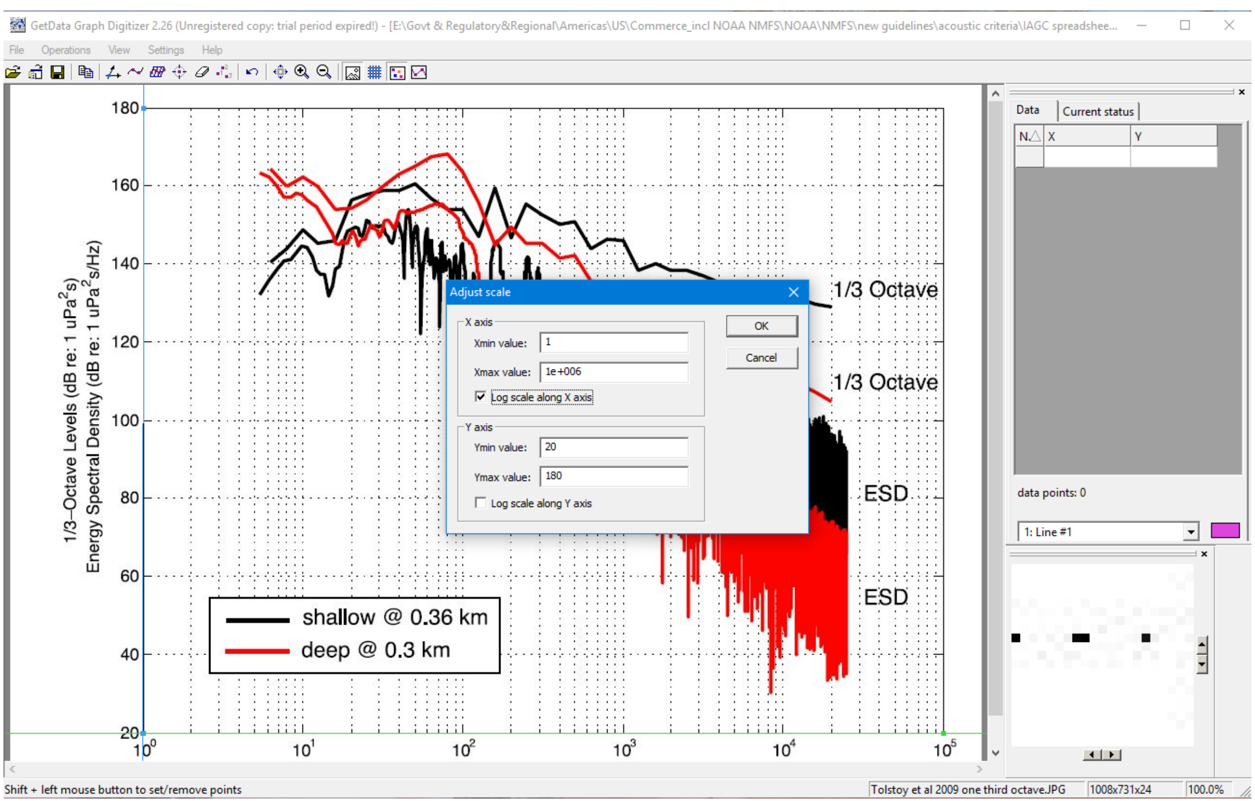


Figure 39. Screenshot of the GetData data point selection process.

Once the axes are set, select the "point capture" button (circled in green below, Figure 41). Points can then be manually selected using the same method used to set the minimum and maximum values for the axes. On a click, the x and y coordinates of the point populate in the window in the upper right, shown in the purple box of Figure 41. (For this example, these points correspond to the 1/3 octave line in deep water at 0.3 km; upper red line.)

In order to digitize the figures utilized for the analysis, a point with the x-coordinate approximately corresponding to the center frequency of each third octave band was selected as accurately as permitted by the resolution of the spectrogram figure being used. In places where a notch or irregularity in the data was apparent, the slope was visually smoothed relative to the neighboring TOB to provide a conservative estimate of average energy in the band (Figure 41). Not all sample spectra provided a full 1 Hz to 20+ kHz spectrum. These spectra were digitized within their given range without extrapolation, and bands with no data were omitted from the calculation of the geometric mean for the generic pulse (i.e., not all TOB values in the generic spectrum were derived from the same number of exemplars).

All selected references provided data up through 20 kHz TOB at the high end of the spectrum. The amount of energy in a pulse from a CA array above the 22.3 kHz upper boundary of the 20 kHz TOB is less than 0.01% of total pulse energy and would not contribute significantly to the derivation of isopleths, and is therefore not included in the generic spectrum tool.

Parameters of the array acoustic output were based on the vertical (maximum SPL) parameters. "Horizontal" spectra or slant angle spectra were avoided. We have outlined our rationale for preferring to use the nominal vertical array parameters in Sections A and C of the proposed revised guidance.

That said, a spectrum other than vertical can easily be generated, if concurrence is reached within the expert community about an appropriate angle from the array to use as the standard for simplified modeling purposes. Selecting an option other than vertical means that the relationships between pulse SPL, SEL, spectral distribution of energy, and pulse duration will all co-vary. As noted earlier, whatever the chosen standard, the peak source level, pulse duration and spectrum all need to match. Mixing parameters from different angles and ranges will lead to incorrect isopleth predictions: e.g., a vertical maximum source level should not be combined with a pulse duration or derived spectrum from some other slant angle from the array.

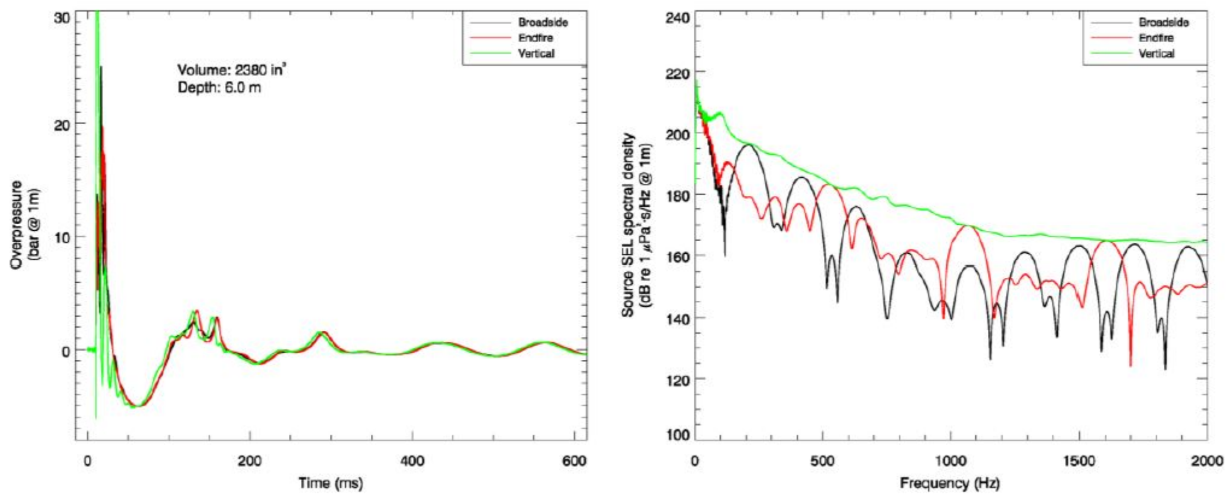


Figure D-5. Predicted source level details for the 2380 in^3 array towed at a depth of 6 m. (Left) the overpressure signature and (right) the power spectrum for broadside (perpendicular to tow direction) and endfire (directly aft of the array) directions, and for vertically down.

Figure 40. Back-calculated nominal vertical waveforms (left) and spectra (right) from McPherson et al. (2018). The "horizontal" endfire and broadside spectra are derived from multipath data in very shallow water (80 m or less) at ranges much greater than 2x the water depth. The McPherson et al. (2018) data were not used in the Generic Pulse table in Tab F4).

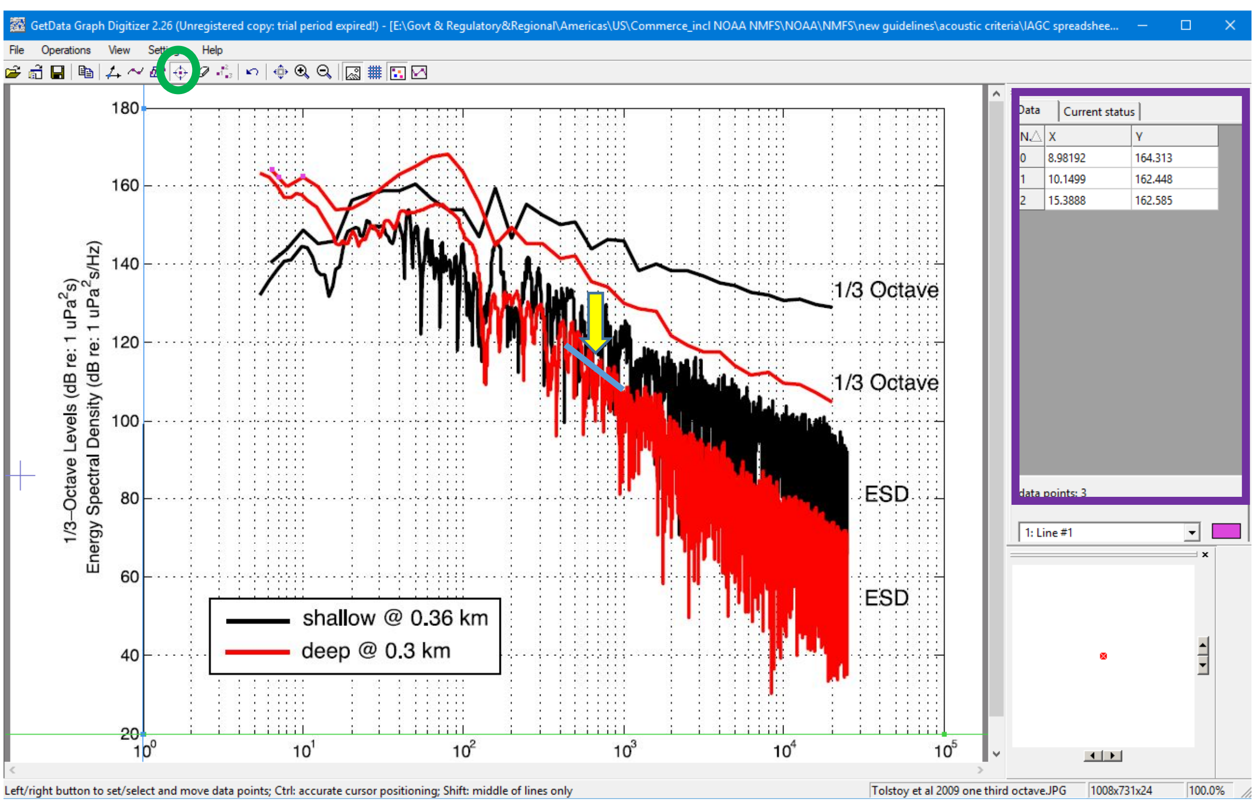


Figure 41. Smoothing process for avoiding peaks and valleys in center frequency value selections with spectra containing multiple peaks and valleys. This is an illustrative hypothetical example only.

Smoothing peaks and valleys in raw spectra

As Figure 40 above illustrates, the vertical pulse (green line), without the interference of the surface-reflected "ghost", is a smooth curve, lacking the peaks and valleys in energy distribution that result from interference between the vertical pulse and its surface-reflected inverse ("ghost"). Some spectra used to create the generic curve were peak-to-peak spectra, with the characteristic "ghost notches" at interference frequencies between the pulse and reflected pulse. For our TOB calculations notches (and peaks) were smoothed to avoid generation of unrepresentative center frequency SEL values. A point in line with the two adjacent TOB center frequency SEL levels to either side of the TOB in question was used to smooth the variance in single frequency values within the band. The peaks appear less dramatic than the valleys due to the logarithmic decibel scale, but it is nevertheless important not to simply bridge peak to peak, or select a point midway between the highest and lowest points, but to approximate a true geometric mean, as illustrated by the smoothed spectra provided by Sidorovskaia (unpublished) in Figure 42.

The greater uncertainty or variance in SEL values below 5 Hz in Figure 42 is due to FFT calculation uncertainties at very low frequencies. This phenomenon of time/frequency trade-offs in derivation of spectra from a time/amplitude waveform is beyond the level of discussion for this analysis, but is due to the time resolution versus frequency resolution trade-offs inherent in frequency-transformation equations; the need for high time resolution at higher frequency bands means poorer frequency resolution at low frequency bands). Since frequencies below 5 Hz fall below the range of hearing for marine mammals, even for LF Cetaceans, the variance at those frequencies does not affect the SEL-based threshold calculations in the revised Spreadsheet Tool.

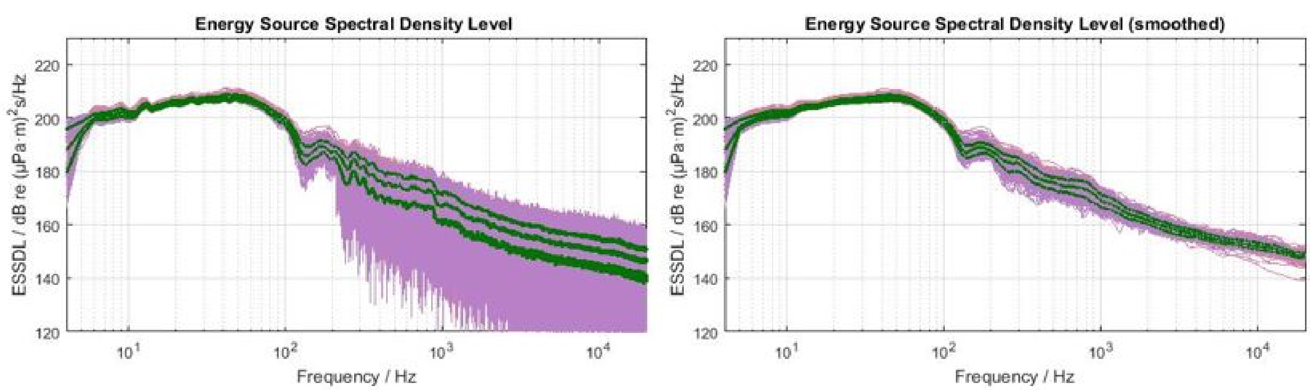


Figure 42. Sidorovskaia (unpubl.) generated 26th, 50th, and 84th decile average values (in green) for 326 measured pulses from a 4140 cubic inch array; raw data on the left and smoothed spectra on the right. The highly variable high frequency values illustrate the point that metrics of central tendency for a logarithmic scale like dB SEL are not arithmetic means but geometric means and do not sit at the center of the distribution of individual data points but at a point consistent with the logarithmic scale of values. The central green line indicating the 50th or mean decile average value was used as the smoothed frequency spectrum applied in Tab F4.

Distribution of Energy Across the Frequency Spectrum

The rough scale of energy distribution across the generic spectrum illustrated in Figure 43, below, is representative of the general energy distribution seen in all CA array pulses: nearly equal high levels of energy in the TOB spanning the 7-100 Hz frequency range (approximately 95% of total pulse energy, then a decline in energy across frequency bands from 100 – 2000 Hz (almost all of the remaining 5% of pulse energy), and finally a slower, highly stochastic (varying) decline in energy at frequencies above 2 kHz (in aggregate making up less than 1% of total pulse energy).

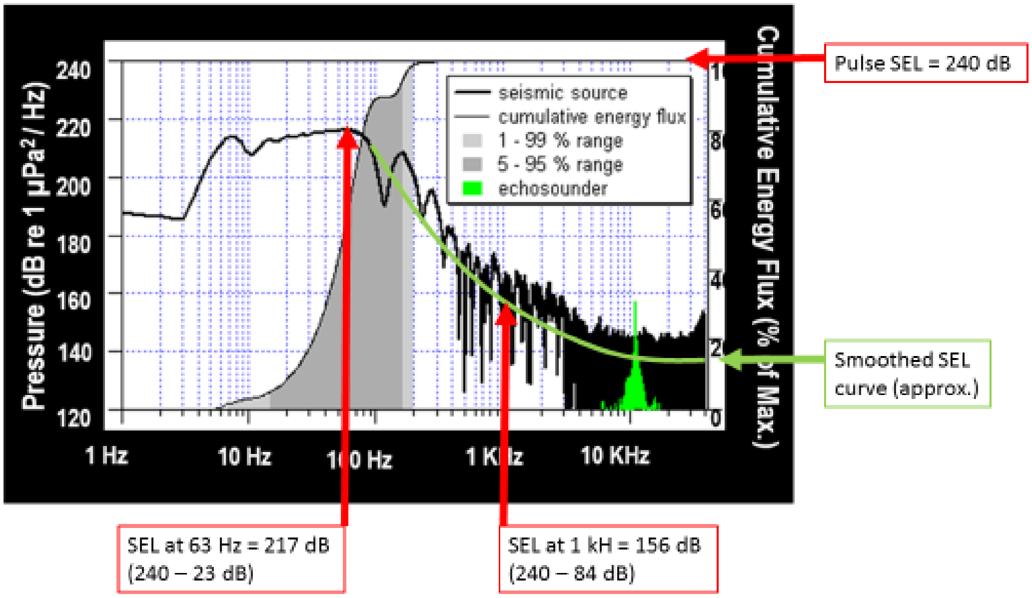


Figure 43. How 1/3 octave center frequency SEL values were derived. In these examples, the total back-calculated pulse SEL was 240 dB SEL. The green line illustrates how a smoothed spectrum was fitted to reported spectra that, like this example, included interference interactions with the reflected ghost. (This example is from a PowerPoint presentation by Jack Caldwell, and was not used in generating the generic spectrum in Tab F3).

Precautionary Adjustment of High Frequency Bands

The spectra from CA arrays can vary considerably at higher frequencies due to a number of factors, including:

- Cavitation bubbles produced by interaction of the pulse and the surface-reflected ghost;
- Turbulent flow from the ports through which the compressed air is released;
- Slight variation in the time synchrony of the elements within the array; and
- The presence of noise from other sound sources such as vessel noise, multi-beam echosounders, wind or rain, the properties of the propagating environment, and biological sound sources such as snapping shrimp.

Because of this variability at the high frequency end of the spectrum, the high frequency bands of the generic pulse have been slightly inflated above the geometric mean as one of several precautionary assumptions embedded in the use of the Alternative Methodology. Our advice, as has been the case throughout this Guidance, is to use a fully realized model of the specific source and propagating environment of concern to get the best results, and to use the Alternative Methodology only when the cost or complexity of the fully realized model is beyond what can reasonably be expected of an applicant, while acknowledging that the resulting prediction is not a slight over-estimate of risk but a significant over-estimate of risk.

Scaling Metrics for the Generic Pulse spectrum

In order to create a Generic Spectrum that could be scaled to any selected pulse SEL value, we calculated a geometric mean of differences between total SEL values and the highest single frequency value for our five selected exemplars and then scaled all other TOB center frequencies relative to this relationship. In other words, if the highest frequency-specific TOB value for a given spectrum is 210 dB at 50 Hz but the total pulse SEL is 230 dB then the difference between the spectrum peak and total pulse SEL would be 230-210 dB or -20 dB. All other TOB values are similarly scaled proportionally to the total unadjusted pulse SEL as illustrated in the Generic Pulse spreadsheet (Tab F4) and replicated in figure 44, below.

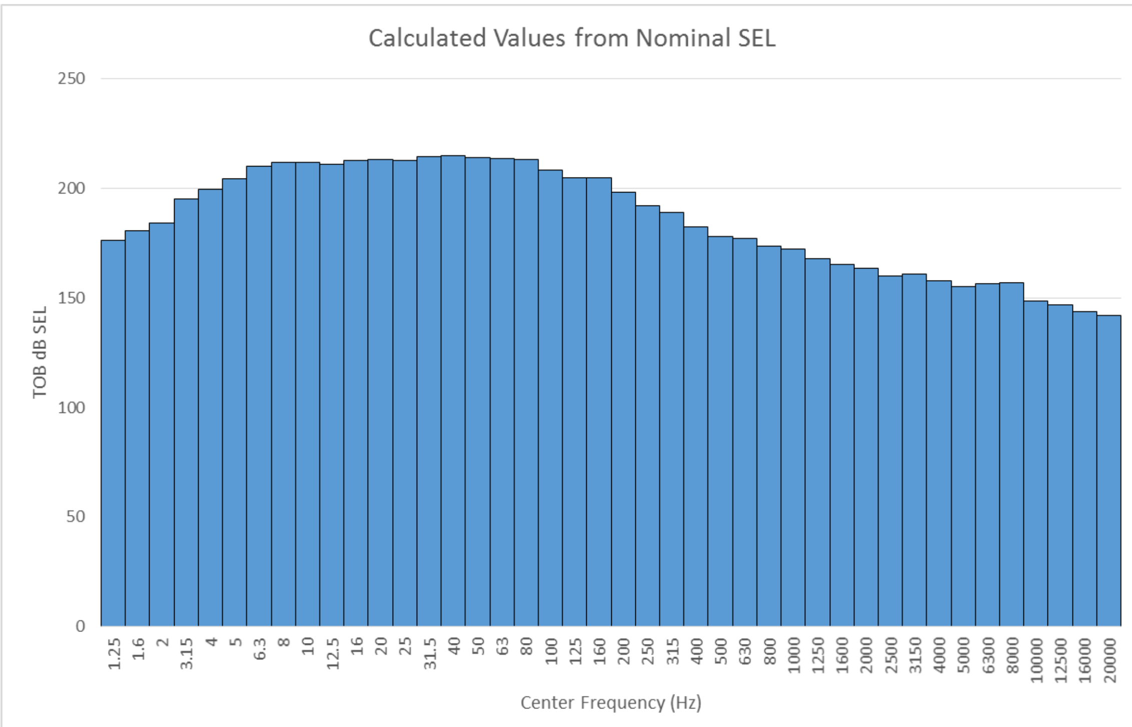


Figure 44. The derived Generic Spectrum from the revised Supplemental User Spreadsheet Tool tab F4.

Selection of Spectra for Inclusion in the Generic Spectrum

Over 17 measured and modeled spectra were examined and are listed in the Literature Cited section (Section D). Ultimately, we selected five suitable spectra that were representative of CA arrays commonly used in geophysical exploration and research, and which provided sufficient detail about the way the spectra were derived to provide the user with a high level of confidence that the spectra were representative of actual array output near the source.

Spectra are sometimes presented with different measurement units. Most examples used the standard metric of dB re 1 μPa^2, with the squared pressure reference (μPa^2) indicating that the values are not a point pressure measure, but are average pressure over a square area, and thus scaled to SEL. However, one spectrum (Gardline, 2014) provided values for TOB already adjusted for bandwidth, meaning that the center frequency had to be derived by subtracting the bandwidth adjustment. This was done solely to facilitate comparison with the other spectra that did not present bandwidth-corrected center frequency values and did not affect calculation of individual and averaged weighted TOB values employed in the User Spreadsheet Tool. MacGillivray et al. (2018) provided their spectrum in Pascals, which is easily converted to dB re 1µPa using the conversion tool in Tab F1 of the revised user spreadsheet tool. For our purposes the inconsistency in units does not matter because the units scale proportionally.

Spectra from single CA sources, clusters of CA sources or the single strings of CA sources commonly used in VSP surveys or similar life-of-field monitoring were omitted from this the analysis because the spectra differed from those of a full array of two or more strings (e.g., Breitzke et al., 2008; Zykov et al., 2016; and Hermannssen, 2015).

Other potential candidate spectra either lacked sufficient bandwidth (e.g., Gulland and Walker, 1998); provided data with insufficient recording amplitude range (such as the 'clipped' values reported in Tronstad and Hoven, 2011), or provided spectra for some unspecified angle other than vertical (e.g., BOEM, 2016).

We selected five spectra that were representative of CA arrays commonly used in geophysical exploration and research, and which provided sufficient detail about the way the spectra were measured and/or modeled to provide the user with a high level of confidence that the spectra were representative of actual array output near the source.

The spectra selected for inclusion in the creation of the generic spectrum are described one-by-one in detail below, accompanied by notations about the array parameters. Table 2, below, lists all references reviewed in developing the generic spectrum, and indicates whether the spectrum was included or excluded.

Reference	Array Volume (CUI)	nominal source level	source level units	How SL derived: Model, Back-calc?	spectrum units (Y axis)	spectrum resolution	lower f limit	upper f limit	closest recording distance	used in generic spectrum? Y/N
Caldwell (2005)	3590	not provided	n/a	Back-calc w/ on site prop data	dB SPL re 1 uPa²/Hz	1 Hz	10 Hz	24 kHz	730 m	Y
Caldwell (unpubl.)	3590	240	dB SPL re 1 uPa²/Hz	Back-calc w/ on site prop data	dB SPL re 1 uPa²/Hz	1 Hz	1 Hz	40 kHz	730 m	N
Gardline (2014)	3397	247	dB SPL pk	Back-calc w/ on site prop data	dB SPL re 1 uPa²/Hz	1/3 octave	40 Hz	25 kHz	100 m, 380 m	Y
Blees et al (2010)	3000	244	SPLrms	Back-calc w/ on site prop data	dB SPL re 1 uPa²-s/Hz	1 Hz	1 Hz	24 kHz	90 m	Y
MacGillivray et al (2018)	3333	90.1 bar (259 dB)	barm peak to peak	model	Pa-m/Hz	1 Hz	1 Hz	25 kHz	model	Y
Sidorovskaia et al (unpubl.)	4140	262	SPLpp	Back-calc w/ on site prop data	dB re (uPa-m)²s/Hz	1 Hz	1 Hz	20 kHz	122 m	Y
Coste et al (2014)	3300	n/a	n/a	model	dB re (uPa-m)²s/Hz	1 Hz	5 Hz	24 kHz	n/a	N
Khodabandeleroo (2018)	2730	n/a	n/a		dB re (uPa-m)²s/Hz	1 Hz	3.5 Hz	62.5 kHz	60 m	N
McPherson et al (2018)	2380, 2495 and 3090	249	SPLpk	Back-calc w/ on site prop data	dB re (uPa-m)²s/Hz	1 Hz	1 Hz	2 kHz	74-130 m	N
BOEM (2016)	8000	232	SEL	model	dB SPL re 1 uPa²/Hz	TOB	10 Hz	1 kHz (5 kHz)	model only	N

OGP/IAGC publ 448 (2011)	3397	n/a	n/a	model?	db re J/m^2.	1 Hz	2 Hz	60 kHz	model?	N
Breitzke et al (2008)	n/a	n/a	n/a	Back-calc w/ on site prop data	dB re 1 uPa and re J/m^2	1 Hz	2 Hz	70+kHz (single guns only)	263-564 m	N
Gulland and Walker (1998)	3090	118	barm peak to peak	model	relative dB (0-60)	1 Hz	1 Hz	250 Hz	model	N
Hermannssen et al (2015)	40									N
Martin et al (2017)	3480			measured					0.1-150+km	N
Tolstoy et al (2009)	6600	259	SPL pk	measured	dB re $(uPa\text{-}m)^2 s/Hz$	1 Hz and TOB	5 Hz	25 kHz	300-360m	N
Tronstad and Hovem (2011)	3460	255	SPL pk	modeled						N
Wisloff et al (2014)	4135	n/a								N
Diebold et al (2010)										N
Breitzke et al (2010)										N
Llandro et al (2013)	2730				relative normalized amplitude zero to minus 60 dB					N
Llandro et al (2011)										N
Matthews and MacGillivray (2013)	n/a	n/a	n/a							N
McCauley et al (2016)										N
SAE Inc, (2013)										N

Table 2. List of all reviewed references for development of the generic spectrum.

CA Array Spectra Used to Develop the Generic Spectrum in Tab F4

Caldwell (2005)

Caldwell (2005) provides data from the collection of a high-quality operational data set in deep water in the Gulf of Mexico in 2003. The spectrum (Figure 45) was derived from measured data collected at a distance of 730 m directly below the array. The array was a 31 element, 3590 cubic inch array frequently used for surveys in the Gulf of Mexico. The maximum recorded SPL_{pk} was 200 dB and the corresponding maximum recorded SEL was 177 dB (Newcomb et al., 2005). The difference between total pulse SEL and the SEL at the highest frequency (62 Hz) was -19 dB, but was not used in calculating the adjustment factor used in the Generic Pulse because no back-calculated source level was provided, only the measured levels at 730 m below the array.

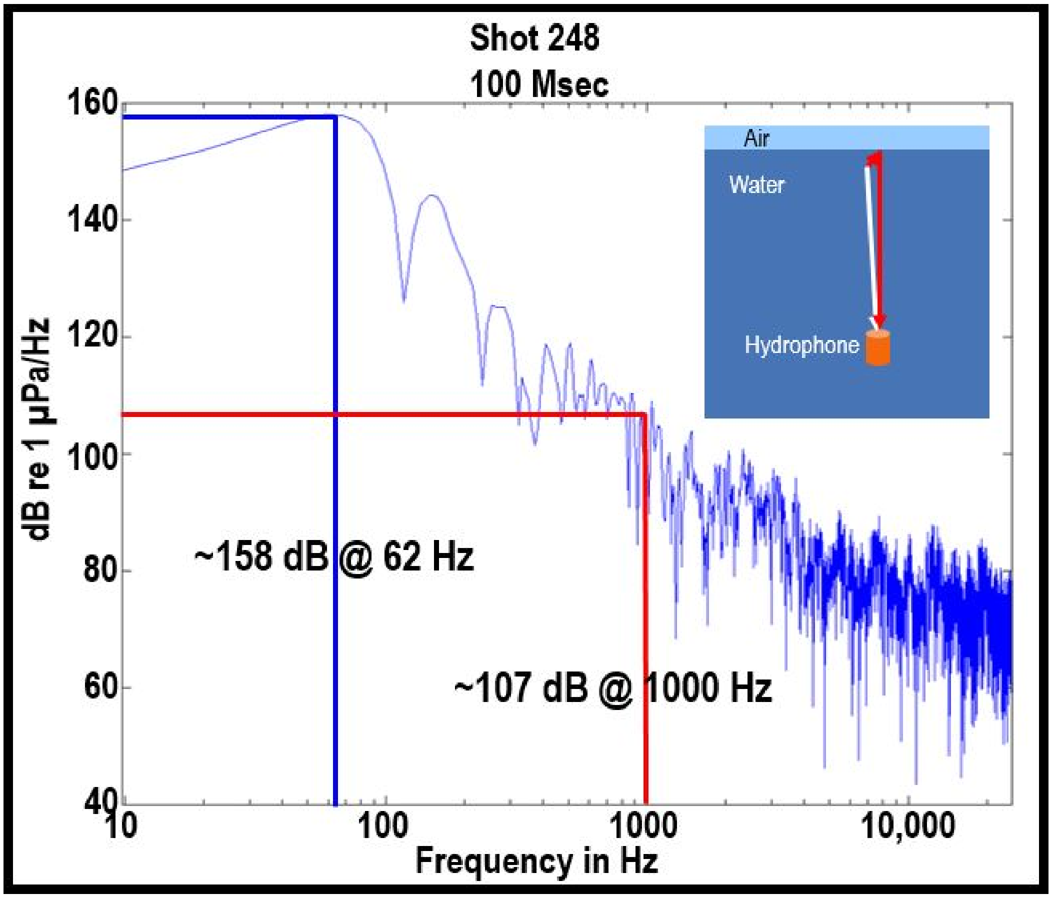


Figure 45. Caldwell (2005) spectrogram for a 3590 cubic inch array recorded at 733 m below the array.

Gardline (2014)

Gardline (2014) is an unpublished report submitted to the New Zealand Marine Wildlife department under the terms of a permit issued to Anadarko New Zealand Company and available from Gardline Ltd. UK. The spectrum (Figure 46) is back-calculated by the report authors from data obtained at 100 m and 580 m from a 3397 cu in array of 32 elements. The spectrum is presented in TOB, indicated by the open circles in the figure below. Comparison with other single frequency spectra requires reduction of the TOB value by the bandwidth adjustment factor or (10log(bw)).

The measured SPL_{pk} was 196 dB at 100m, back-calculated to 247 dB at the nominal point source at the center of the array using measured transmission loss properties of the ambient environment recorded on site at the same time. The corresponding SEL can therefore be estimated to be 247-16 dB = 231 dB. The highest TOB SEL at 40 Hz was 217 dB. The SEL at the center frequency SEL of the 40 Hz band, adjusted for bandwidth, would be 207 dB, or 10 dB less than the 1/3 octave band SEL at 40 Hz. The difference between the SEL for the entire pulse and the SEL at the highest frequency would therefore be 231-207 dB = 24 dB, similar to a difference obtained from the other array data sets for which both pulse SEL and peak single frequency SEL are known.

Using the propagation loss obtained through the model, the received levels were back propagated to the source, giving an estimated maximum zero-to-peak SPL of 246.86 dB re 1 μPa²m², peak-to-peak SPL of 251.34 dB re 1 μPa²m² at 50 Hz and a un-weighted SEL at TOB of 216.82 re 1 μPa²m²s (Figures 4.16 and 4.17).

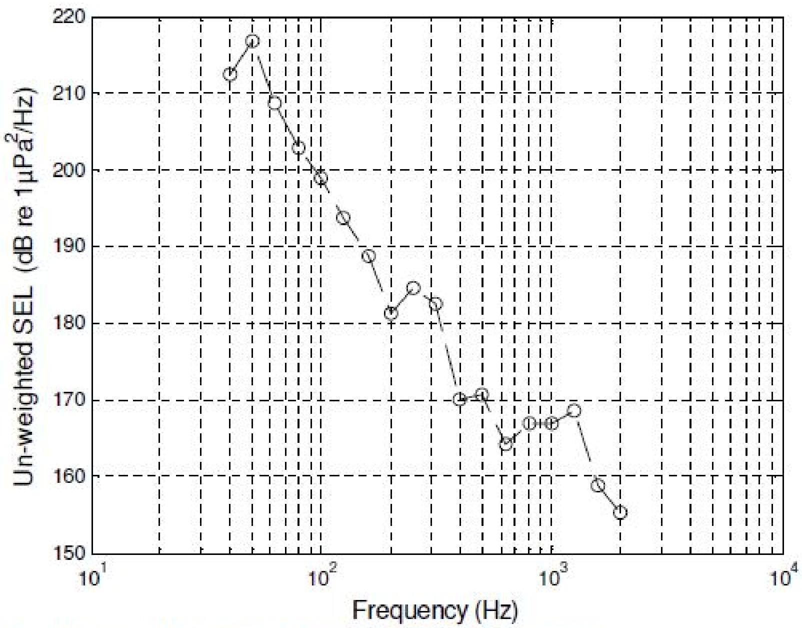


Figure 4.16 Un-weighted SEL at the source (TOB frequencies)

Figure 46. The back-propagated source spectrum in 1/3 octave bands for the Anadarko 3610 cui source array. (Gardline CGG, 2014).

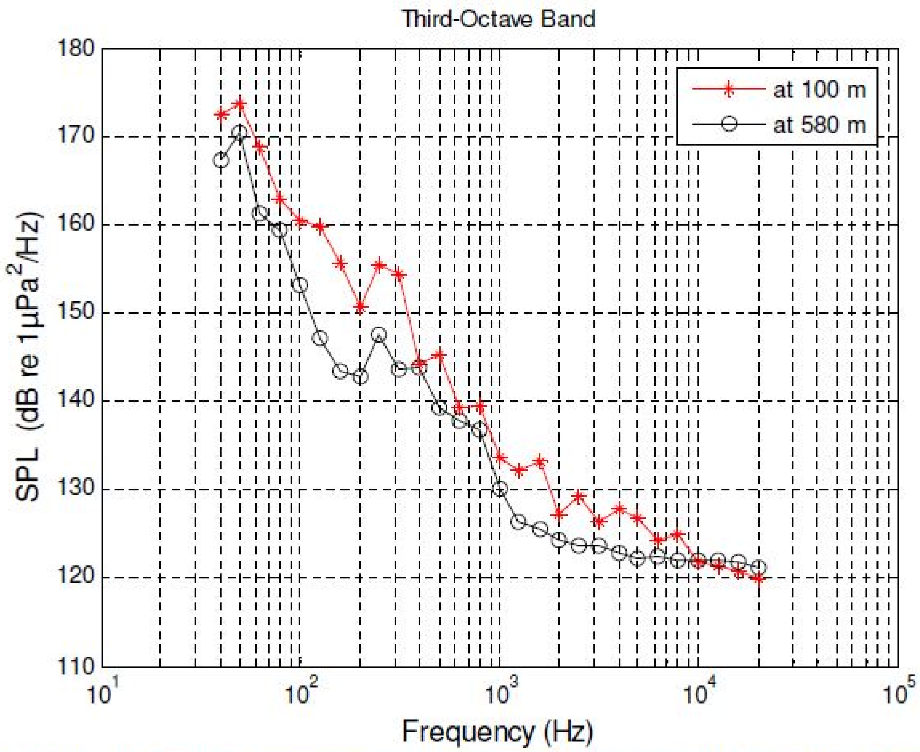


Figure 4.12 Example of comparison between spectral density levels in TOB of airgun noise measured at 100 m and 580 m from the airgun array during a test line at full power (moored monitoring method)

Figure 47. Measured 1/3 octave band values at two distances, 100 m and 530 m, from which the spectrum at source in Figure A-10 was derived. Measured values above 2 kHz in Figure 46 were not extrapolated by the authors to a nominal source value for those bands.

Gardline (2014) provided measured and back-calculated 1/3 octave values down to only 40 Hz. This source did not, therefore, contribute to the derivation of the estimated Generic Pulse values below 40 Hz. Gardline (2014) similarly did not provide back-calculated SEL values above 2000 Hz, though measurements were made up to 25 kHz. We derived values for the TOB SEL in bands between 2500 to 20000 Hz by adjusting the directly measured 1/3 octave values shown in Figure 47, by the geometric mean difference between measured and back-calculated values for 1000, 1250, 1600 and 2000 Hz (the four bands closest to the 2500-20000 Hz bands, or 31.3 dB). For example, the 1/3 octave band value for 10000 Hz is the measured SEL of 122 dB at 100 m, plus 31 dB = 153 dB.

Blees et al. (2010)

Blees et al. (2010) conducted measurements at 90 m from the array and back-calculated to a nominal point source using environmental data collected at the time of acoustic data collection. The back-calculated measurements yielded a transmission loss function of 19.7*log(r), or near-spherical spreading (20*log(r)). The back-calculated SPL_{rms} was 244 dB, so the comparable back-calculated SPL_{pk} would be 250 dB and the back-calculated SEL would be 234 dB, using the generic relationships described in Sections A and C of this document.

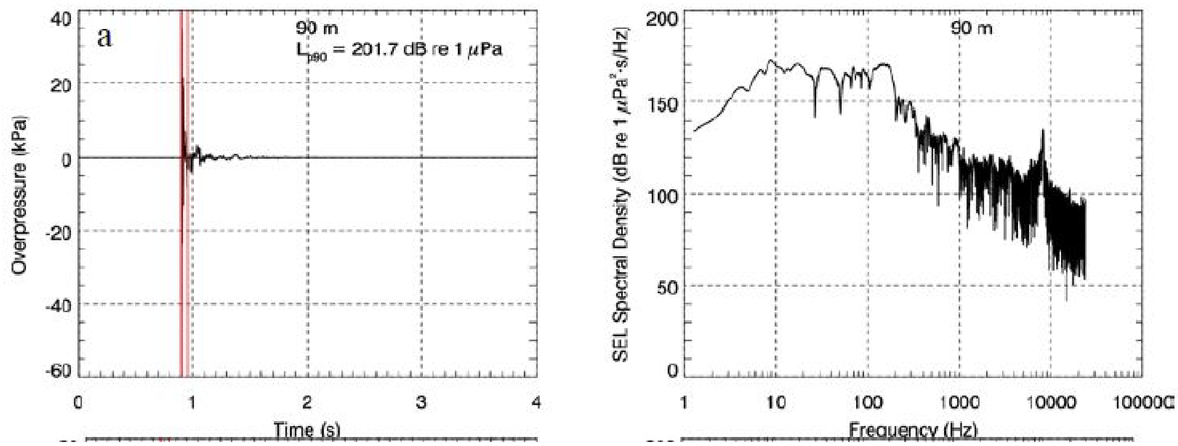


Figure 48. SEL for a measured pulse from a 3000 cui array at 90 m range. An anomalous spike in energy at 7-8 kHz may be a multibeam sonar or other sound source and was smoothed out of the values used in generating the Generic Pulse.

The anomalous data points in the 6300 and 8000 Hz bands were smoothed as for other frequency peaks and valleys, though this peak was likely not due to the array and its surface-reflected ghost but possibly originated from a multi-band sonar or other sound source picked up in the recorded data.

MacGillivray et al. (2018)

MacGillivray et al. (2018) published a spectrum derived from a data set provided for a workshop on CA array modeling (Ainslie et al., 2016). The original data set, cited by Ainslie et al (2016) as “nlog” (2008), came from a Final Survey Report for a contract survey performed by CGG Veritas for Shell EPE in September-October 2008 and shared by Shell with the participants in a 2016 Dublin workshop in which MacGillivrary et al. and others participated. The link cited by Ainslie et al. (2016) to access that report was still active as of 23 September 2019 and a copy has been archived at IAGC as part of the support materials for this revised Guidance.

The survey was conducted in shallow water in the North Sea, near The Netherlands coastline. The nominal SPL_{pp} was 90.1 bar-m, or 259 dB re 1 µPa-m. The derived pulse SEL using the relationships applied in this Guidance document would be 259-22 = 237 dB SEL. The highest single frequency SEL values occurred in the 30-60 Hz bands at 212 dB SEL, or 25 dB below the SEL of the full pulse, again consistent with other spectra showing peak frequency SEL values 19-25 dB below the total pulse SEL. The original modeled spectrum generated by the Nucleus survey planning software is shown in Figure 49, and the closely corresponding spectrum derived from data by MacGillivray et al (2018) is in Figure 50. Only the MacGillivray et al. (2018) spectrum was used in the development of the generic spectrum, and not the Nucleus planning model spectrum. However, comparison of the two re-affirms the good correspondence between models like Nucleus, Gundalf, and JASCO’s AASM with the actual measured pulse waveform and spectrum when measured data are available. Khodabandeleroo (2018) and others have noted the poorer correspondence between model and measurements at high frequencies, and that source of variability/uncertainty has been compensated for in the generic spectrum through precautionary, conservative SEL values used for frequencies above 2000 Hz, as described in Sections A and C.

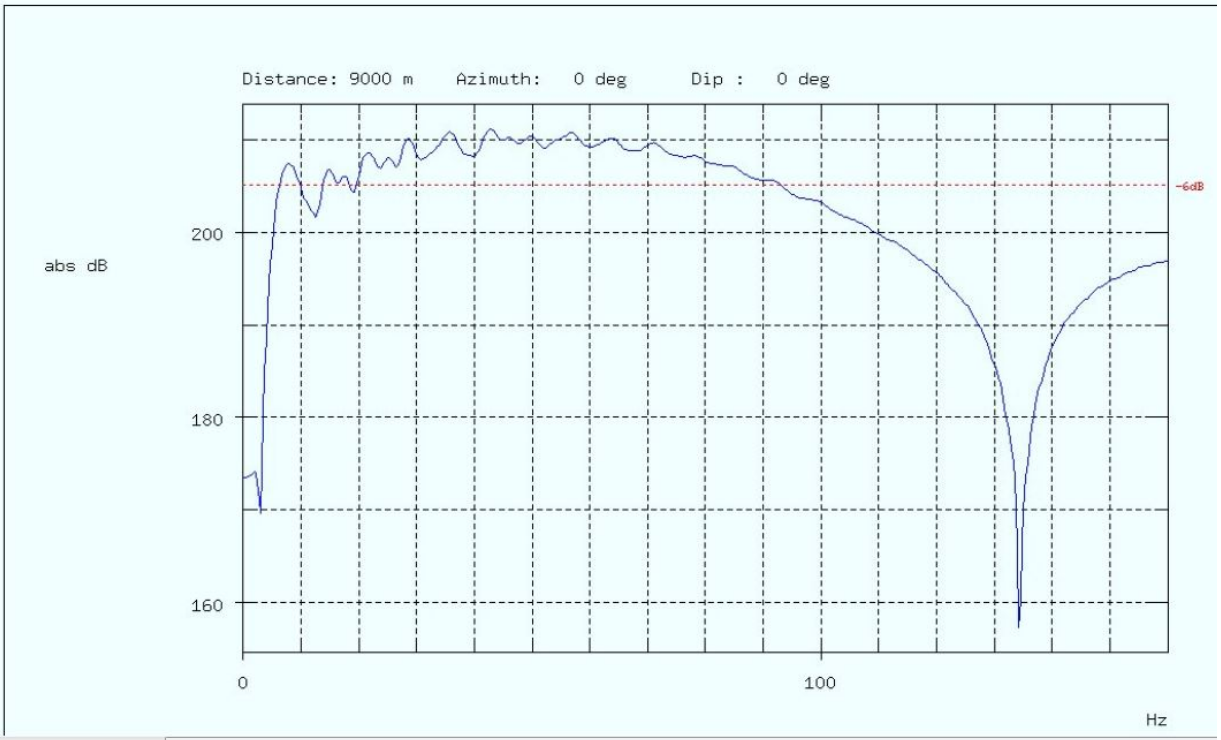


Figure 49. A modeled spectrum (0-160 Hz only) for the 3333 cui array used in the 2016 Dublin workshop dataset analyzed by MacGillivray et al. (2018).

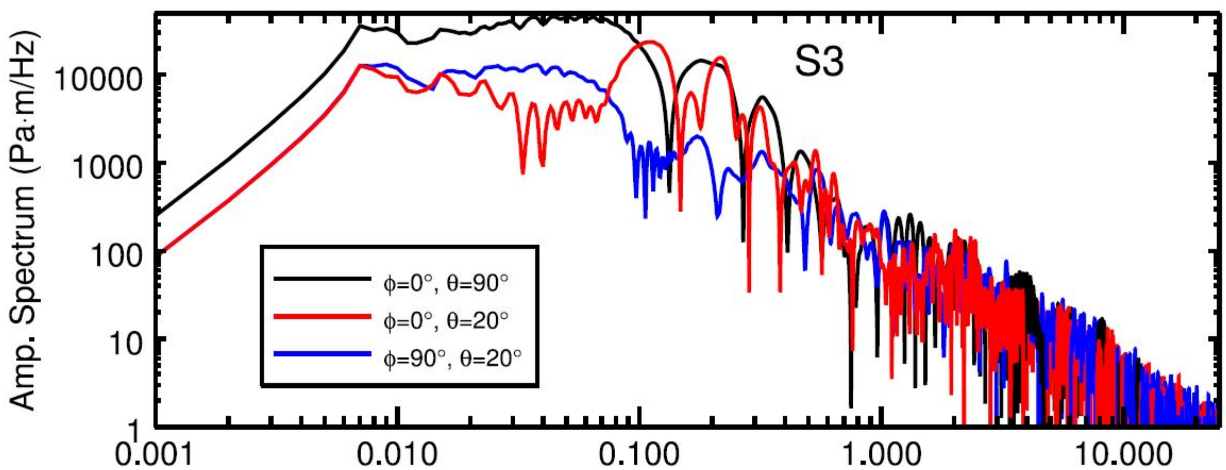


Figure 50. The analyzed data-derived spectrum produced by MacGillivray et al (2018) for the same array (S3 data set) at vertical (black line, Θ = 90°), horizontal inline/endfire (red line, Θ = 20°) and horizontal broadside (blue line, Θ = 20°).

MacGillivray chose to present their results in Pascals (Pa), but the corresponding dB re 1µPa values are 10 Pa = 140 dB; 100 Pa = 160 dB; 1000 Pa = 180 dB, etc. A unit conversion tool has been provided as Tab F1 of the revised User Spreadsheet toolkit to assist in conversion of bars or Pascals to dB re 1µPa as the conventional unit for expressing measures of underwater sound.

Sidorovskaia et al. (Unpublished)

Sidorovskaia et al. (Figure 51; unpublished) provide data from a 2014 large scale array data collection in the Gulf of Mexico. Although these data are not yet fully published, they will be published in the near

future and include the largest set of high-quality data collected to date. Their consistency with the other examples cited above further reinforces confidence in including the as-yet unpublished data.
The array was a 4140 cubic inch array commonly used for deep water surveys in the Gulf of Mexico. The back-calculated vertical peak-to-peak source level was 262 dB $SPL_{pp,}$ making the total pulse SEL 262-22 dB = 240 dB SEL. The difference between the total pulse SEL and the highest single frequency peak at 50 Hz was 240-215 dB = 25 dB. The range of single frequency values between the highest at 215 dB and the lowest at 20 kHz at 143 dB is 72 dB, comparable to the distribution of energy in other CA spectra.

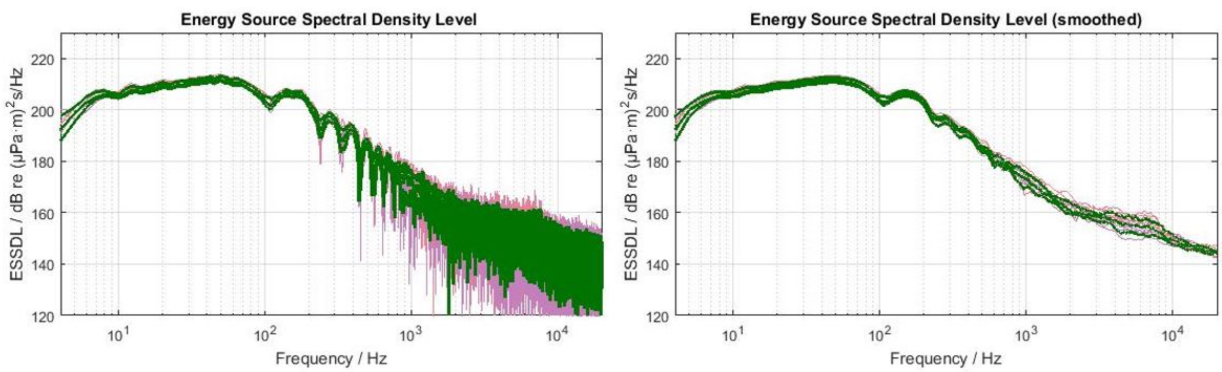


Figure 51. Raw and smoothed spectrum data produced by multiple high-resolution recordings at multiple depths and ranges from an array in deep water in the Gulf of Mexico (Siderovskaia et al., unpubl.).

Spectra Considered but Removed from Analysis

The following examples help reinforce the consistency of CA array spectra generally, including the spectra chosen for inclusion, but the following cases lacked sufficient information or had other problems that led to their not being used in the derivation of a generic spectrum.

Coste et al. (2014)

Coste et al. (2014, Figure 52) offers a comparison of spectra from an array made up of standard CA sources and an array composed of a new source design; the Bolt e-Source, which was designed to produce less high frequency energy. Only the spectrum from the standard sources was used in this analysis, since use of e-Sources is still not widespread. If use of the e-Source expands, it may be desirable to offer two different generic spectra: one for an array of e-Sources and another for the conventional sources currently in widespread use.

The Coste et al. (2014) spectrum was not based on direct measurements, but was derived using a common standard modeling software, most likely Gundalf (https://www.gundalf.com/), based on high quality near-field measurements (range = 2 m) from single CA sources of the type and size used in the modeled arrays. This is a common and well verified modeling methodology and has been verified frequently with field data, however we were somewhat concerned about acceptance of such modeled results by a non-expert audience.

The total array volume was 3300 cubic inches. Pulse SPL and SEL values were not provided.

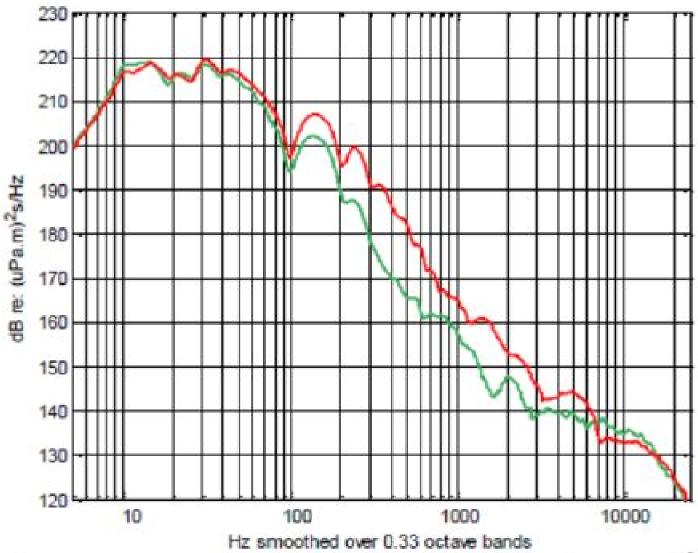


Figure 5: Example vertical far-field energy spectra of a 3,300 in^3 array (simulated from near-field measurements) of: air-guns with the new design (green) and standard air-guns (red) with the same mix of volumes and the same firing pressure. The source arrays are at a depth of 7.5 m. Note that the spectra differ significantly only above the ghost notch (100 Hz).

Figure 52. Sample array spectrum from Coste et al. (2014).

Khodabandeleroo (2018)

Khodabandeleroo (2018, Figure 53) includes spectra for single CA sources, a single string of sources ("single array 1500 in^3"), and a full array of 2730 cu in. Only the spectrum for the 2730 cu in full array was considered. The data are recorded data from a bottom mounted sensor at 60 m depth. Notches are present in the spectrum, so the spectrum is presumed to include both the pulse and its reflected ghost, necessitating fitting of a smoothed spectrum to the curve. Source SPL and SEL data were not provided.

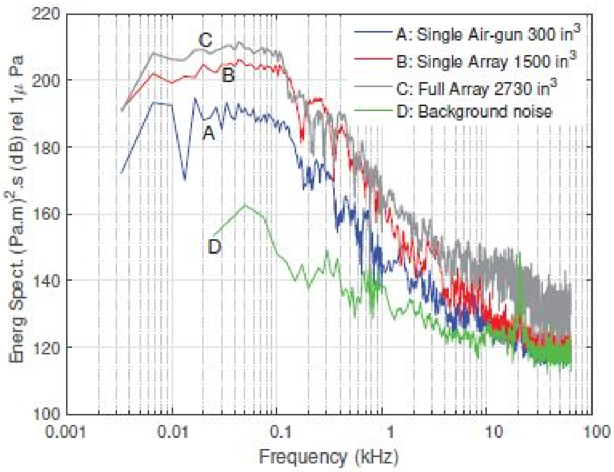


Figure 1.6: Energy spectrum densities (ESDs) of signals generated by different sources and recorded by a broad-band hydrophone (bandwidth=125 kHz). The sources were a single air-gun 300 in^3, single array 1500 in^3, and a full air-gun array 2730 in^3. ESD of background noise is plotted with green line.

Figure 53. Comparison of single element (blue), single string (red) and full array (gray) spectra (Khodabandeleroo, 2018).

McPherson et al. (2018)

McPherson et al. (2018, Figure 54) collected data with bottom-mounted receivers placed at varying distances from a CA array operated in shallow water (80m). As with most JASCO modeled waveforms, the surface-reflected "ghost" is omitted as a propagation effect, but the SPL_{pk}, $SPL_{rms0.9}$, and SEL scaling relationships are consistent with the material discussed in Section C of the Guidance and the spectrum scales similarly to the other examples used in the creation of the Generic Spectrum.

The back-calculated vertical source level was 249 dB SPL_{pk} (rounded to the nearest whole decibel value). A difference of -16 dB between SPL_{pk} and SEL would predict a total pulse SEL of 233, but that is admittedly a conservative precautionary value and the measured and back-calculated differences between SPL_{pk} and SEL in this case are -25 dB or about 224 dB SEL. The spectrum data were presented on a linear frequency scale instead of the standard log frequency scale, making it impossible to discriminate details in the frequencies of highest energy between 8 and 100 Hz. Requests to the authors for more details had not received a response at the time of preparation of this document. Another concerning detail was the use of bottom mounted hydrophones. This seems to have produced some anomalous values at different distances that may have corresponded to bottom-bounce or other propagation effects. The data were collected in very shallow water (80 m or less) so recordings at lateral distances more than 160 m potentially contain multiple surface and bottom reflected pulses as well as the direct pulse.

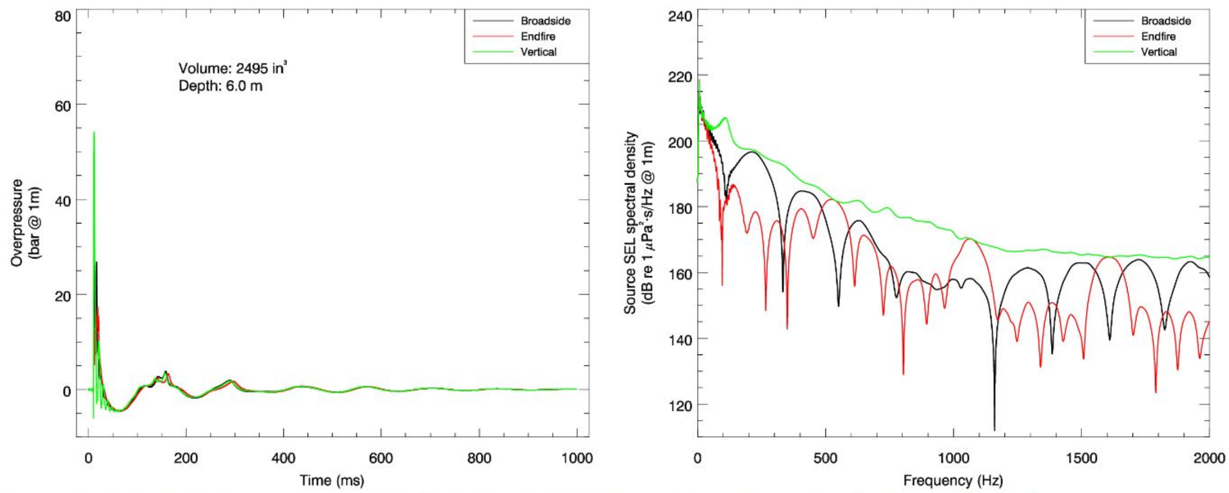


Figure D-8. Predicted source level details for the 2495 in³ array towed at a depth of 6 m. (Left) the overpressure signature and (right) the power spectrum for broadside (perpendicular to tow direction) and endfire (directly aft of the array) directions, and for vertically down.

Figure 54. Spectra from McPherson et al. (2018), showing back-calculated single frequency spectra for vertical (green), and horizontal (red and black) source waveforms.

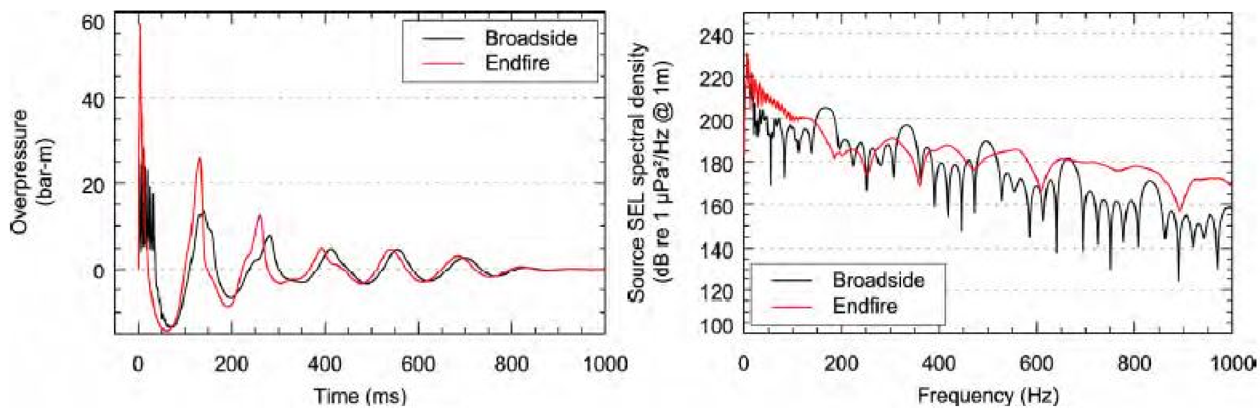
BOEM (2016)

In their 2016 Final Environmental Impact Statement (FEIS) for geophysical survey permitting in the Gulf of Mexico, the BOEM used data from an 8000 cu in array. The details of the array geometry and acoustic properties are provided in Appendix D of the BOEM FEIS (2016) (Figure 55). Arrays of 6000-10000 cui are typically achieved by simultaneous activation of two side-by-side arrays of 3000-5000 cui each instead of the typical alternating activation of the A then B array. Thus, the 8000 cu in array in this case would presumably be two identical side-by-side 4000 cui arrays activated simultaneously instead of alternately. Since the array parameters used in the BOEM (2016) FEIS are not from an actual operationally employed array, its configuration and performance are entirely hypothetical. The array described in BOEM (2016) is, however, consistent with the general features of arrays used in operations in deeper water (over 1000 m depth) and with dense geological layers over the layers of interest for possible oil and gas deposits, which sometimes require the use of larger arrays (in the Gulf of Mexico these dense structures are usually salt domes). About one third of recent surveys in the GOM have employed this double array technique, though the mean or median array size for all surveys is around 4000-4500 cui.

The 8000 cu in array was a hypothetical array and not an array in actual use in the Gulf of Mexico. We do not have actual recorded acoustic data for this particular array configuration, nor has its realism as an actual survey tool for the geology of the GOM been verified by analyzed data. The fact that these data were model-only data was one of the reasons the data set was rejected from consideration, but not the only reason.

The modeled 1/3 octave spectrum for the BOEM (2016) 8000 cui array looks similar to the data from the arrays selected for generic spectrum development, with peak energy in the 10-100 Hz range, frequency bands, and the dynamic range in TOB from 200 Hz to 4000 Hz is about the same at 40 dB. However, there are no modeled spectrum data above 4000 Hz, which is where the greater uncertainty/variance is observed in the other datasets. The stochasticity of high frequency data from CA arrays has been discussed in detail by the BOEM (2016) Appendix D treatment of high frequencies, which BOEM created statistically from data derived from single CA sources (see p. D-19). This stochastic approach to modeling the variable high frequency output of CA arrays seems to hold up well against data as reviewed by Ainslie et al (2016), but since there are a sufficient number of examples from real data in the other exemplars selected for usage, we were inclined to wait for further verification and validation studies of this alternative protocol for deriving the high frequency content of generic CA array spectra before opting to include it in the calculation of a generic array frequency spectrum.

The BOEM (2016) modeling exercise also opts to present "horizontal" rather than vertical array properties. The actual angle of the "horizontal" waveforms and spectrum in Figure 55 was not provided in BOEM (2016) and as we noted in Section C, deviations from vertical can reduce source levels by 5 to 40+ dB, depending on angle, as well as greatly altering the position of peaks and valleys in the spectrum. At these more "horizontal" angles the peaks and valleys owe less to the interaction with the surface-reflected "ghost", but are instead increasingly influenced by the relative positions of the different sized elements within the horizontal plane of the array. Not only does this produce significant arrivals of energy 300-800 msec after the primary pulse, but the azimuthal angle of the receiver relative to the array track (e.g., "broadside" and "endfire") also alters the received spectrum. As noted earlier, a decision will need to be made at some point about what direction of array output to use in simplified regulatory guidelines, but the vertically directed energy is the simplest as well as the "loudest" aspect of the array sound field, whereas terms like horizontal, endfire and broadside will require further refinement in order to produce uniform, simple guidance for regulated activities.



(a) (b)

Figure 15. The 8000 in^3 array: Predicted (a) overpressure signature and (b) power spectrum in the broadside and endfire (horizontal) directions. Surface ghosts (effects of the pulse reflection at

Figure 55. The BOEM (2016) modeled horizontal array Figure waveform and spectrum. The surface-reflected signal is not included in the characterization of the source, but is incorporated into the environmental propagation component of the acoustic risk model. Not only is the source level considerably reduced relative to the vertical signal (>-5 dB), but there is also much more energy radiated from the source after the primary pulse (peaks at 150, 300, 400, 550 and even 700 msec) and there is much less energy, relatively, in the 7-100 Hz band due to the loss of constructive gain at those frequencies obtained in the vertical direction.

Finally, the stated full spectrum SEL in Table 13, page D-47 is approximately 232 dB SEL, but the highest single TOB SEL levels in Figure 16, also on page D-7, at 10 and 16 Hz for example, are themselves very near or even higher than the nominal source SEL. The summed energy from the spectrogram in Figure 16 would be closer to 255 dB, based on the relationships observed in all other spectra where the bands with greatest energy are typically 19-25 dB below the total SEL. There is clearly some kind of mathematical error or mismatch between Table 13 and Figure 16 of the BOEM (2016) Appendix D that would have to be resolved before the TOB spectrogram presented in BOEM (2016) and reproduced on page 13 of the NMFS Supplemental User Guidance (2018b) could be used in generic spectrogram development.

OGP/IAGC (2011)

The Oil and Gas Producers Association (OGP, now IOGP) and the International Association of Geophysical Contractors (IAGC) produced a report in 2011 to acquaint the general user with the technical aspects of seismic survey sound sources and operations. Their Figure 25 (here, Figure 56) presents a sample energy spectrum (in Joules/m^2) that looks very similar to the other spectra included in our development of a generic spectrum. The array properties; 3397 cubic inch volume, from 24 elements, are provided in the 2011 report but the only reference to the original source material is a personal point of contact: Gary Hampson, Chevron. Without a specific report or published document detailing the origin of the spectrum (e.g., modeled or measured at some unspecified range and back-calculated?) we opted to exclude this spectrum from our analysis.

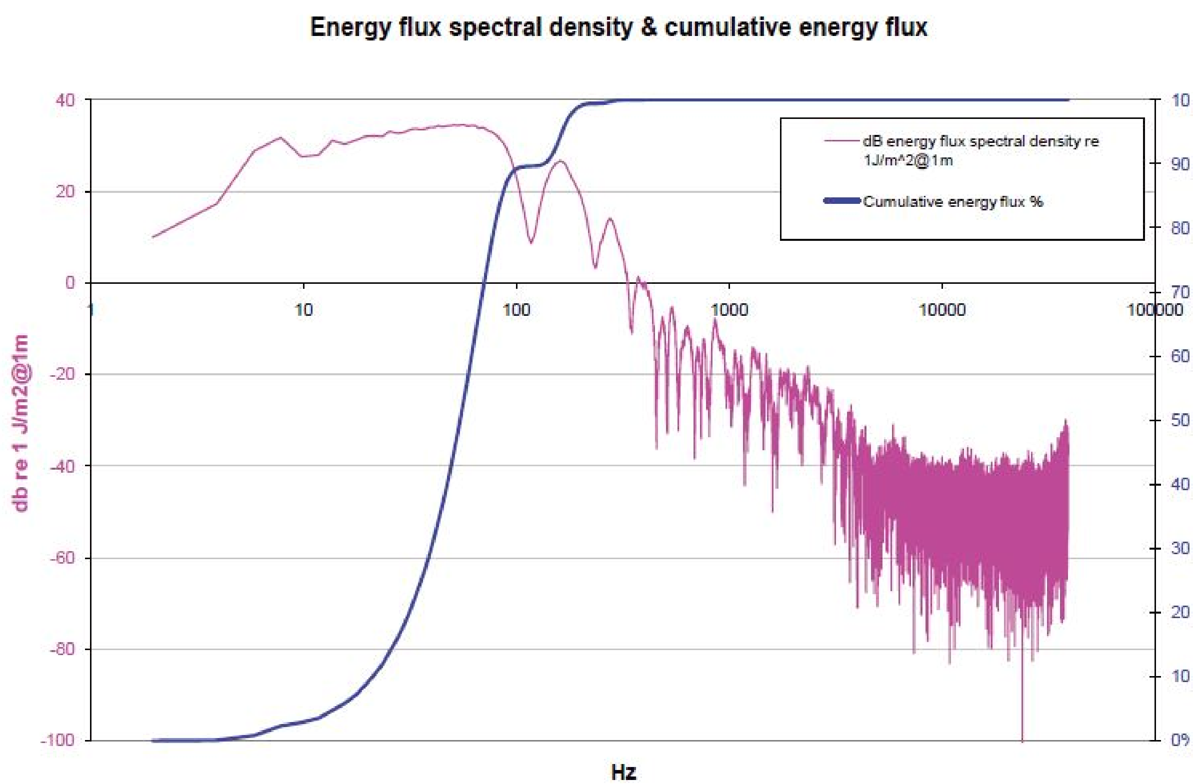


Figure 25 (*credit: Gary Hampson, Chevron*)

Broadband spectrum of the energy flux (proportional to the square of the amplitude) indicated by the vertical axis on the right. The main point from this figure is that 99.9% of the energy is contained in frequencies below 305Hz. These data are for the 3397 cubicinch array that has 24 guns.

Figure 56. Spectrogram published in the IAGC publication on seismic surveys and how they work. Because the original data were not readily recoverable at this time, we opted not to include these data in our analysis.

Conclusion

At present, we believe we have sufficient examples of spectra from real, operating CA arrays to provide confidence in the general shape of most CA array spectra from a range of array sizes between 2000 cubic inches to over 4000 cubic inches. The current generic spectrum is updateable as more sources of both modeled and measured data are found. However, given the consistency across array spectra evaluated thus far, we are confident that the generic spectrum will not differ significantly from other spectra, since the constraints imposed for geophysical imaging are reflected in all CA source arrays designed for that purpose. The tools for creating a generic spectrum have been described in detail and can easily be independently replicated or added to in the future. Likewise, the generic spectrum tool for calculating hearing-weighted SEL values can be modified by the individual user as needed or updated as more information on weighting functions and CA source spectra emerge.