UNDERWATER SOUND RECEIVED FROM SOME DEFENCE ACTIVITIES IN SHALLOW OCEAN REGIONS

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Abstract

The Environmental Protection and Biodiversity Conservation (EPBC) Act 1999 became effective on 16 July 2000. This Act places requirements on the Department of Defence in regard to actions which are likely to have an impact on the environment anywhere in the world. As a consequence, it is essential for Defence to be aware of the environmental implications of its activities. In the area of Defence maritime operations, relevant issues include the radiation of acoustic energy, particularly in regard to sonar systems, and the acoustic signal levels which are expected to be incident upon marine fauna. This paper reviews some of the progress in relevant studies carried out by DSTO, with particular emphasis made on the signals received in shallow ocean areas as a result of detonations of small explosives known as "SUS" charges. Data displayed in this paper, for a particular shallow tropical water location north of Australia, suggest that received peak levels, in particular, may be substantially less than published weak shock theory suggests. Based on the circumstances of these measurements, reasons for the discrepancies between measured and predicted peak levels are suggested.

Nomenclature

IL	received level, dB re $(1\,\mu\text{Pa})^2/\text{Hz}$ (spectrum)
EL	equivalent energy level dB re $(1\,\mu\text{Pa})^2\,\text{s}/\text{Hz}$
P_0	peak pressure amplitude of SUS pulse, Pa
t_0	time constant for SUS waveform, seconds

Introduction

There is strong interest within the Australian Defence Force (ADF), and within defence forces internationally, in their role in the welfare of the maritime environment. In particular, it is a desire of the ADF that it has the capability to conduct its maritime operations and maintain its related equipment in an environmentally responsible manner both within Australian ocean waters and worldwide. For this reason, the Directorate of Environmental Stewardship has a requirement that relevant phenomena are investigated and essential principles are established. Relevant issues include the radiation of acoustic energy, particularly in regard to sonar detection systems. DSTO is providing support to the ADF via relevant scientific advice.

This paper outlines progress in a study of the extent to which Defence maritime activities insonify the underwater ocean environment and overviews techniques used to quantify the levels of underwater sound generated. In particular, this paper shows some recent progress in evaluating the insonification caused in shallow ocean waters in the Australian region by the detonation of small underwater explosives known as Signals Underwater Sound (SUS). The latter work is partly in response to the estimations of high peak pressure levels for SUS presented within a report sponsored by Defence [1].

Signal and Noise Transmission and Data Processing

Received level for signal and noise sources

For sound sources located underwater, the Source Level (SL) is a measure of the sound pressure level corresponding with the acoustic intensity signature, on the axis of maximum output, extrapolated back to a position 1 m from its acoustic centre [2]. For brevity, the term "intensity level" is used herein, in place of "sound pressure level corresponding with intensity".

For any sound source type, the incident, or received level (IL) is herein defined as the acoustic intensity received at a point of interest within the ocean. The IL is then a combination of SL and transmission loss TL, as

$$IL = SL - TL, \tag{1}$$

where IL is incident, or received level, dB re $(1\,\mu\text{Pa})^2$ (line), dB re $(1\,\mu\text{Pa})^2/\text{Hz}$ (continuous spectrum)

It is desirable to make estimates of IL, based on known values of SL and TL, and this intensity-based calculation is routine for continuous tonal signals and continuous broadband signals. For transient signals, however, the temporal nature of the radiated waveform and sound transmission impact on the determination of radiated and Received intensity and must be considered.

Acoustic Intensity

As shown by, for example, Urick section 1.5 [2], instantaneous acoustic intensity I is defined as

$$I = p'^2 / \rho_w\, c_w \ \ \text{Watts/m}^2 \tag{2}$$

where p' is instantaneous acoustic pressure, Pa; ρ_w is density of acoustic medium (sea water), $\mathrm{kg/m^3}$; c_w is speed of sound in acoustic medium (sea water), $\mathrm{m/s}$.

For practical purposes, a measurement of *IL* must be based on an average of intensity *I*, obtained over a duration *T*, which follows from equation (2) as

$$I = \frac{1}{T}\int_0^T \frac{p^2(t)}{\rho_w c_w} dt \ \ \mathrm{Watts/m^2}. \qquad (3)$$

Clearly, the averaging time *T* is significant in determination of *I*, and must be sufficient for the determination of a true average of squared sound pressure.

Note that *IL* is based on an average of intensity, but is determined as follows:

$$IL = 10\log_{10}\left(\frac{\overline{p}^2}{(p_{ref})^2}\right) \ \mathrm{dB\ re}\ (1\ \mu\mathrm{Pa})^2 \qquad (4)$$

where $\overline{p}^2$ is received mean-square sound pressure, Pa; p_{ref} is reference sound pressure, 1×10^{-6} Pa (1 μPa).

Received intensity for impulsive signal sources

If the sonar signal source is impulsive, as from an explosion or implosion, the received signal must be integrated over the signal duration. For signal transients, Urick (section 2.6 [2]) suggests a description of the received signal in terms of an "energy flux density", *E*, as

$$E = \frac{1}{\rho_w c_w}\int_0^\infty p^2(t)\, dt \ \ \mathrm{Joules/m^2}. \qquad (5)$$

An example of a received transient resulting from an explosive SUS source is the acoustic pressure waveform shown in Figure 1. Clearly, the integration in equation (5) need be carried out for the duration of the received signal, only. Applying a limit of time *T* to the integration, and making reference to equation (3), gives

$$E = \frac{1}{\rho_w c_w}\int_0^T p^2(t)\, dt \ \ \mathrm{Joules/m^2} = I \times T \qquad (6)$$

which indicates the relationship between intensity and energy flux density.

In a similar way that a reference for the dB form of intensity (the intensity level) is made to the intensity resulting from a mean-squared pressure of $(p_{ref})^2$ $\left(\mathrm{ie.}\,(1\,\mu\mathrm{Pa})^2\right)$, the energy flux density level, as "equivalent energy level" *EL* in dB, may be referenced to the energy flux density resulting from the equivalent of a mean-squared pressure of $(1\,\mu\mathrm{Pa})^2$ integrated over one second. That is, the reference value of energy flux density is $E_{ref} = (1\ \mu Pa)^2/(\rho_w c_w)\,\mathrm{Joules/m^2}$, and the units of *EL* are stated as $\mathrm{dB\ re}\,(1\ \mu\mathrm{Pa})^2 s$ or $\mathrm{dB\ re}\,(1\ \mu\mathrm{Pa})^2\mathrm{s/Hz}$ depending on whether tonal or spectrum values are considered.

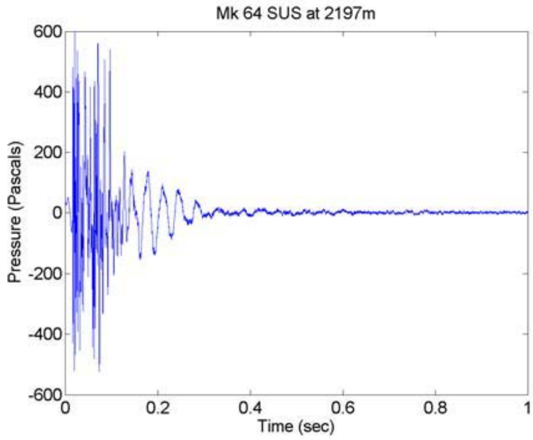

Figure 1. Received signal from Mk 64 SUS at 2197 m range in a shallow ocean

The equivalent energy level, *EL*, received at a given location and due to an impulsive signal, may then be defined as

$$EL = 10\log_{10}\left[\int_0^T p^2(t)dt \Big/ (p_{ref})^2\right]$$
$$= 10\log_{10}\left(\frac{\overline{p}_T^2\, T}{(p_{ref})^2}\right) \mathrm{dB\ re}\,(1\ \mu\mathrm{Pa})^2\mathrm{s/Hz} \qquad (7)$$

where $\overline{p}_T^2$ is mean-square sound pressure determined over duration *T* of signal, Pa.

The concept and use of the equivalent energy level, or its equivalent, is considered by Urick (section 4.4 [2]) and is used in studies conducted by the Centre for Marine Science and Technology at Curtin University ([3], [4]). By comparing equation (7) for $T = 1$ second, with equation (4), we see that the expressions for received level *IL* and equivalent energy level *EL* are the same, numerically, as the term in *T* disappears. Thus, it follows that an expression of a brief transient as *EL* in dB re $(1\ \mu\mathrm{Pa})^2\mathrm{s/Hz}$ is equivalent to a determination of the received level, *IL*, by averaging over 1 second

SUS Charge Noise Source

Signal levels generated by underwater explosions have been studied extensively, eg. see section 4.4 of Urick [2] and Richardson et al [5] section 6.7. There are several types of underwater explosives of interest to the ADF – including the SUS charge.

The radiated waveform is dominated by a very brief, high level sound pressure spike, which is radiated from the very high pressure mass of gas which is generated on detonation of the charge. This mass of gas expands rapidly, and then subsequently collapses. Lower level peaks of reducing amplitude are radiated by the subsequent non-linear resonant expansion and contraction of the bubble mass. The waveform has the approximate appearance as shown in Figure 2.

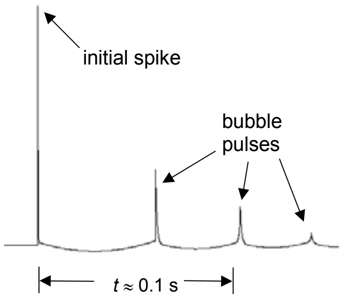

Figure 2. Explosive source waveform (idealized) Mk 64 SUS

As reviewed by Urick, for a TNT charge, the initial spike consists of a sharp rise to a peak of amplitude P_0 followed by an exponential drop to near ambient pressure. The pressure spike then is approximately

$$p(t) = P_o e^{-t/t_0} \quad \text{for } 0 < t \tag{8}$$

where t_0 is time t for SUS waveform pressure to drop to $P_0/e = 0.368P_0$, seconds.

The magnitude of the pressure spike and the time constant are dependent upon the charge weight and range from the explosion [2] as

$$P_0 = 5.24 \times 10^7 \left(\frac{w^{1/3}}{r} \right)^{1.13} \text{ Pa, and} \tag{9}$$

$$t_0 = 9.25 \times 10^{-5}\, w^{1/3} \left(\frac{w^{1/3}}{r} \right)^{-0.22} \text{ s} \tag{10}$$

where w is explosive charge weight, kg; r is range from explosion, m.

In the case of the SUS waveform, an estimate for the broadband EL at 1 m may be based on an integration of the sound pressure trace formed by the initial spike and the exponential decay, as shown by Urick (p. 92 [2]). Using equation (7), this integration may be shown to be

$$EL = 10 \log_{10} \left(\frac{P_0^2\ t_0}{2 \left(p_{ref} \right)^2} \right) \text{ dB re} \left(1\ \mu\text{Pa} \right)^2 \text{s} . \tag{11}$$

More precise determinations of EL may be made by taking into account a more accurate SUS waveform as shown in Figure 2, as appropriate for the detonation depth (see, for example, Gaspin and Shuler [6]). Values for EL at 1 m distance for Mk 61 and Mk 64 SUS, as determined from equation (11), and as determined from a more accurate SUS waveform for a SUS depth of 18.3 m (60 ft) are shown in Table 1 – the former in parenthesis. It is noteworthy that broadband values determined using Equation (11) are very close to those determined by the use of a more detailed waveform, and the approximate result is adequate for all practical purposes. Table 1 also shows peak pressure values and time constant values as determined by Equations (9) and (10). The values of EL at 1 m distance in Table 1 may be regarded as SL values for determination of EL at longer range, if transmission is approximately the same at each frequency.

Table 1. SUS signal source characteristics at 1 m

SUS Type	TNT Charge Weight kg	Peak Pressure P_0 at 1 m Pa	Time Constant t_0 seconds at 1 m	Broadband Equivalent Energy Level dB re $(1\,\mu\text{Pa})^2\text{s}$ at 1 m
Mk 64	0.031	1.4×10^7	0.037 ms	217 (216)
Mk 61	0.83	4.9×10^7	0.088 ms	231 (230)

Determination of Received Level

Multi-path transmission in a shallow ocean has the result that the transient is received along many paths, each with a particular time delay and a particular alteration to the shape of the pulse. The determination of the duration over which the multi-path signals arrive, and their relative amplitude and shape change, is by no means straight-forward and, in general, is unknown. In all cases, however, the many arrivals form an impulse envelope response in the shape of a decay which persists until the higher order arrivals become indistinguishable above the noise. The IL, for a signal received from an impulse or short transient, must be based on an integration of the arrivals over the time τ that the significant arrivals are received. In practice, the impulse will not be greater than 1 second, so the IL may be determined using a 1 second period, this then being numerically the same as the EL.

Received peak pressure for explosive sources

As outlined by Richardson et al, Page 150 [5], Gaspin derived a limiting range r_0 for applicability of equations (8) through (10), as given by $r_0 = 4.76\, w^{1/3}$ m. For ranges greater than r_0, Richardson et al state that Rogers derived the following expressions for the peak pressure P_0 and time constant t_0 of an exponential wave from weak shock theory:

$$P_0(r) = P_0(r_0) \left[\frac{\left[1 + \left[2\, r_0/L_0 \right] \ln(r/r_0) \right]^{1/2} - 1}{\left[r/L_0 \right] \ln(r/r_0)} \right] \text{ Pa} \tag{12}$$

$$t_0(r) = t_0(r_0)\left[1 + \left[2\,r_0/L_0\right]\ln(r/r_0)\right]^{1/2} \text{ s} \quad (13)$$

for $L_0 = \rho_w\, c_w^3\, t_0(r_0) / (P_o(r_0)\,\beta)$

where $P_0(r_0)$ is peak pressure at limiting range r_0, Pa; $t_0(r_0)$ is time constant at limiting range r_0, s; β is dimensionless constant of value 3.5.

Values of peak pressure and time constant for ranges of relevance, as determined by use of Equations (12) and (13) are shown in Table 2. Also shown are estimates of the broadband equivalent energy *EL* for these ranges, as based on the values of $P_0(r)$ and $t_0(r)$ determined from Equations (12) and (13) and the use of equation (11).

Table 2. SUS signal characteristics at large range

SUS Type	Range m	Peak Pressure $P_0(r_0)$, Equ (12) Pa	Time Constant $t_0(r_0)$, Equ (13) seconds	Broadband Equivalent Energy dB re $(1\,\mu\text{Pa})^2$s Equ (11)
Mk 64	1000	8200	0.095 ms	155 dB
	5000	1500	0.105 ms	141 dB
	10,000	740	0.109 ms	135 dB
Mk 61	1000	25,000	0.26 ms	169 dB
	5000	4700	0.29 ms	155 dB
	10,000	2300	0.30 ms	149 dB

It is noteworthy that the values of time constant shown in Table 2 are greater than for a 1 m distance shown in Table 1 – indicating a slight spreading with range. As shown in Table 2, this spreading increases very slowly beyond close range.

The authors acknowledge that the precise waveform of a direct impulse from a SUS, or explosive, is a subject of active research. The above expressions from weak shock theory were used in the present study, as the same approach had been used in an earlier study sponsored by Defence [1]. As the report from that study [1] had been distributed to some organizations external to Defence, a comparison of peak values from weak shock predictions and from measurements was desirable.

Measured Data

DSTO's Maritime Operations Division has measured underwater signals received from SUS charges along a number of tracks within continental shelf waters in the Australian region. Most of this data was obtained from horizontal ranges as close as a kilometre, approximately, to about 30 km or more. For each track, the *in-situ* details obtained include water temperature versus depth for at least one point along the track (from which sound speed versus depth has been obtained). The recordings of the data presented below were obtained using a measurement system which was designed with the expectation that SUS peak levels would be as indicated by equation (9). All signals selected for analysis were examined for the presence of overload and any exceeding system criteria were rejected [7].

Track A

Data for Track A is based on Mk 64 SUS detonated at 18.3 m (60 ft) depth and received at 18.3 m. The data sampling rate for these recordings was 20 kHz, giving a maximum frequency, taking account of anti-alias filtering, of 8kHz. (The effective data sampling rate then becomes 16,000 Hz.) The bathymetry along the track showed a near constant depth at 56 m. The sound speed profiles obtained at each of the start and end of the track, are shown in Figure 3. An acoustic ray diagram to 3 km along the Track is shown in Figure 4. Received pressure time series data are shown in Figures 5 to 7. Measured and predicted data are shown in Table 3.

The received time series data shown in Figure 1 is, in fact, the full waveform for range 2197 m along Track A.

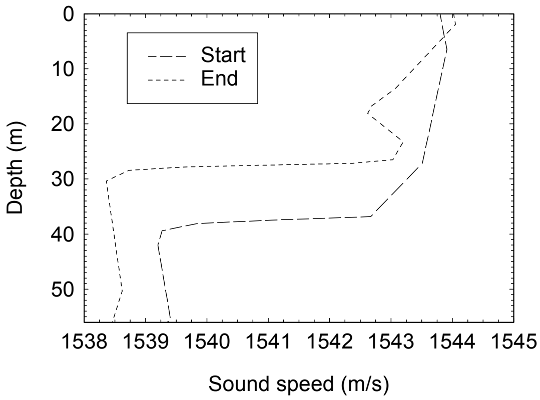

Figure 3. Sound Speed Profile for Track A

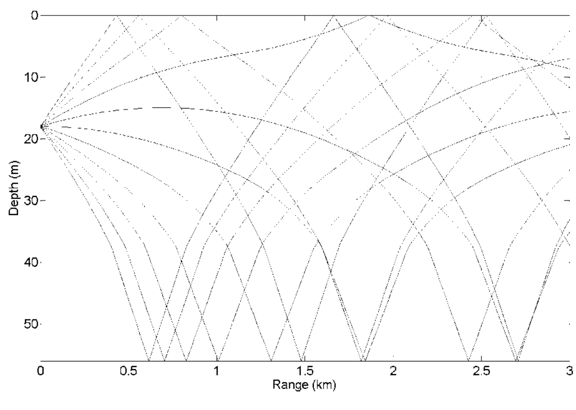

Figure 4. Ray plot for Track A

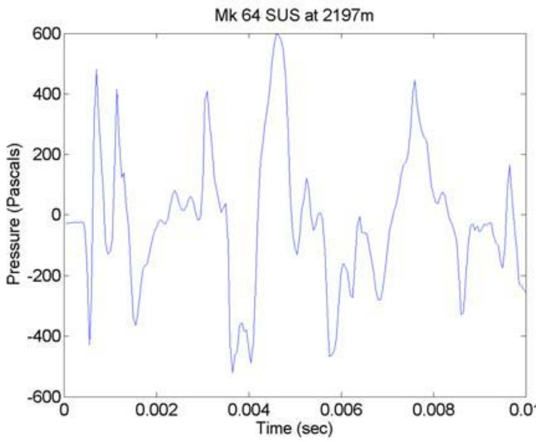

Figure 5. Received sound pressure time series, Track A, initial 0.01 s, at 2.20 km

The time series detail in Figure 5 shows a complex series of arrivals. By looking at the ray plot, Figure 4, it is sufficiently clear that at 18.3 m depth and about 2.20 km range (conditions of measurement for data in Figs. 1 and 5), the received signal will include a direct arrival, a surface reflection and a bottom reflection. This ray plot contains 11 rays launched at angles evenly spaced between ± 2½ degrees. This ray plot is range independent and uses the sound speed profile at the start of the Track. Clearly, if rays at steeper angles were included, ray arrivals at the receiver at 2.20km range would include those with combinations of surface and bottom bounces.

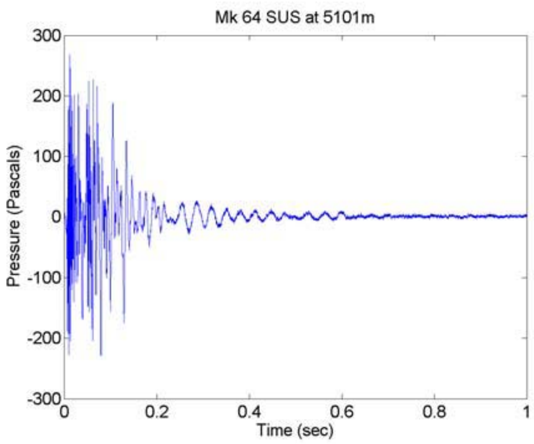

Figure 6. Received sound pressure time series, Track A, full pulse, 5.10 km

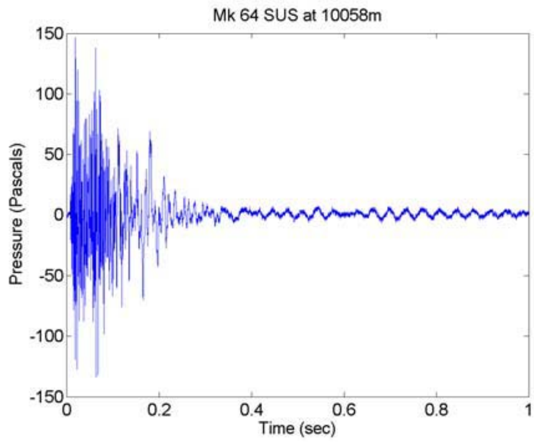

Figure 7. Received sound pressure time series, Track A, full pulse, 10.1 km

Table 3. SUS signal characteristics measured and predicted along Track A

	Horizontal Range		
	2.20 km	5.10 km	10.1 km
Peak pressure (measured)	597 Pa	268 Pa	146 Pa
Peak pressure Equ (12)	3560 Pa	1490 Pa	732 Pa
Time constant Equ (13)	0.10 ms	0.10 ms	0.11 ms
Broadband *EL* dB re $(1\,\mu\text{Pa})^2\,\text{s}$ (meas)	157 dB	150 dB	144 dB
Broadband *EL* dB re $(1\,\mu\text{Pa})^2\,\text{s}$ (data from Equ (12), (13) in Equ (11))	148 dB	140 dB	135 dB

Note that the theoretical derivations for the received peak pressure, as determined by Equation (12), and for the received *EL*, as determined by Equation (11), are for a single arrival of the SUS detonation time series along a direct path. In a realistic shallow ocean scenario, the arrival structure will be highly multi-path in nature, as shown in Figures 1, 6 and 7, and will be comprised of many arrivals superimposed.

If a $20\log r$ reduction is applied to the Source Level values, that is the data at 1 m, shown in Table 1 for Mk 64 SUS, the data in Table 4 may be obtained (here, the more accurate value of *EL* used). It is noteworthy that the values obtained using Source Level data and simply allowing for spherical spreading are, as a first order estimate, close to the theoretical derivations for peak pressure and the *EL* (2nd and last rows of Table 3, respectively).

Table 4. SUS signal characteristics predicted along Track A, based on 1 m data

	Horizontal Range		
	2.20 km	5.10 km	10.1 km
Peak pressure Table 1 $-20\log r$	6,360 Pa	2750 Pa	1390 Pa
Broadband *EL* dB re $(1\,\mu\text{Pa})^2\text{s}$, value at 1 m $-20\log r$	150 dB	143 dB	137 dB

Discussion

Equivalent Energy Level *EL*

The data in the last two rows of Table 3 show that the measured received values of *EL* are indicative of about 10 dB less loss than values of *EL* predicted for the single direct path arrival of the SUS pulse received at each respective range. This may be seen as indicating that the broadband *TL*, taking account of shallow water multi-path phenomena, and the details of surface and bottom loss, is about 10 dB less than for spherical spreading.

The data obtained for Track A for *EL* received at large range is then, roughly, in accord with expectations for certain realistic conditions.

Received Peak Pressure

The data in the first two rows of Table 3 show that the amplitude of the received pressure peak, as measured at each range value, is much less than the peak predicted from Equation (12) for the direct path arrival at the corresponding range. This discrepancy is of the order of a factor of over 5, that is, about 15 dB.

A conceivable reason for this discrepancy may be that the time delays between arrivals are so small that the surface reflection, which is negative, simply cancels the direct and bottom bounce positive arrivals. This has been investigated, very briefly, for arrivals at the closest range for which data exists – 2.20 km, as explained below.

Assuming straight ray path transmission, the first three arrivals are as shown in Figure 8.

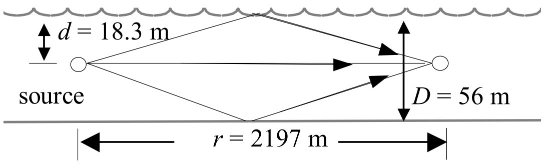

Figure 8. Ray path for first 3 arrivals, Track A, isovelocity (idealized for straight rays)

It may be shown, that the path difference between the direct and surface reflected paths is very nearly $2d^2/r$ metres. For range 2.20 km, a source/receiver depth 18.3 m, this gives a path difference of 0.30 m, and, for isovelocity, an arrival time difference of 0.19 ms. From Table 3, the theoretically-derived time constant is 0.10 ms. Whether the surface reflection will cancel the direct path peak will be very dependent upon exact arrival times. The data in Figure 3 indicate that the average sound speed is slightly higher for the surface reflection, such that the signal will travel slightly faster along the surface reflected path than along the direct. If the surface reflected path is assigned an average sound speed 0.3 m/s greater, it follows that the surface reflected arrival precedes the direct path arrival by 0.08 ms, and would cause some measure of cancellation of the direct arriving peak. The time series data in Figure 5 is inconclusive, but does show that the first arrival has negative pressure, thus identifying it as the surface reflected arrival.

For straight ray paths, it may be shown that the bottom reflected path is 1.29 m longer than the direct, and for isovelocity will be expected to arrive 0.8 ms later. Based on data in Figure 3, an average sound speed of about 1542 m/s may be guessed for the bottom bounce path, giving a corrected delay of 2.7 ms. Data in Figure 5 shows a positive peak about 2.5 ms after the first positive peak, but a second positive peak exists about 0.5 ms later – not explained by this simple ray analysis.

For specular reflection from a reflective sea surface or seafloor, the reflected arrival is expected to have an amplitude of the order of the direct arrival. Figure 5 shows that the first peaks have similar amplitudes of about 400 Pa, but each is much less than the predicted peak value of 3560 Pa shown in Table 3. This may be indicative of one or more of the following: lack of coherence in transmission due to medium irregularities; lack of coherence of reflection due to surface irregularities; chance cancellation of positive pulse by corresponding surface reflected path. In fact, a lack of coherence along each path would be associated with some time spreading, enhancing the possibility of pulse cancellation. It must be acknowledged that the exact phenomena are unknown. The main point, however, is that the measured peal amplitude is less than the theory.

The measured peak pressure data shown in Table 3 indicates a decrease with range, which is not unexpected. At the longer range values of 5.10 km and 10.1 km, it may be shown that no direct path exists and every arrival has combinations of surface and bottom reflections. In each case the measured peak pressure is much less than that predicted for a direct arrival, however, this may well be expected to be a result of reflection losses and coherence losses on reflection.

Data sampling issues

The rate of data sampling used in the description of the time series has implications in the ability to follow the impulse waveform and capture the peak amplitude P_0. If the waveform is a sudden rise followed by an exponential decay, a maximum error may be postulated for a digital sampling system based on “missing” the peak value. For the present data, assuming an effective data sampling rate of 16,000 Hz, for the time constant given by Equation (13) for a Mk 64 SUS gives a maximum error (worst case of missing the peak) of about 5 dB at ranges between 1000 m and 10,000 m.

Data Integrity

It is the authors' understanding that the data acquisition system was specifically designed for the receipt of SUS signals and that all received data was checked for overloading and that data exceeding pre-set criteria were rejected. Data were obtained using SSQ-41B sonobuoys for which the electronics were modified for a flat frequency response and for the attenuation of expected high amplitude levels [7]. It is the authors' understanding that the peak waveform data discussed in this paper are within the design limits of the sonobuoy system.

Data for other Tracks

Data available for two other tracks in different shallow ocean regions show received peak pressure values similarly about 15 dB less than values predicted by Equation (12) for the direct path arrival.

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Conclusions

Data presented above show that levels of peak sound pressure received in a particular shallow ocean at ranges greater than about 2 km from a small underwater explosion are much less than predicted by weak shock theory for a direct arrival pulse. In this study of data obtained along several tracks within the Australian region, the measured peak values are about 15 dB less than those predicted from weak shock theory. The reasons for this discrepancy are still under active study, however it is believed that loss of coherence in in-water transmission, and loss of coherence on reflection from ocean boundaries are the most likely causes.

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