THE EFFECT OF WIND-GENERATED BUBBLES ON SEA-SURFACE BACKSCATTER

Robbert van Vossen[a] and Michael. A. Ainslie[a]

[a]TNO Defence, Security and Safety, The Netherlands

Robbert van Vossen, TNO Defence, Security and Safety, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands, Fax: +31 70 374 0654 e-mail:robbert.vanvossen@tno.nl

Abstract: *Predictions of sea-surface back-scattering strength are needed for sonar performance modelling. Such predictions are hampered by two problems. First, measurements of surface back-scattering are not available at small grazing angles. These are of special interest to low-frequency active sonar since they mainly contribute to long range propagation. Second, existing theoretical models based on a bubble-free interface underestimate the surface back-scattering strength at larger grazing angles. We investigate whether wind-generated bubbles can explain this deficit. For this purpose, we develop a theoretical description that includes the effect of refraction and scattering of sound by wind-generated bubbles. The comparison of the theoretical predictions to Critical Sea Test measurements show that a good fit is obtained between theoretical predictions and measurements for wind speeds up to 10 m/s. For larger wind speeds, the surface back-scattering strength critically depends on the population density of large (radius > 1 mm) bubbles. This provides an opportunity to estimate the number of large bubbles. We observe a change in the spectral slope in the bubble population model for large bubbles that is in agreement with high-speed camera observations in breaking waves and with the Hinze scale.*

Keywords: *sonar, scattering, bubbles, sea-surface, LFAS*

1. INTRODUCTION

Scattering of sound at the sea surface can have a significant impact on the performance of low-frequency active sonar (LFAS). For this application, the scattering at small grazing angles (i.e. below 5 degrees) is of special interest since these are most relevant for long range propagation, e.g. in a surface duct. It remains nevertheless a challenge to assess the consequences on the LFAS performance since rough-surface back-scattering measurements are not available at these low grazing angles [1],[2].

Empirical or semi-empirical models, such as proposed by Ogden and Erskine [3] are generally used for the extrapolation to small grazing angles. The Ogden-Erskine empirical formula is tuned on a comprehensive set of low-frequency measurements (in the range between 70 and 940 Hz) of surface back-scattering strength available from the Critical Sea Test (CST) experiments [3],[4]. These cover grazing angles in the range 5 to 30 degrees and wind speed values up to 18 m/s. The measured reverberation levels exceed those expected from rough-surface scattering alone, especially for large wind speeds [1],[4],[5]. The Ogden-Erskine empirical formula combines the rough-surface scattering term with the Chapman-Harris empirical model [6] which predicts the surface back-scattering strength at high frequencies and wind speeds.

For small grazing angles, the existing empirical predictions are not constrained by measurements. In this region, the Ogden-Erskine model uses a theoretical extrapolation based on rough-surface scattering (perturbation theory). Since this mechanism is not able to explain the measurements at large wind speeds, we question whether the extrapolation provides reliable results in (say) sea state 4. This is especially relevant in winter conditions; high wind speeds are then commonly observed and cooling at the sea-surface results in an upward-refracting sound speed profile.

In order to improve the reliability of sonar performance prediction, a physical model that captures all essential processes governing the sea-surface back-scattering is therefore needed. Several authors proposed a surface scattering model that contains, in addition to the sea-surface contribution, a volume scattering term. At high frequencies, resonant scattering from individual bubbles is known to contribute significantly to the back-scattering strength [4],[7],[8]. At lower frequencies (below 5 kHz), scattering from bubble clouds is proposed as a mechanism [9]-[11].

In this paper, we hypothesize that scattering from individual bubbles may contribute significantly to the total surface back-scattering strength, at or around 1 kHz. We investigate to what extent this mechanism, combined with rough-surface scattering, may suffice to explain the total of CST measurements.

2. THE EFFECT OF BUBBLES

We study both the reflection and scattering of sound by the rough sea surface and the absorption and scattering of sound by entrained gas bubbles. The gas bubbles have two effects on the back-scattering:

- A modification of the sea-surface scattering contribution: As a result of the bubbles in the near-surface layer, the bulk modulus and therefore the sound speed decrease, leading to an increasing ray grazing angle θ at the sea-surface (see Figure 1). According to perturbation theory, the surface contribution is proportional to θ^4 [3].
- Introduction of a volume scattering contribution due to scattering of sound at the bubbles. We consider both the direct scattering contribution and the interaction with the sea-surface. As shown in Figure 2, this results in four scattering contributions for each bubble [12].

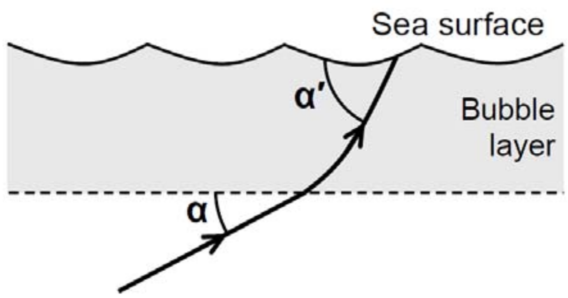

Fig. 1. The effect of a near-surface bubble layer on the grazing angle

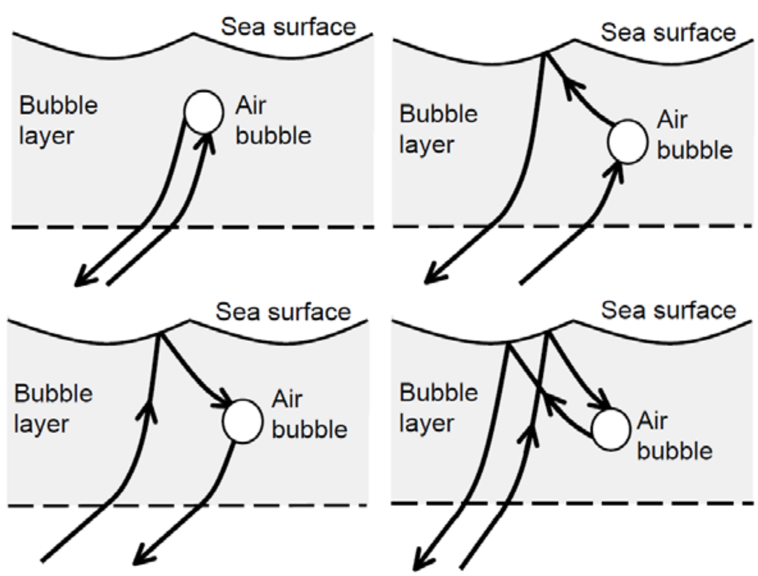

Fig. 2. The four different volume scattering contributions for a single bubble.

In our physical model, the near-surface bubble layer is parameterized using the empirical "Hall-Novarini" (HN) bubble population model. This model describes the distribution of air bubbles as a function of wind speed, depth, and radius [1],[13],[14] quantified using the bubble population spectral density (PSD). It gives the number of bubbles per unit volume of ocean that have radii within a unit increment in radius. The PSD varies with depth z, bubble radius a, and wind speed (at a height of 10 m) v_{10}. The HN model assumes that no bubbles exist with a radius a less than $a_{\min} = 10\,\mu\text{m}$, or greater than $a_{\max} = 1000\,\mu\text{m}$. Figure 3 shows the PSD as a function of radius for wind speed v_{10} = 14 m/s at three different depths. It shows that the bubble PSD rapidly decreases with depth. Furthermore, it illustrates the discontinuous nature of the HN model through a bubble radius of 1 mm.

Figure 4 shows the theoretical back-scattering predictions based on the HN model. It shows that for wind speeds larger than 10 m/s, the theoretical model underestimates the backscatter, whereas there is a good agreement between the model predictions and the observations for lower wind speeds.

The target strength of an individual bubble (Figure 5) suggests that only a small number of large bubbles contribute significantly to the backscattering strength. The scattering strength of individual bubbles increases quadratically with radius and at 940 Hz bubbles may be excited close to their resonance frequency. This motivated us to investigate whether large bubbles are able to explain the underestimation of the sea-surface back-scattering by the theoretical model. For this purpose, we extended the HN model that truncates the bubble PSD at a radius of 1 mm to include larger bubbles, i.e. bubbles with a radius larger than 1 mm (see Figure 3). The spectral slope of the bubble PSD for these large bubbles is determined using a least-squares fit to the observations.

The extrapolated HN model at v_{10} = 14 m/s is shown in Figure 3, and the corresponding fit to the observations in Figure 6. Based on the improvement in the match between the theoretical predictions and the observations, we conclude that a small number of large bubbles significantly contribute to the sea-surface back-scattering strength.

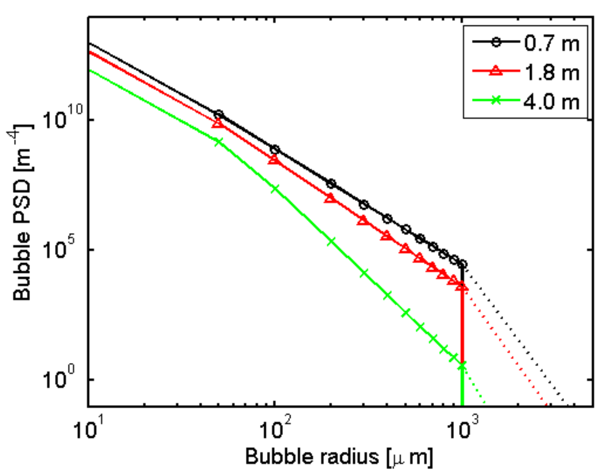

Fig. 3. Hall-Novarini bubble population spectral densities for a wind speed (v_{10}) of 14 m/s (solid). The dashed curves show the extrapolation of the Hall-Novarini model for large bubbles. The curves correspond to 0.7, 1.8 and 4.0 m depth, respectively.

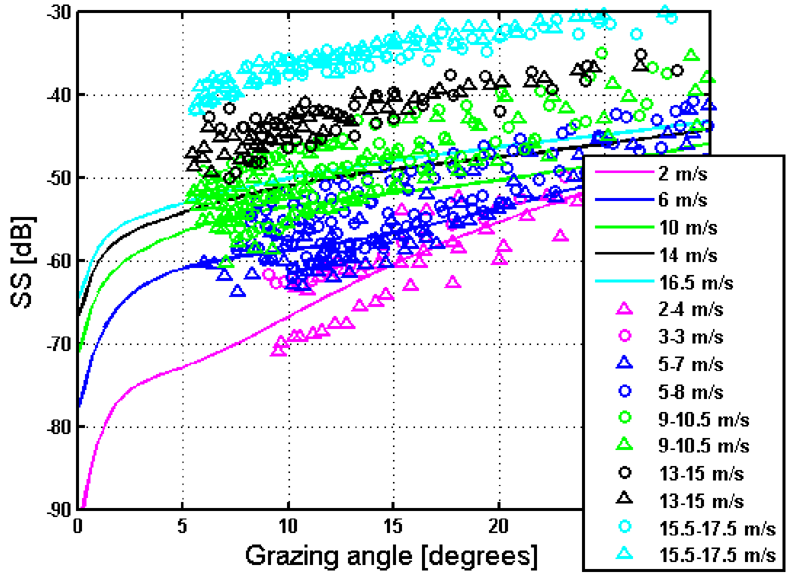

Fig. 4. Theoretical (curves) total backscattering predictions at 940 Hz based on the HN model compared to surface back-scattering measurements (symbols) obtained during the Critical Sea Test Experiments [4]. The legend indicates the wind speed values (v_{10}).

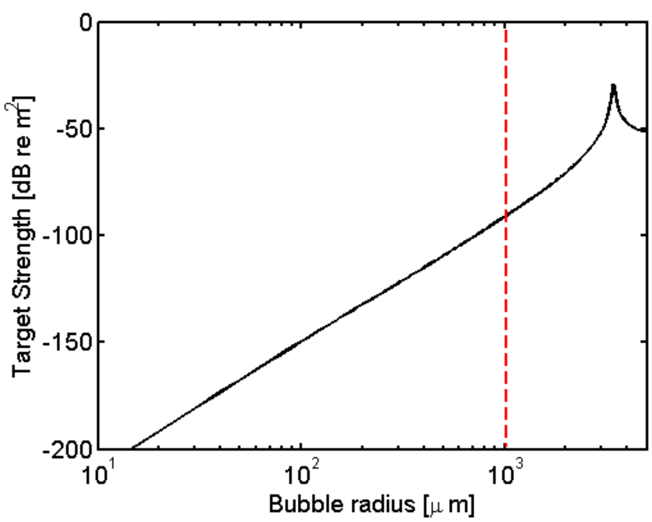

Fig. 5. Bubble target strength as a function of radius at 940 Hz. The red line indicates the separation between the bubbles that are included in the HN model and the extended HN model.

Comparing the theoretical predictions to the Ogden-Erskine empirical curves reveals that there are significant differences at low grazing angles for all wind speeds. As a consequence, including the effect of gas-entrained bubbles in the near-surface layer is expected to be of importance to sonar performance prediction.

A final observation is that the discontinuity in the spectral slope of the bubble PSD (Figure 3) is in agreement with observations obtained with high-speed cameras in breaking waves. This phenomenon is referred to as the Hinze scale [15][16].

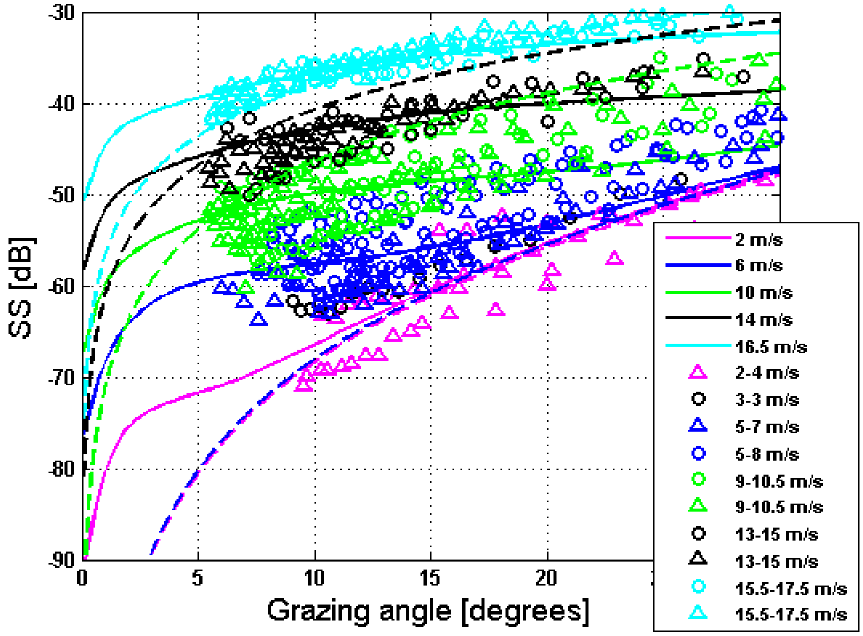

Fig. 6. Theoretical (solid curves) total backscattering predictions at 940 Hz based on the extended HN (including bubbles larger than 1 mm) model compared to surface back-scattering measurements (symbols) obtained during the Critical Sea Test Experiments [4]. The legend indicates the wind speed values (v_{10}). The dashed lines are the empirical Ogden-Erskine predictions for the same conditions as the solid lines.

3. SUMMARY AND CONCLUSIONS

A theoretical model is formulated that is able to explain sea-surface back-scattering measurements at 940 Hz obtained during the Critical Sea Test Experiments.

- This model reveals that a small number of large bubbles, i.e. bubbles with a radius larger than 1 mm, significantly contribute to the sea-surface back-scattering strength at 940 Hz.
- For all wind speeds, we observe large differences with the empirical Ogden-Erskine curves at low grazing angles (> 10 dB), while both the theoretical predictions and the empirical Ogden-Erskine curves have a good fit to the observations that are available for larger grazing angles. These differences at small grazing angles are important for sonar performance prediction.
- The results obtained with the theoretical model are sensitive to the prescribed bubble PSD. As a result, the theoretical model can provide indirect observations for the bubble PSD by matching the predictions to observations. The shape of the bubble PSD obtained in our theoretical model is in agreement with high-speed camera observations, i.e. the Hinze scale.

4. ACKNOWLEDGEMENTS

This work was sponsored by the Defence Research and Development Department of the Netherlands Ministry of Defence. The authors thank Peter Dahl for bringing the Hinze scale phenomenon to their attention (Refs. [16][17]).

REFERENCES

[1] **Keiffer, R.S., Novarini, J.C., and Norton, G.V.**, The impact of the background bubble layer on reverberation-derived scattering strengths in the low to moderate frequency range, J. Acoust. Am., vol. 97, pp. 227-234, 1995.

[2] **Keiffer, R.S., Novarini, J.C., and Zingarelli, R. A.**, Finite-difference time-domain modeling of low to moderate frequency sea-surface reverberation in the presence of a near-surface bubble layer, J. Acoust. Am., vol. 110, pp. 782-785, 2001.

[3] **Ogden, P.M. and Erskine, F. M.**, Surface scattering measurements using broadband explosive charges in the Critical Sea Test experiments, J. Acoust. Soc. Am., vol 95, pp. 746-761, 1994.

[4] **Ogden, P.M. and Erskine, F. M.**, Surface and volume scattering measurements using broadband explosive charges in the Critical Sea Test 7 experiment, J. Acoust. Soc. Am., vol. 96, pp 2908-2920, 1994.

[5] **McDaniel, S.T.**, Sea surface reverberation, a review, J. Acoust. Soc. Am., 94, 1905-1922, 1993.

[6] **Weston, D.E. and Ching, P. A.**, “Wind effects in shallow-water transmission,” J. Acoust. Soc. Am., 86, 1530-1545, 1989.

[7] **Chapman, R.P. and Harris, J.H.**, Surface backscattering strengths measured with explosive charges, J. Acoust. Soc. Am. 34, 1592-1957, 1962.

[8] **APL-UW author team**, “APL-UW High-Frequency Ocean Environmental Acoustics Models Handbook”, Tech. Rep. APL-UW 9407, Applied Physics Laboratory, University of Washington, 1994.

[9] **Dahl, P.**, The contribution of bubbles to high-frequency sea surface backscatter: A 24-h time series of field measurements, J. Acoust. Soc. Am., 113, 769-780, 2003.

[10] **Gilbert, K.E.**, A stochastic model for scattering from the near-surface oceanic bubble layer, J. Acoust. Soc. Am., vol. 94, pp 3325-3334, 1993.

[11] **Trevorrow, M.V.**, Measurements of near-surface bubble plumes in the open ocean with implications for high-frequency sonar performance, J. Acoust. Soc. Am. 114, 2672-2684, 2003.

[12] **Gauss, R.C., Gragg, R.F., Wurmser, D., Fialkowski, J.M., Nero, R.W.**, Broadband models for predicting bistatic bottom, surface, and volume scattering strengths, Tech. Rep. NRL/RF/7100-02-10,042, Naval Research Laboratory, Washington DC, 2002.

[13] **Dahl, P. H., and Kapodistrias, G.**, Scattering from a single bubble near roughened air-water interface: Laboratory measurements and modeling, J. Acoust. Soc. Am., 113, 94-101, 2003.

[14] **Ainslie, M. A.**, Effect of wind-generated bubbles on fixed range acoustic attenuation in shallow water at 1-4 kHz, J. Acoust. Soc. Am., vol 118, pp 3513-3523, 2005.

[15] **Hall, M. V.**, A comprehensive model of wind-generated bubbles in the ocean and predictions of the effects on sound propagation at frequencies up to 40 kHz, J. Acoust. Soc. Am., vol. 86, pp 1103-1117, 1989.

[16] **Deane, G.B., and Stokes, M.D**., Scale dependence of bubble creation mechanisms in breaking waves, Nature, 418, 839-844, 2002.

[17] **Dahl, P. H., J.W. Choi, N.J. Williams, H.C. Graber**, Field measurements and modeling of attenuation from near-surface bubbles for frequencies 1-20 kHz, J. Acoust. Soc. Am, 123, EL 163-EL 169, 2008.