Estimating received sound levels at the seafloor beneath seismic survey sources

Alec J Duncan[1]

[1]Centre for Marine Science and Technology, Curtin University, Bentley, Western Australia

ABSTRACT
The offshore seismic survey industry typically uses arrays of devices called airguns to generate the intense, low-frequency sounds required for imaging the seabed geology. Concerns have arisen about the impacts that these high intensity sounds may have on benthic species, such as shellfish, site attached fish and crustaceans, that have little or no capacity to move out of the way of an approaching seismic vessel. In order to assess the impacts a survey may have on these species it is essential to have a means of predicting the sound levels they are likely to be subjected to. This paper discusses the characteristics of the sound field beneath a typical seismic airgun array and compares results obtained using some simplistic formulae for predicting sound exposure level and peak sound pressure level, that are applicable in the acoustic far-field of the array, to those obtained using a more accurate model that includes array near-field effects. For the typical medium-sized 49.2 l (3000 in^3) airgun array considered here the predicted near-field to far-field transition distance was 14.5 m and a simple equivalent point source model was found to over predict the sound exposure level by 1.1 dB and to over predict the peak sound pressure level by 3.3 dB at this distance below the array. At double this distance these errors had reduced to 0.6 dB and 1.4 dB respectively.

1. INTRODUCTION
Marine seismic surveys use intense pulses of underwater sound to image the seabed geology, either for scientific purposes or, more often, in the search for oil and gas. By far the most common sound source used for these surveys is the airgun (Berger and Hamblen, 1980), which consists of a chamber filled with compressed air, typically at a pressure of about 14 MPa (2000 psi). The air is suddenly released into the water in response to an electrical trigger signal, which results in an initial high amplitude acoustic pressure pulse that occurs when the high pressure air first comes in contact with the water, followed by a decaying series of so-called bubble pulses due to the oscillation of the resulting air bubble. From the point of view of seismic exploration the initial pressure pulse is desirable, but the subsequent bubble pulses are not. Various strategies are therefore used to minimise the amplitude of the bubble pulses, including deploying arrays consisting of airguns of different volumes, which results in bubble pulses with different periods that tend to cancel out, and deploying pairs of closely spaced airguns (known as clusters) such that the acoustic pressure wave from one airgun tends to suppress the oscillation of the bubble due to its neighbour and vice-versa.

Using arrays of airguns is also advantageous for a number of other reasons, including focusing the acoustic energy downwards and giving a higher peak pressure for a given total volume of air (and hence compressor capacity) than can be obtained with a single airgun. As a result, the vast majority of marine seismic surveys are carried out using arrays of airguns. Figure 1 shows the layout of a typical medium-sized airgun array consisting of 27 individual airguns and with a total air chamber volume of 49.2 l (3000 in^3). Depending on its location and aim, the airgun array used for a particular seismic survey may have a total volume ranging from less than one quarter to more than three times the volume of this array. In most cases all the airguns in an array are located at the same depth below the water surface with this depth carefully chosen to optimise the signal in the vertically downward direction that necessarily consists of the sum of the direct signals from the individual airguns and their surface reflections. The interference between the direct and surface reflected signals results in a notch in the spectrum of the combined signal that limits the highest frequency usable for seismic processing. Placing the array deeper lowers this upper frequency limit, which gives poorer resolution of the detailed geology, but increases the amount of low frequency energy in the signal, allowing images to be obtained to greater depths.

In recent years there has been growing concern about the potential effects of the intense acoustic signals produced by airgun arrays on site attached benthic species, particularly shellfish, crustaceans and site attached fishes that are unable to move out of the way of an approaching seismic vessel. In order to predict these effects it is first necessary to be able to predict the sound levels that a given seismic array will produce at the seafloor directly below the array when operating in a given depth of water. This paper describes some simple relationships that can be used to make such predictions and compares their results to those of a numerical airgun array model. This comparison provides insight into the applicability of the simple relationships.

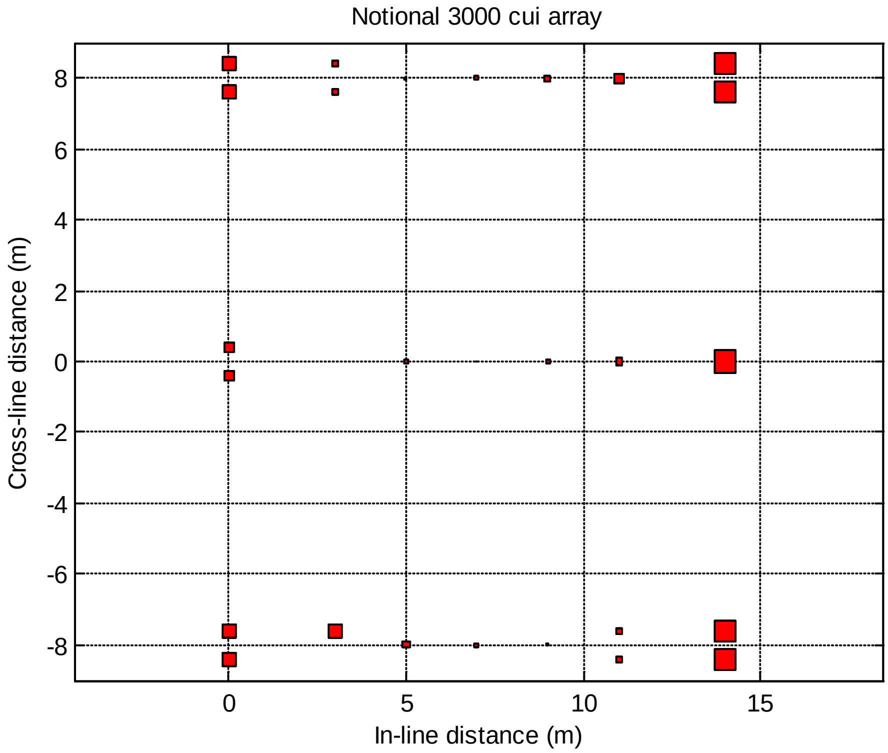

Figure 1: Plan view showing the layout of the airguns in a typical medium-sized seismic airgun array. The squares are much larger than the actual airguns but are scaled so their linear dimensions are proportional to the linear dimensions of each airgun's air chamber. All airguns are at a depth of 6 m below the sea surface. The total volume of the 27 airguns in this array is 49.2 l (3000 in^3) and the individual airguns have volumes ranging from 0.33 l (20 in^3) to 4.1 l (250 in^3). This array would be towed in the negative in-line direction.

2. SIMPLE EQUATIONS FOR THE VERTICALLY DOWNWARD DIRECTION

2.1 The acoustic signal incident on the seafloor

Sufficiently far from any acoustic source located in an infinite, lossless, homogeneous medium, the amplitude of the acoustic pressure will be inversely proportional to the distance from the source. This region is known as the far-field of the source. The region closer to the source where this condition is not met is known as the near-field (Kinsler et. al. 2000). In the far-field the received signal levels due to the incident wave can be calculated by representing the real source as an equivalent point source and using the well-known spherical spreading relationship to calculate the received level:

$$L_i = SL - 20\log_{10}(d), \tag{1}$$

where L_i is the sound level due to the incident wave, SL is the source level of the equivalent point source in the direction of interest, and d is the distance from the source to the receiver (m). There are several choices for the source level, depending on the particular received level that is required. Common choices for received levels when considering the environmental effects of seismic sources are the peak sound pressure level, $L_{p,pk}$ (dB re 1 μPa), and the sound exposure level, SEL (dB re 1 μPa^2.s). Corresponding source levels are the peak source level, SL_{pk} (dB re 1 μPa.m), and the exposure source level ESL (dB re 1 μPa^2.m^2.s). Note that source levels are commonly quoted with units of dB re 1 μPa @ 1m (SL_{pk}) or dB re 1 μPa^2.s @ 1m (ESL). These are equivalent to the units used here, which have been chosen for consistency with the draft ISO standard on underwater acoustic terminology, and also to highlight the fact that the measurements used to determine the source level must be made in the far-field of the source, and that for a large source such as an airgun array, the source levels do not equate to the actual sound levels at a distance of 1 m from the real source as implied by the second set of units.

Another important point is that the source levels and source spectra of airgun arrays are strongly dependent on direction in both the horizontal and vertical planes, and so when specifying a source level it is important to also specify the direction it applies to.

For the purposes of simple calculations, when considering the signal from an airgun array in the vertically downward direction it is most straightforward to consider the surface reflection as part of the far-field source waveform. This combined signal is known as the surface affected source waveform, and is usually provided by the seismic contractor as it is important for seismic data processing. The surface affected source waveform for the airgun array shown in Figure 1, in this case calculated using CMST's airgun array model (Cagam), is shown in Figure 2. (Cagam is based on a free bubble oscillation model of an airgun (Johnson, 1994), with empirical corrections derived from measured data to account for the finite rise-time of the initial pressure pulse and increased damping of the bubble oscillation.) The initial positive pulse is the direct arrival of the initial pressure pulse from the airgun, and the subsequent negative pulse is its surface reflection. (The surface reflection is inverted because air has a much lower acoustic impedance than water, leading to what is effectively a zero pressure boundary condition at the sea surface.) The remaining undulations are the combined effect of the bubble pulses from the various guns. The peak sound pressure can be read directly from this waveform and converted to decibels to give SL_{pk} for the vertically downward direction, which in this case is 257.5 dB re 1 μPa.m. The ESL can be calculated by integrating the squared pressure and then converting the result to decibels, which for this signal gives an energy source level of 233.0 dB re 1 μPa^2.m^2.s.

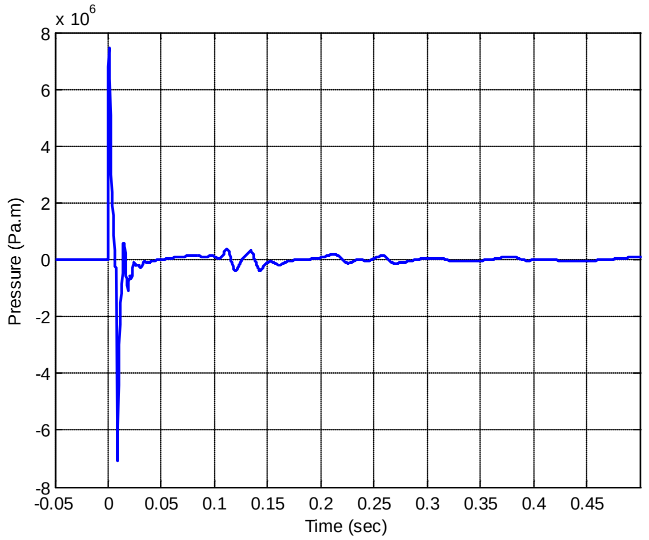

Figure 2: Surface affected source waveform for the vertically downward direction for the airgun array shown in Figure 1.

Alternatively, the surface reflection can be considered to arise from an image source the same distance above the water surface as the real source is below it, that emits the inverse of the true source waveform. This introduces a subtlety when applying Equation (1): what value of the source-receiver distance, d should be used? The positive peak sound pressure level will be governed by the direct path signal, and the appropriate distance to use is therefore the distance of the receiver below the true source: $d = z_r - z_s$, where z_r is the receiver depth and z_s is the source depth. The negative pressure peak originates from the image source, and so the appropriate value of d to use for estimating this would be $d = z_r + z_s$.

The sound exposure level is calculated from the entire received waveform, and includes energy from both the real source and its image, so determining an appropriate value of d is less straightforward. When $z_r \gg z_s$, the direct path and surface-reflected waveforms will have similar amplitudes (although opposite sign) and therefore similar energies. The effective centre of the combined source is therefore midway between the true and image sources, which is at the sea surface, and in this case it is appropriate to use $d = z_r$. At smaller values of z_r the direct path arrival will have a higher amplitude than the surface reflected arrival and this approximation breaks down. However, for this case it is possible to obtain an expression for d as follows:

Equation (1) can be written in terms of sound exposure (integrated squared pressure) as:

$$E_r = \frac{E_{0,1}}{d^2}, \tag{2}$$

where $E_{0,1}$ is the sound exposure one metre from the equivalent point source in the direction of the receiver, and E_r is the received sound exposure. We seek a relationship for d that makes Equation (2) a good approximation to the total sound exposure that would be received from the combination of the true source and its image.

We now consider both the true source and its image source to be separate point sources, and recognise that the distance the signal travels from the true source at depth z_s to a receiver vertically below it at a depth z_r, is $z_r - z_s$, whereas the distance from the image source to the receiver is $z_r + z_s$. Adding the sound exposures due to the true and image sources (which is justified because the initial positive and negative impulses that contain most of the energy only slightly overlap in time at the receiver) and assuming no energy loss due to the surface reflection yields a total received sound exposure of:

$$E_r = E_{0,2}\left(\frac{1}{(z_r - z_s)^2} + \frac{1}{(z_r + z_s)^2}\right), \tag{3}$$

where $E_{0,2}$ is the source sound exposure of the true source, which is assumed the same both downward and upward. Equating E_r in equations (2) and (3) and setting $E_{0,1} = 2E_{0,2}$ to account for the upward and downward travelling energy, leads to:

$$\frac{2E_{0,2}}{d^2} = E_{0,2}\left(\frac{1}{(z_r - z_s)^2} + \frac{1}{(z_r + z_s)^2}\right), \tag{4}$$

which can be solved for d to give:

$$d = \frac{z_r^2 - z_s^2}{\sqrt{z_r^2 + z_s^2}}, \tag{5}$$

The limits of this equation are $d \to 0$ when $z_r \to z_s$, which is consistent with the fact that the signal at a receiver close to the true source is dominated by the direct path component, and $d \to z_r$ when $z_r \to \infty$ which is consistent with the discussion above.

Note that, when applied to airgun arrays, Equation (5) is strictly only valid for a receiver far enough below the array that the array can be treated as a point source. This approach is referred to as the equivalent dipole source model in what follows.

2.2 The effect of the seafloor

A receptor, such as a crustacean, fish or shellfish, located on the seafloor will be subject to both the downward going incident signal from the airgun array and its upward going reflection from the seafloor. If the seafloor is in the far-field of the airgun array the total received sound pressure level can be calculated from:

$$L_p = SL - 20\log_{10}(d) + 20\log_{10}(|1 + R|), \tag{6}$$

where R is the seafloor normal incidence pressure reflection coefficient. R has a magnitude between zero (no reflection) and 1 (complete reflection) which, for the common case of the incident and reflected waves being in phase, results in L_p being between 0 dB and 6 dB higher than L_i .

2.3 Near-field to far-field transition

According to Sherman and Butler (2007, p 531), for arrays operating at a single frequency the far-field corresponds to receiver distances, d, that satisfy:

$$d \gg l^2/(2\lambda) \quad \text{(m)}, \tag{7}$$

where l is the maximum dimension of the array perpendicular to the direction of sound propagation (m), and λ is the acoustic wavelength (m). Applying this formula to a broad-band source such as an airgun array is by no means straightforward as it shows that a given receiver may be in the far-field of the array at low frequencies (long wavelengths) but in the near-field of the array at high frequencies (short wavelengths). Equation (7) also assumes a fully populated array of identical sources, which is not the case for an airgun array. Nevertheless it serves as a useful guide.

One approach to applying Equation (7) to an airgun array is as follows. Figure 3 shows the spectrum of the surface affected source waveform plotted in Figure 2. (The deep notches at multiples of 125 Hz are due to the interference between the direct and surface reflected signals discussed above.) The spectral level is 3 dB below its maximum at a frequency of approximately 90 Hz, which corresponds to a wavelength of 16.7 m at a sound speed of 1500 ms^{-1}. For downward propagation (i.e. normal to the plane of the array) the maximum relevant array dimension is the array diagonal, so $l = \sqrt{14^2 + 17^2} = 22$ m. Substituting these values into Equation (7) predicts that to be in the far-field, and therefore to be able to apply equations (1) and (6), requires $d \gg 14.5$ m.

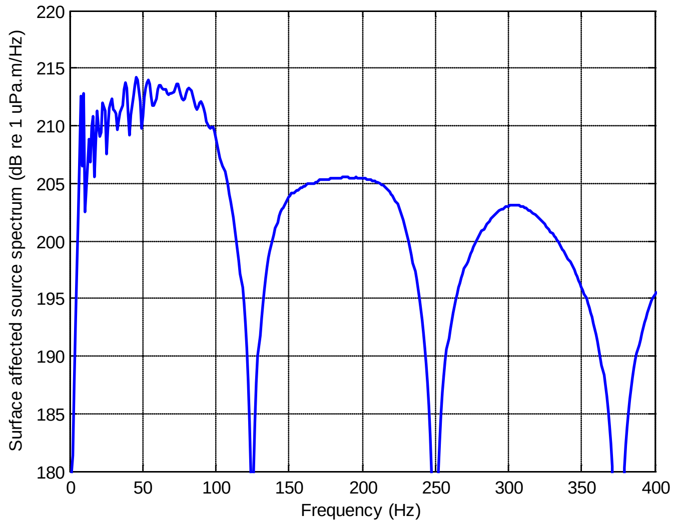

Figure 3: Spectrum of the surface affected source waveform for the vertically downward shown in Figure 2.

3. COMPARISONS WITH MODELLED LEVELS BELOW AN AIRGUN ARRAY

The utility of the equations given above has been investigated by comparing their predictions for the 49.2 l (3000 in^3) array described above with levels calculated using Cagam. Cagam calculates the acoustic pressure source waveform due to each individual airgun in the array and then calculates the received signal at any required location by summing these signals with appropriate time delays and scalings to account for the propagation from each airgun to the receiver and the reduction in amplitude due to spherical spreading. This approach is valid in the far-field of the individual airguns which, due to their small size, have much smaller near-field to far-field transition distances than the array as a whole.

In Figure 4(a) the received sound exposure levels calculated by three different methods are plotted as a function of the receiver depth below the sea surface. It is apparent that, at shallow depths, using an equivalent point source at the surface (i.e. Equation (1) with $d = z_r$) gives a result closer to the Cagam result than using an equivalent dipole source (Equation (1) with d given by Equation (5)). This somewhat counterintuitive result occurs because of the breakdown of the assumption inherent in the derivation of Equation (5) that the array and its image can both be treated as point sources.

As expected, both equivalent source methods converge to the Cagam result as the receiver depth increases. This represents the transition from the near-field to the far-field of the array and it is important to note that this is a smooth transition and not a sudden change at some particular range.

Figure 4(b) shows the difference between each of the equivalent source results and the Cagam result as a function of the depth of the receiver below the array. At the near-field to far-field transition distance of 14.5 m predicted by the method described in Section 2.3, the equivalent point source at the surface over predicts the received SEL by 1.1 dB and the equivalent dipole calculation over predicts the received SEL by 2.2 dB. At double this distance the errors are 0.6 dB and 1.0 dB respectively.

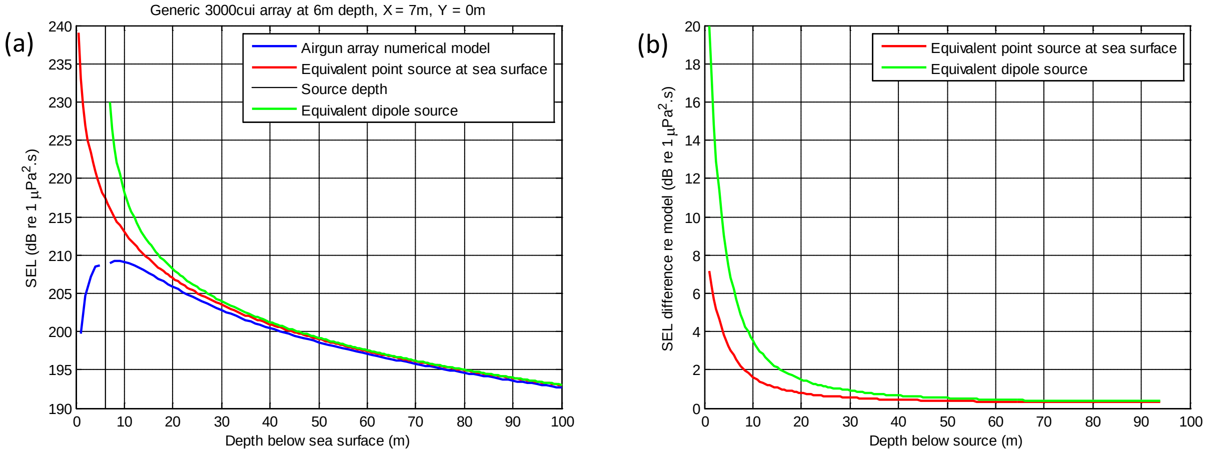

Figure 4: (a) Received sound exposure level vs. receiver depth below the sea surface as calculated using Cagam (blue), an equivalent point source at the sea surface (i.e. Equation (1) with $d = z_r$, red), and an equivalent dipole source (i.e. Equation (1) with d given by Equation (5), green). (b) The dB difference between the equivalent source models and the Cagam result as a function of the depth of the receiver below the array.

Similar plots are given in Figure 5 for the for the peak sound pressure level, but in this case the comparison is only between Cagam and an equivalent point source at the depth of the array. Again the equivalent point source prediction converges to the Cagam result as the receiver depth is increased, but the convergence is slower than it was for SEL, with an error of 3.3 dB at a distance below the array of 14.5 m and an error of 1.4 dB at double this distance. This is likely to be because the peak level is more sensitive to the high frequency content of the signal than the SEL and that therefore, from Equation (7), the near-field to far-field transition for peak level would be expected to occur at a longer range than is the case for SEL.

4. CONCLUSIONS

The main conclusions from this work are as follows:

- An equivalent point source model with source levels derived from the far-field surface affected source waveform for the vertically downward direction can be used to calculate the sound exposure level and peak sound pressure level beneath an airgun array providing the receiver is in the acoustic far-field of the array.

- The equivalent point source model will overestimate the received levels at a receiver in the near-field of the array.
- For positive peak sound pressure level calculations, the equivalent point source should be placed at the depth of the array, and for negative peak pressure calculations it should be placed at the position of the image source, i.e. an equal distance above the water surface.
- For sound exposure level calculations, an equivalent point source at the sea surface was found to give better results for the airgun array considered here than an equivalent dipole model.
- The transition between the acoustic near-field and far-field of the array is smooth, but the use of Equation (7) together with an acoustic wavelength corresponding to the upper -3 dB point of the surface affected source spectrum for the vertically downward direction provided a useful estimate of the near-field to far-field transition distance. For the array considered here the predicted near-field to far-field transition distance was 14.5 m and the equivalent point source model was found to over predict the SEL at this distance below the array by 1.1 dB and to over predict $L_{p,pk}$ by 3.3 dB. At double this distance these errors had reduced to 0.6 dB and 1.4 dB respectively.
- The larger errors associated with $L_{p,pk}$prediction are attributable to this measure's greater sensitivity to the high-frequency content of the signal.

One note of caution when applying these methods to estimate received levels at the seafloor directly below the array is that the example waveforms for the vertically downward direction provided by seismic contractors are often filtered to a bandwidth corresponding to the bandwidth of the seismic data acquisition system, which can be as low as 120 Hz. This has the effect of artificially reducing both ESL and SL_{pk}, with the effect on the latter being the largest and often being 3 dB or more. Therefore, when these calculations are carried out for environmental purposes they should always be carried out using source levels derived from unfiltered waveforms.

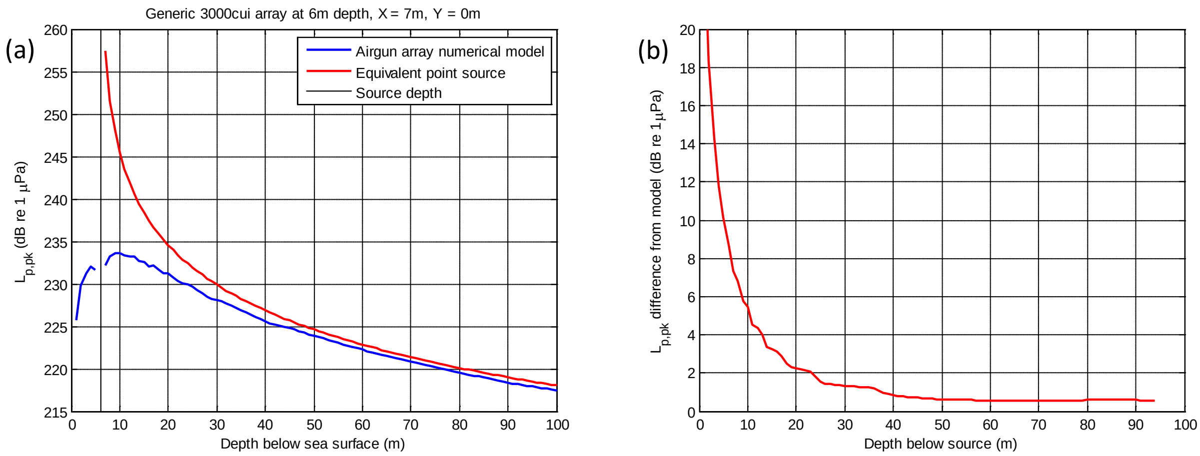

Figure 5: (a) Received peak sound pressure level vs. the receiver depth below the sea surface as calculated using Cagam (blue), and an equivalent point source at the source depth (i.e. Equation (1) with $d = z_r - z_s$, red),. (b) The dB difference between the equivalent source model and the Cagam result as a function of the depth of the receiver below the array.

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