Revisions and Notes on a Model for Bubble Attenuation in Near-Surface Propagation

by Peter H. Dahl

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Applied Physics Laboratory University of Washington
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ABSTRACT

A revised model for predicting surface bubble loss (SBL) as a function of wind speed, surface grazing angle, and frequency is discussed. SBL is defined as the residual loss (i.e., the loss in excess of that due to spreading and chemical absorption) in acoustic energy propagating near the sea surface that is attributable to attenuation by near-surface bubbles. This loss is a key input parameter for predicting bubble attenuation in simulations of weapon-system performance in near-surface environments. The original SBL model was introduced by the Applied Physics Laboratory, University of Washington, in 1993. The revision consists of a new wind-speed threshold for breaking waves and the subsequent onset of bubble production, and an alternative formulation capable of handling more general ray geometries such as a ray vertexing near the surface. Model/data comparisons and examples of the model applied to a linear sound-speed profile are presented.

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EXECUTIVE SUMMARY

In the report APL-UW TR 9307, a model was introduced for the loss of acoustic energy propagating near the sea surface that is attributable to bubbles. This loss is referred to as the surface the bubble loss, or SBL. This report documents (1) a revision in the wind-speed threshold given in the original model for breaking waves and subsequent onset of bubble production, and (2) an alternative formulation of the SBL model capable of handling more general ray geometries such as a ray vertexing near the surface. The alternative formulation consists of a depth-dependent bubble attenuation coefficient.

The revised model is

$$\begin{aligned} \text{SBL (dB)} &= \frac{1.26 \times 10^{-3}}{\sin\theta} U^{1.57} f^{0.85}, \quad U \geq 6 \text{ m/s} \\ &= \text{SBL}\big|_{U=6}\ e^{1.2(U-6)}, \qquad U < 6 \text{ m/s}, \end{aligned} \tag{1}$$

where U is wind speed measured 10 m above the sea surface, f is acoustic frequency in kilohertz, and θ is the nominal grazing angle of the surface bounce path ($\theta > 0°$). In the revised model, the wind-speed threshold has been increased from 4 m/s to 6 m/s and the form of the decay for wind speeds < 6 m/s has been changed to reduce the likelihood of predicting anomalously high SBL at very low wind speeds.

The alternative formulation of the model is

$$\text{SBL (dB)} = 2 \int_{z_v}^{10} \frac{\alpha(z)}{\sin[\theta(z)]} dz\ , \tag{2}$$

where $\alpha(z)$ is the depth-dependent bubble-attenuation coefficient, z_v is the turning point depth of the ray, and $\theta(z)$ is the local grazing angle of the ray at depth z. The depth-dependent bubble-attenuation coefficient is integrated between a depth of 10 m and z_v to form an estimate of the two-way depth-integrated bubble attenuation, which is equivalent to SBL. An equation is given for $\alpha(z)$ as a function of wind speed and frequency.

Starting with Eq. (2), the report derives useful analytic expressions for SBL based on a linear sound-speed profile. Unless the ray undergoes vertexing near the surface, Eq. (1) gives the same result as Eq. (2), and the user should consider this fact in deciding whether to employ the simpler version in Eq. (1) vs the depth-dependent version in Eq. (2). For ray vertexing, Eq. (1) is no longer valid, and the formulation given in Eq. (2) must be employed.

1. INTRODUCTION

In the report APL-UW TR 9307,[1] APL-UW introduced a model for the residual loss (i.e., the loss in excess of spreading and chemical absorption) of acoustic energy propagating near the sea surface that is attributable to bubbles. Since the bubbles are generated by breaking waves and reside within a few meters of the sea surface, this loss is referred to as the surface bubble loss, or SBL. This report documents (1) a revision in the wind-speed threshold given in the original model for breaking waves and the subsequent onset of the production of bubbles, and (2) an alternative formulation of the model capable of handling more general ray geometries such as a ray vertexing near the surface. The alternative formulation consists of a depth-dependent bubble-attenuation coefficient.

Section 2 presents the revised wind-speed threshold and includes some model/data comparisons. Section 3 presents the alternative formulation of the model and includes examples of its use with a linear sound-speed profile. A summary and notes on model usage are presented in Section 4.

2. MODEL REVISION

The revised model is

$$\begin{aligned} \text{SBL (dB)} &= \frac{1.26 \times 10^{-3}}{\sin\theta} U^{1.57} f^{0.85}, \quad U \geq 6 \text{ m/s} \\ &= \text{SBL}\big|_{U=6}\, e^{1.2(U-6)}, \qquad U < 6 \text{ m/s}\,, \end{aligned} \tag{1}$$

where U is the wind speed measured 10 m above the sea surface, f is the acoustic frequency in kilohertz, and θ is the nominal grazing angle of the surface-bounce path ($\theta > 0°$). The model includes a wind-speed threshold of 6 m/s for the production of breaking waves (also known as the Beaufort velocity) and the subsequent production of bubbles. The revised model shown in Eq. (1) differs from the original model *only* in the wind-speed threshold and in the functional form of the decay for wind speeds less than the threshold speed. The wind-speed threshold has been increased from 4 m/s to 6 m/s to reduce the likelihood of predicting anomalously high SBL at very low wind speeds.

Figures 1–3 show representative model/data comparisons for data collected between 20 and 40 kHz in the open ocean from the research platform *FLIP*[1] and in coastal waters off Whidbey Island.[2] Because the data were collected at different grazing angles, all data have been normalized to a 10° grazing angle using the formula

$$\mathrm{SBL}(10^\circ) = \frac{\sin\theta}{\sin 10^\circ}\,\mathrm{SBL}(\theta)\ ,$$

where $\mathrm{SBL}(\theta)$ is the actual measured loss at surface grazing angle θ. The model (Eq. (1) with θ set to 10°) provides a reasonable representation of both the open-ocean and coastal data, with nearly all the data points falling within ±3 dB of the predicted curves.

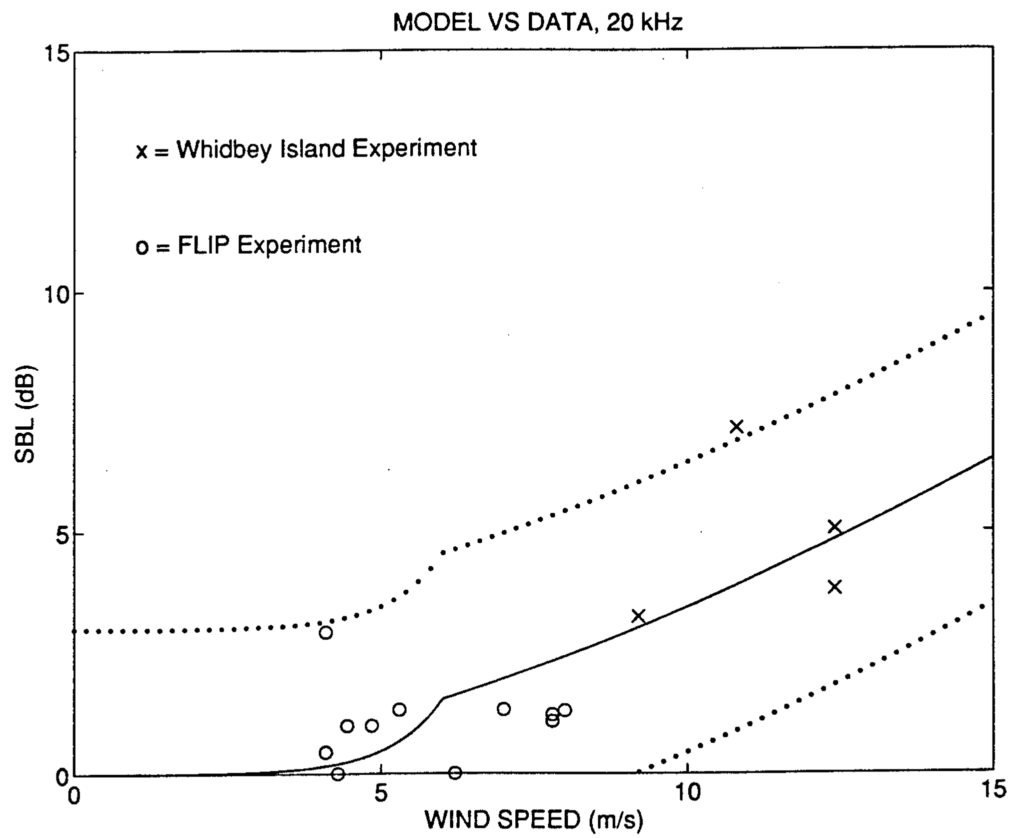

Fig. 1. Comparison of model predictions and measured 20-kHz data from the FLIP and Whidbey Island experiments. Data from various grazing angles have been normalized to a 10° grazing angle. Upper and lower dotted lines represent a ±3 dB interval about the predicted curve.

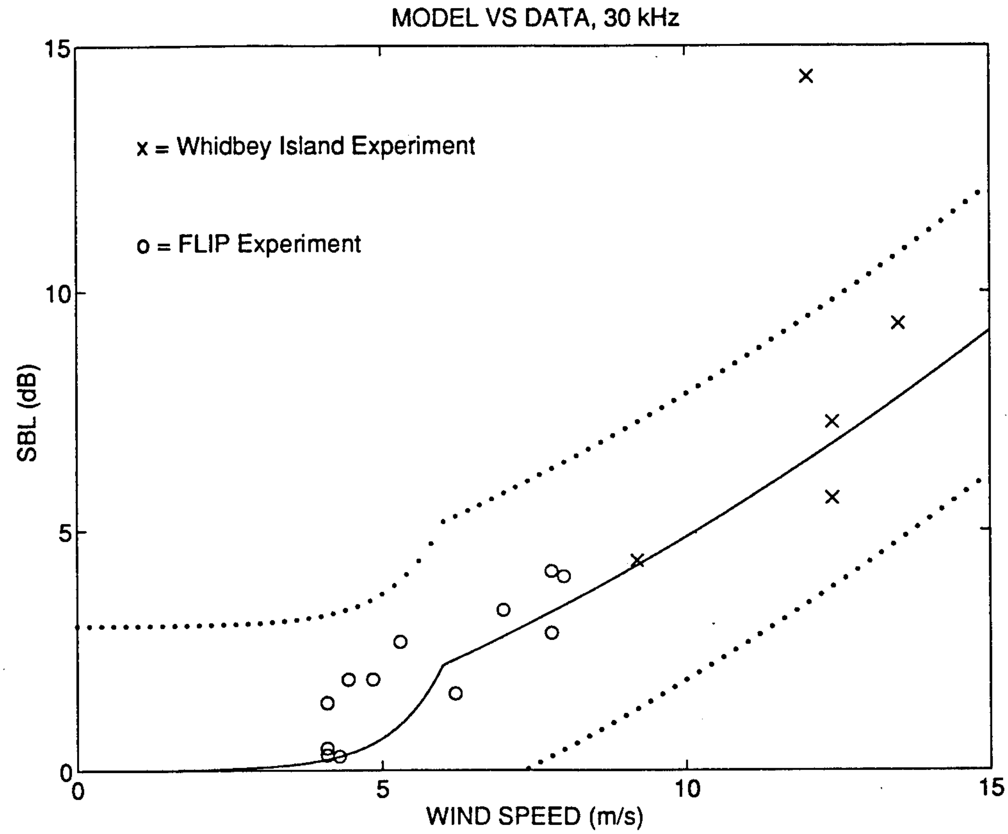

Fig. 2. Comparison of model predictions and measured 30-kHz data from the FLIP and Whidbey Island experiments. Data from various grazing angles have been normalized to a 10° grazing angle. Upper and lower dotted lines represent a ±3 dB interval about the predicted curve.

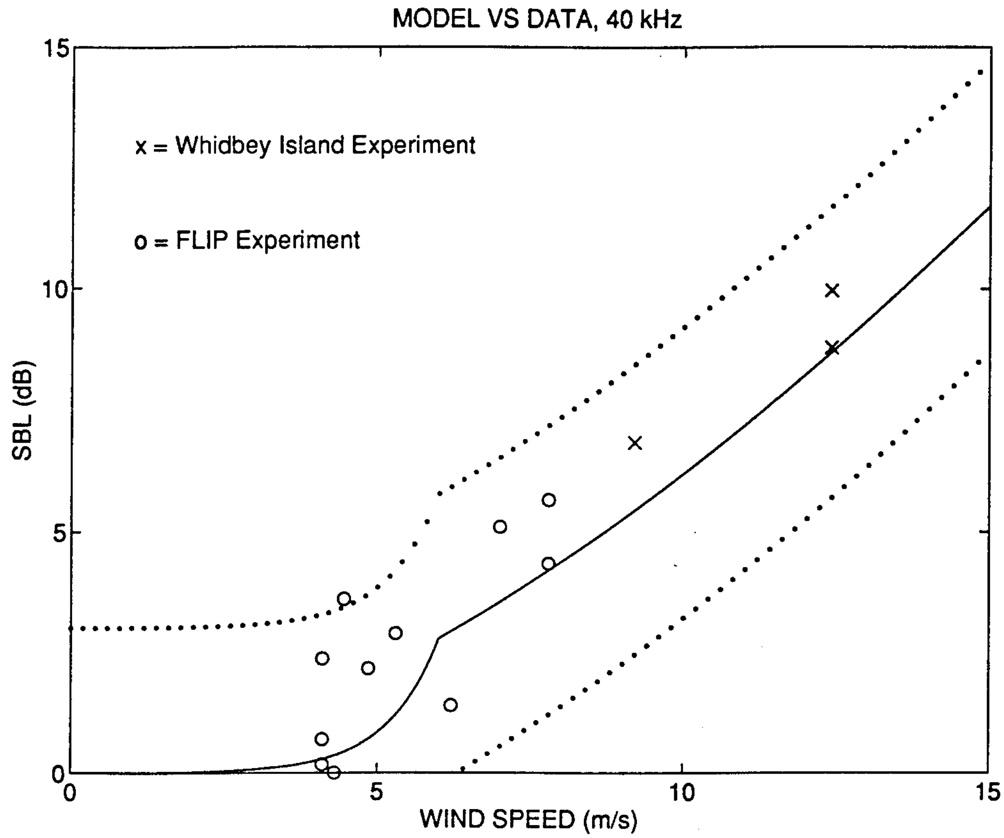

Fig. 3. Comparison of model predictions and measured 40-kHz data from the FLIP and Whidbey Island experiments. Data from various grazing angles have been normalized to a 10° grazing angle. Upper and lower dotted lines represent a ±3 dB interval about the predicted curve.

3. ALTERNATIVE FORMULATION OF THE SBL MODEL

In this section, an alternative formulation of the SBL model is presented which is capable of handling more general ray geometries, including rays vertexing near the surface.

3.1 Depth-Dependent Formulation

The formulation in Eq. (1) represents the two-way depth-integrated bubble attenuation for a surface-reflecting ray under isovelocity conditions. It is simple to implement, and summarizes in a compact way the effects of wind speed, frequency, and surface grazing angle on SBL. Since isovelocity is assumed, however, the model cannot account for refraction effects, and in the case of ray vertexing ($\theta \to 0$) it becomes invalid.

By assuming an equivalent, depth-dependent bubble-attenuation coefficient that decays exponentially with depth, we can write Eq. (1) as

$$\text{SBL (dB)} = 2\int_{z_v}^{10} \frac{\alpha(z)}{\sin[\theta(z)]}\, dz \ , \tag{2}$$

where $\alpha(z)$ is the depth-dependent bubble-attenuation coefficient,

$$\alpha(z) = \alpha_0 e^{-z/L_B} \ , \tag{3}$$

z_v is the turning point depth of the ray, and $\theta(z)$ is the local grazing angle at depth z. The ray reaches a turning point by either reflection or refraction; in any case, z_v may fall within the range $0 \leq z_v < 10$ m. We assume SBL is negligible for rays that undergo vertexing at depths greater than 10 m, or $z_v > 10$ m.

In Eq. (3) L_B is the decay constant, or e-folding depth, for the exponential decay in bubble attenuation with depth and

$$\begin{aligned} \alpha_0 &= 0.63 \times 10^{-3} U^{1.57} f^{0.85} / L_B, && U \geq 6 \text{ m/s} \\ &= \alpha_0\big|_{U=6}\ e^{1.2(U-6)}, && U < 6 \text{ m/s} \ . \end{aligned} \tag{4}$$

Several works[2–6] incorporate an exponential decay model to describe bubble concentration vs depth which can be directly related to $\alpha(z)$. A simple model describing L_B vs wind speed for bubbles within the resonant size range most relevant to torpedo frequencies is $L_B = 0.07 \times U$. This equation, which describes measurements reported in Ref. 7, produces estimates of L_B that fall approximately between estimates derived from similar models reported in Refs. 3 and 4.

The attenuation coefficient $\alpha(z)$ is integrated between a depth of 10 m and z_v and multiplied by 2 to estimate the two-way depth-integrated bubble attenuation, which is equivalent to SBL. For example, if the ray reflects from the sea surface, z_v equals 0; if the ray vertexes, then z_v is the vertex depth. For practical implementation, the maximum vertex depth is set to 10 m because bubble attenuation will be extremely weak beyond this depth. An expression similar to Eq. (2) is given in Ref. 8, which discusses a model for bubble loss at frequencies of 1–10 kHz. The user is cautioned that Eq. (2) has a singular point when $\theta(z) \to 0$ which will cause numerical problems if not handled correctly.

3.2 Examples Using a Linear Sound Speed Profile

For an arbitrary sound-speed profile, Eq. (2) must be implemented numerically; however, instructive analytic results are possible using a linear sound-speed profile of the form

$$c(z) = c_0 + gz \ , \tag{5}$$

where c_0 is the sound speed at the surface, g is the sound-speed gradient in inverse seconds, and z is depth measured from the sea surface. For a linear sound-speed profile, all ray paths can be described by circular arcs with a radius of curvature R_c equal to $(|g|\sigma)^{-1}$, where the ray launch parameter σ is equal to $\cos[\theta(z)]/c(z)$, with θ being the local grazing angle at depth z (Fig. 4). Because σ is an invariant property of the ray, it can be evaluated anywhere along the ray path. For example, if the ray is surface reflecting, a convenient point to evaluate σ is at the surface such that σ equals $\cos(\theta_s)/c_0$, where θ_s is θ evaluated at the surface. If the ray vertexes ($\theta \to 0$) near the surface, then σ equals $1/c_v$, where c_v is the sound speed at the vertex depth z_v.

The different cases of $g > 0$ and $g < 0$ are now analyzed. Note that $g = 0$ means the sound speed is isovelocity in the upper 10 m, the ray paths are straight lines, and there is no advantage in using Eq. (2) instead of Eq. (1). We begin with the case of downward refraction, or $g < 0$, and the instance of a surface-reflecting ray (Fig. 4A). Using the small-angle approximation for the sin of the angle (valid for $\theta \lesssim 20°$), we can write Eq. (2) as

$$\mathrm{SBL} = 2\alpha_0 \int_0^{10} \frac{e^{-z/L_B}}{\theta(z)} dz. \tag{6}$$

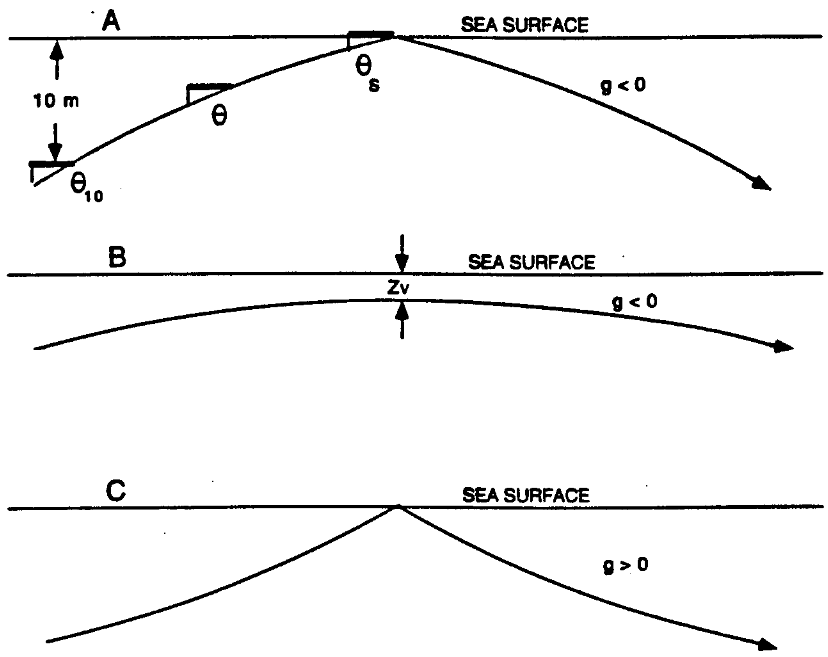

Fig. 4. Ray geometries for a linear sound-speed profile where θ is the local grazing angle, $\theta_s = \theta$ at the surface, and $\theta_{10} = \theta$ at 10-m depth. Geometries in (A) and (B) show downward refraction ($g < 0$), with (A) showing a surface-reflecting ray and (B) showing a ray vertexing at depth z_v. Geometry in (C) shows upward refraction ($g > 0$) and a surface-reflecting ray.

Now, again using the small-angle approximation, we can relate the depth z to local grazing angle $\theta(z)$ by

$$z = \frac{R_c}{2}\left[\theta(z)^2 - \theta_s^2\right] , \tag{7}$$

recalling that $\theta(z)$ will always be $\geq \theta_s$ for $g < 0$. We recast Eq. (6) using θ as the integration variable, giving

$$\mathrm{SBL} = 2\alpha_0 R_c e^{k\theta_s^2} \int_{\theta_s}^{\theta_{10}} e^{-k\theta^2} d\theta , \tag{8}$$

where $k = R_c/(2L_B)$. The limits of integration are now from θ_s to θ_{10}, where θ_{10} is θ evaluated at 10-m depth. Evaluating this integral gives

$$\mathrm{SBL} = 2\alpha_0 R_c e^{k\theta_s^2} \frac{1}{2}\sqrt{\frac{\pi}{k}}\left[\Phi(\sqrt{k}\theta_{10}) - \Phi(\sqrt{k}\theta_s)\right] , \tag{9}$$

where Φ is the tabulated probability integral, or error function,[9] defined as

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt \ .$$

Although the solution is exact, evaluation of the difference between error functions that both have large arguments is prone to numerical error. An asymptotic evaluation of this difference, which is more reliable, gives

$$[\Phi(\sqrt{k}\theta_{10}) - \Phi(\sqrt{k}\theta_s)] \approx \frac{e^{-k\theta_s^2}}{\sqrt{\pi k}\theta_s}, \tag{10}$$

and thus Eq. (9) reduces to simply

$$\text{SBL (dB)} = \frac{2\alpha_0 L_B}{\theta_s}. \tag{11}$$

If we replace θ_s with $\sin(\theta)$, where θ is the ray's grazing angle at the sea surface, this is precisely the formulation for SBL given in Eq. (1). Thus the effect of downward refraction on a surface-reflecting ray is accounted for by simply using the surface grazing angle $\theta = \theta_s$ in Eq. (1).

Next we examine a ray vertexing within 10 m of the sea surface for the same case of $g < 0$ (Fig. 4B). In this instance, we have

$$\text{SBL (dB)} = 2\alpha_0 \int_{z_v}^{10} \frac{e^{-z/L_B}}{\theta(z)}\, dz \ . \tag{12}$$

Following the above procedure, we get

$$\text{SBL} \ = 2\alpha_0 R_c e^{-z_v/L_B} \int_0^{\theta_{10}} e^{-k\theta^2} d\theta. \tag{13}$$

The solution of the integral now gives

$$\text{SBL} \ = 2\alpha_0 R_c e^{-z_v/L_B} \frac{1}{2}\sqrt{\frac{\pi}{k}}\, \Phi(\sqrt{k}\theta_{10}). \tag{14}$$

The argument $\sqrt{k}\theta_{10}$ will in many cases be $\gtrsim 2$, making Φ nearly unity. Thus it is sufficient to write

$$\text{SBL (dB)} = 2\alpha_0 \sqrt{R_c L_B \pi/2}\, e^{-z_v/L_B} \tag{15}$$

as the surface bubble loss for the vertexing ray.

For a vertexing ray, Eq. (2) does give a different solution than Eq. (1), as the latter is invalid when $\theta \rightarrow 0$. Figure 5 shows SBL vs wind speed for a ray that vertexed 2 m below the sea surface owing to a sound-speed gradient of $g = -0.2$ s^{-1}. This value represents the maximum negative gradient within the upper 10 m of ocean, as measured during the FLIP experiment[1] in late afternoon CTD casts. Note that Eq. (15) provides a useful guide for the effect of z_v on SBL. The main influence is the factor e^{-z_v/L_B} (R_c changes very little with z_v). If, for example, z_v changes from 2 to 3 m, SBL is reduced by a factor of e^{1/L_B}.

Finally, the case of upward refraction, or $g > 0$, and a surface-reflecting ray (Fig. 4C) produces the same result as a surface-reflecting ray for $g < 0$ (Fig. 4A) although the intermediate steps are different. Ray vertexing within 10 m of the sea surface is not possible when $g < 0$. These results depend only on the grazing angle being sufficiently small that the small-angle approximation holds and not on the magnitude of g. For large angles, the additional path length incurred (compared with straight-line propagation) owing to refraction within 10 m of the sea surface is small, and therefore Eq. (1) remains a useful approximation.

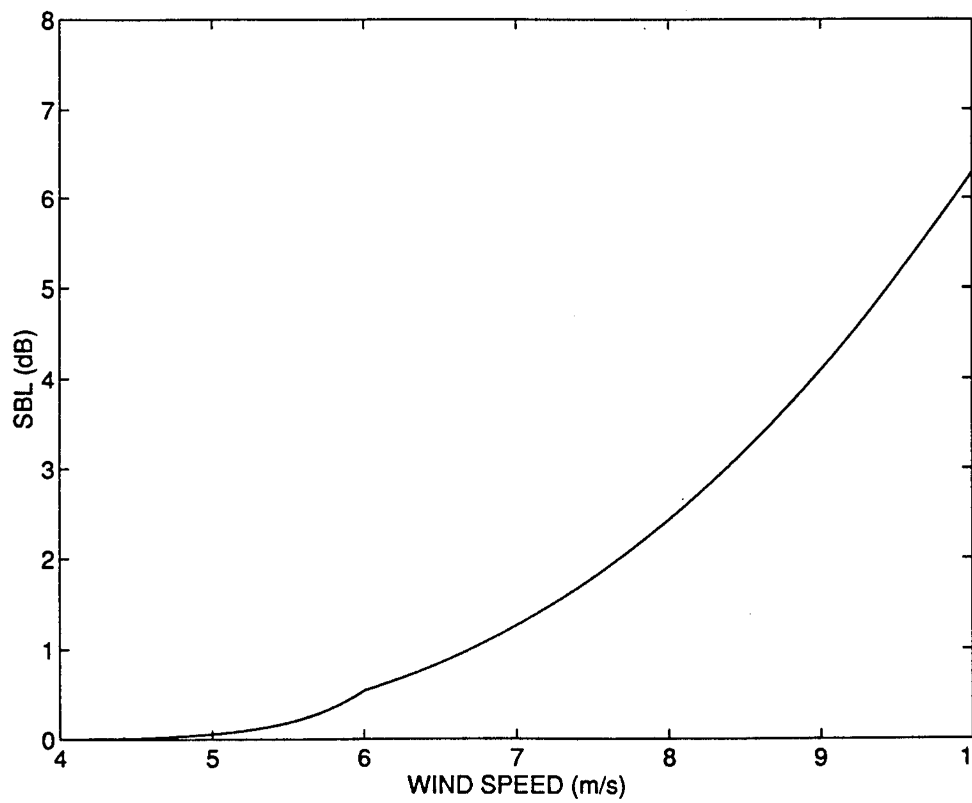

Fig. 5. SBL vs wind speed (frequency = 30 kHz) for a ray undergoing vertexing 2 m below the sea surface, $g = -0.2$ s^{-1}.

4. SUMMARY AND ADDITIONAL NOTES ON MODEL USAGE

Two changes were presented in the model for surface bubble loss (SBL) introduced in APL-UW TR 9307: (1) a revision in the wind-speed threshold for the production of bubbles, and (2) an alternative formulation based on a depth-dependent attenuation coefficient due to bubbles, $\alpha(z)$. The change in the wind-speed threshold affects SBL predictions for wind speeds less than 6 m/s. The alternative formulation of the model is capable of handling total refraction, or vertexing, of a ray within 10 m of the sea surface, and also any refraction that surface-bounce paths may undergo.

Useful analytic expressions for SBL based on the depth-dependent formulation of Eq. (2) were derived using a linear sound-speed profile. For surface reflection, it was shown that the model in Eq. (1) gave the same result as the formulation in Eq. (2). The user should consider this fact in deciding whether to employ the simpler version in Eq. (1) vs the depth-dependent version in Eq. (2).

For ray vertexing (i.e., $\theta \to 0$), Eq. (1) is no longer valid, and simple expressions for SBL as a function of z_v, the ray's vertexing depth, and R_c, the ray's radius of curvature, were derived on the basis of Eq. (4). Because of the exponential decay of bubble attenuation with depth, SBL is set equal to 0 dB for rays that undergo vertexing at depths greater than 10 m.

Some remarks on model usage follow:

1. The coefficients in the model are based on acoustic measurements made at 20–50 kHz. The model is therefore a high-frequency model; as a broad guideline, it is applicable at frequencies from 10–100 kHz. However, its results have recently been shown to be consistent with those of a model developed at the Naval Undersea Warfare Center for lower ship-sonar frequencies.[10]

2. Scattering from bubbles will prevent SBL from becoming arbitrarily large. A nominal limit for SBL is 30 dB, based on scattering from the underside of a uniform layer of near-surface bubbles. However, such a limiting value for SBL has not been observed in data, because the patchiness of the bubble layer will nearly always allow some surface-scattered energy to pass. Thus we recommend an upper limit of $SBL_{\max}$ equal to 15 dB. This value is based on the SBL measurements reported in Refs. 1, 2, and 11.

3. The effect of near-surface bubbles on the real part of the sound speed (known as the sound-speed anomaly) is ignored, since within the model's applicable

frequency range bubbles affect mainly the imaginary part of sound speed, or attenuation.[12]

4. The model is based on measurements from a single surface bounce. To compute SBL for propagation channels with multiple surface (and bottom) interactions, the total SBL is considered to be the sum of the individual SBL values computed for each surface interaction. We caution that the model's accuracy for these conditions has not been evaluated.

5. The model does not address geographical dependencies. We expect that, in general, littoral waters and more pristine oceanic waters will differ in terms of bubble properties. With few exceptions, however, bubble measurements reported in the literature show within-region variability that is greater than between-region variability (compare, for example, Refs. 2 and 7). This fact, together with the data shown in Figs. 1–3 for both coastal and oceanic environments, supports use of a single model at the present time.

Additional remarks concerning basic assumptions employed in the model are contained in APL-UW TR 9307.[1]

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13. ABSTRACT *(Maximum 200 words)*

A revised model for predicting surface bubble loss (SBL) as a function of wind speed, surface grazing angle, and frequency is discussed. SBL is defined as the residual loss (i.e., the loss in excess of that due to spreading and chemical absorption) in acoustic energy propagating near the sea surface that is attributable to attenuation by near-surface bubbles. This loss is a key input parameter for predicting bubble attenuation in simulations of weapon-system performance in near-surface environments. The original SBL model was introduced by the Applied Physics Laboratory, University of Washington, in 1993. The revision consists of a new wind-speed threshold for breaking waves and the subsequent onset of bubble production, and an alternative formulation capable of handling more general ray geometries such as a ray vertexing near the surface. Model/data comparisons and examples of the model applied to a linear sound-speed profile are presented.

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