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EFFECT OF WIND ON LONG RANGE PROPAGATION IN SHALLOW WATER

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Long range acoustic propagation in isothermal conditions is considered, involving multiple reflections from the sea surface. If the sea is calm there is almost perfect reflection and hence low loss. The effect of wind is to increase propagation loss due to the interaction with near-surface bubble clouds and rough surface scattering. Both mechanisms are modelled using the FFP program OASES. The model predictions are compared with published measurements for a frequency of 2 kHz and wind speeds up to 10 m/s. It is shown that the effect of each mechanism separately is insufficient to explain the measured reflection losses, but the combined predicted effect of both is consistent with observation.

1. INTRODUCTION

Long-range propagation in shallow water often involves multiple interactions with the sea surface, especially in winter conditions with an isothermal sound speed profile. Thus the reflective properties of the sea surface are of interest for prediction of propagation loss in shallow water. Measured values of surface reflection loss are higher than the theoretical prediction due to rough surface scattering alone [1]. Near-surface bubbles, induced by breaking waves, are thought to be responsible for the difference [2]. Possible physical effects of the bubbles include refraction, absorption and scattering of the sound close to the sea surface.

The present purpose is to evaluate the relative role of the various acoustic effects. In particular, can bubbles explain the difference between theory and experiment and, if so, through which mechanism? Acoustic predictions are made using rough surface perturbation theory, combined with a sound speed and attenuation profile computed for a representative average bubble population model.

2. INTERACTION OF SOUND WITH THE SEA SURFACE

The low impedance of air compared with that of sea water means that the sea surface can often be treated as a perfect reflector (with phase change π). That is, the reflection loss in dB is zero. In reality, although the loss is small, it is not exactly zero, and for small grazing angle θ increases linearly with θ, with a constant of proportionality α of 4.8×10^{-3} dB/rad.

The real sea surface is never perfectly smooth. A moderate wind can create waves whose height is of order 1 m, and these must be taken into account for modelling sound propagation for acoustic frequencies of order 1 kHz or higher. In fact no energy is lost at a rough surface, only scattered. So if one defines the reflection coefficient $|R|^2$ as the ratio of reflected to incident energy for a single interaction, the reflection loss (defined as $-20\log_{10}|R|$), neglecting the transmitted paths, is zero. But the scattered energy contributes little to long range propagation, and therefore it can be useful to define instead a 'coherent' reflection coefficient $|R|$ as the ratio of the mean reflected pressure amplitude to the incident amplitude. The average is usually over an ensemble of different realisations of a randomly rough surface, but it can also be thought of as an average in time over a randomly varying rough surface. Kuo [3] shows that if the reflection coefficient is defined in this way, the parameter α (in dB/rad) is $Df^{3/2}v^4$, where f is the frequency, v is the wind speed and D is a constant equal to $2.6\times10^{-8}\,\mathrm{Hz}^{-3/2}\mathrm{s}^4\mathrm{m}^{-4}$.

Good measurements for known conditions are rare, and perhaps the best documented are the Perranporth data of Weston & Ching [1], abbreviated hereafter as WC89. Losses reported by WC89 are of the form $\beta_{WC89} = Af^{3/2}v^4$ (dB per bounce), where A is a 'constant' that takes a different value for each of two different extended measurement periods: $A = 1.8\times10^{-9}\ \mathrm{Hz}^{-3/2}\ \mathrm{s}^4\ \mathrm{m}^{-4}$ for the period Sep-Oct 1968; and $A = 3.5\times10^{-9}\ \mathrm{Hz}^{-3/2}\ \mathrm{s}^4\ \mathrm{m}^{-4}$, for May-Jun 1969. Similar measurements are reported by Wille et al [4].

The above comments are summarised in Table 1, presenting typical numerical values for the predicted and measured reflection loss. It is apparent that rough surface theory on its own is insufficient to explain the measurements, although its predictions are of the correct order and it turns out also to give the correct power law dependence on both frequency and wind speed [1]. For the example given, there is a discrepancy in magnitude of 0.9-2.4 dB per bounce. More generally, the measured losses are on average about 3 times the rough-surface-scattering theoretical ones [1]. Can the discrepancy be attributed to bubbles?

description	**loss per bounce β (dB)**	
	theory	**experiment**
Plane boundary theory (vacuum)	0.0	-
Plane boundary theory (air)	$1.5\text{x}10^{-4}$	-
Rough boundary theory (v = 10 m/s, f = 2 kHz)	0.7	-
Measurement (v = 10 m/s, f = 2 kHz, spring)	-	1.6
Measurement (v = 10 m/s, f = 2 kHz, summer)	-	3.1

Table 1: Typical values of theoretical predictions and Perranporth measurements of surface reflection loss β for a grazing angle of 0.0303 rad (1.74°).

3. OVERVIEW OF THE PERRANPORTH MEASUREMENTS

The measurements of WC89 were made in the Bristol Channel (UK), near Perranporth, during two periods in 1968 (September-October) and 1969 (May-June). Propagation loss data for frequencies 0.87-4.0 kHz were collected for a fixed range of 23 km and water depth 39 m. Both source and receiver were mounted on the seabed, described by WC89 as “a sand and shell bottom”. The conditions were approximately isothermal, with predominantly westerly winds, up to 26 kt (13.4 m/s).

4. METHOD

For each combination of frequency and wind speed considered, the RMS roughness, correlation length and bubble distribution are calculated using standard methods. The bubble distribution used is that of Keiffer *et al* [5], extrapolated to include larger bubbles radius up to a maximum $a_{\max}$ of 7 mm. The resulting sound speed and attenuation profiles, calculated using the algorithm of Hall [6], are shown in Fig. 1.

It is assumed that conditions are isothermal, and that all energy arriving at the 23-km receiver does so via the resulting surface duct. This is justified by the observation that, even in calm conditions, only one third of the energy arrives via bottom-paths [7]. This proportion is expected to decrease with increasing wind speed.

Theoretical effects of roughness and bubbles, both separately and together, are modelled using the fast-field program OASES [8] to calculate the mean (coherent) field. Miles *et al* [9] show that the coherent field calculated in this way at 400 Hz is almost identical to an ensemble average over multiple deterministic realisations of a randomly rough surface of RMS wave height 0.534 m. This corresponds to a wind speed, for the Pierson-Moscowitz spectrum, of 10 m/s. Further (unpublished) comparisons at 1 kHz show similar results.

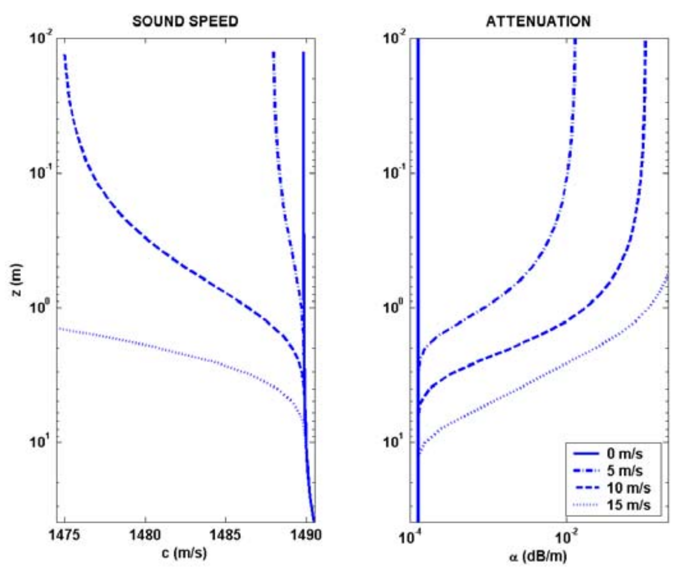

Fig. 1: Sound speed and attenuation profiles using the Hall-Keiffer population model [5] extrapolated to a_{max} = 7 mm, for a frequency of 2 kHz and wind speed 0-15 m/s.

5. RESULTS

Propagation loss (PL) was computed, using the method described above, for frequencies 1-4 kHz and wind speeds up to 10 m/s. Results are presented for 2 kHz only, as these are representative of the overall spread, and also enable a comparison with the predictions of Norton & Novarini [2], hereafter abbreviated as NN01.

Sample PL results are presented in Fig. 2 for a wind speed of 10 m/s. All four combinations of bubbles and roughness on or off are included in the figure, as indicated. It is clear from this graph that, as expected, losses are highest with both effects switched on and lowest with both off. Plots for bubbles only and roughness only show intermediate losses, and this too is expected.

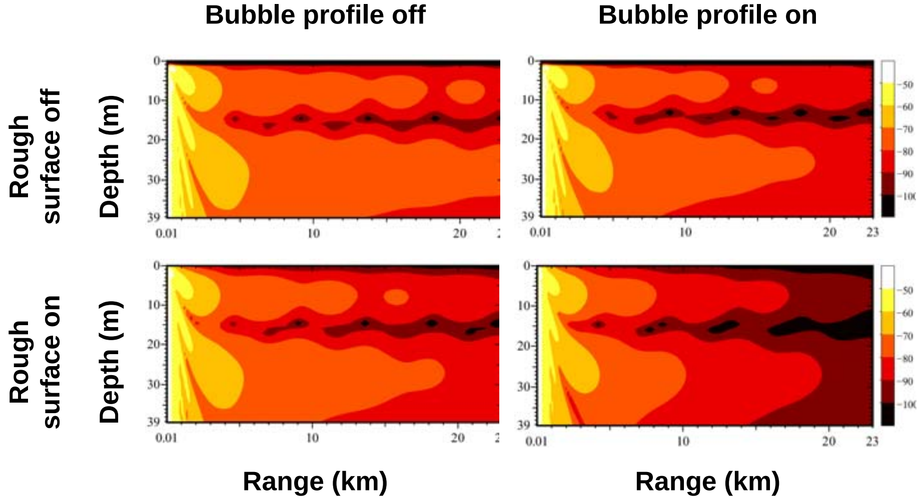

Fig. 2: PL vs range (0-23 km) and depth (0-39 m) showing the effect of bubbles and a rough surface for v=10 m/s and f = 2kHz. The source depth is 37 m. PL contours run from 50 dB re 1 m^2 (brightest) to 100 dB re 1 m^2 (darkest), in 10 dB steps.

The solid curve in Fig. 3 (upper plot) shows the total wind-induced attenuation at 23 km predicted for 2 kHz. Also shown in the same graph (dashed lines) are the Perranporth data for the same frequency. Compared with these measurements, it is clear that the predictions are of the correct magnitude, but increase too quickly with increasing wind speed.

There are two more points in the upper graph, both for v = 10 m/s ($v^4 = 10^4$ m^4/s^4), and almost superimposed on one another. These, a large square and triangle, are taken respectively from the top-right (bubbles only) and bottom-left (roughness only) graphs of Fig. 2. These points are much lower than the measurements, demonstrating that each mechanism on its own is not enough, consistent with earlier findings [1 ,2]. The combined effect is greater than the sum of the parts, and close to the spring 1969 measurement. A possible explanation for the enhancement is that the low sound speed near surface refracts sound upwards and increases the surface grazing angle. (Theoretical expectation is for loss to increase with increasing angle). This hypothesis can be tested by selectively switching on and off the refraction and absorption effects separately. The lower graph of Fig. 3 shows the result of doing this for the same wind speed of 10 m/s (single triangle and square), keeping roughness on for both. The three curves from the upper graph are reproduced in the lower graph, without symbols, as a reference. Switching off the absorption makes practically no difference (square), whereas switching off refraction reduces the predicted loss by more than a factor of 2 (triangle). This confirms that the role of absorption is negligible and that refraction acts as a catalyst to increase the scattering loss. Keiffer *et al* [5] report a similar behaviour of enhanced sea surface *back*-scattering due to bubble-induced refraction. The behaviour of the solid line in Fig. 3 can be compared with the theoretical predictions of NN01, and the lower graph includes four points from their FIG 1 (circles with error bars). The NN01 data are in reasonable agreement with the 1969 measurements, and overestimate the 1968 data by a factor of 2 or so.

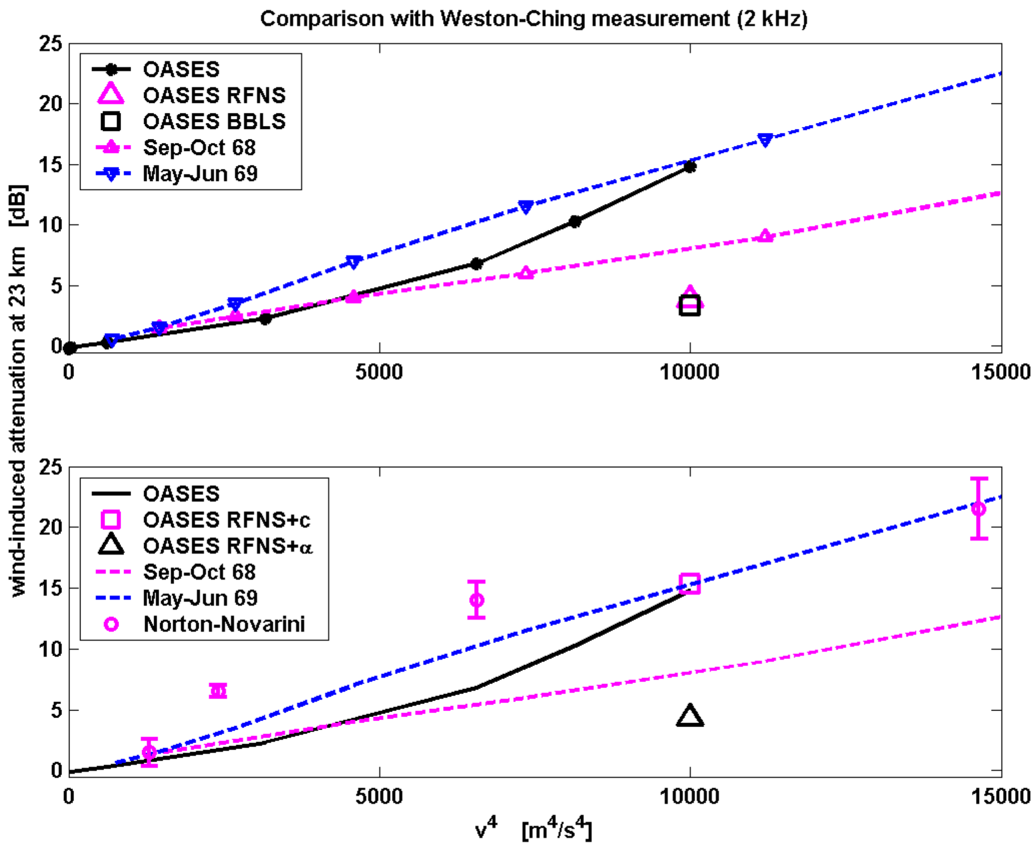

Fig. 3: Wind-induced attenuation vs wind speed at 2 kHz.

6. CONCLUSIONS AND DISCUSSION

- Neither bubbles nor surface roughness on their own are enough to explain the magnitude of wind-related attenuation measurements of WC89 (referred to as the 'Perranporth' data);
- the dominant loss mechanism is rough surface scattering, but refraction in the bubbly medium plays an essential catalytic role, enhancing the attenuation through a near-surface lens action;
- absorption from resonant bubbles makes a negligible contribution to the total attenuation;
- the magnitude of the Perranporth measurements can be explained without the need to invoke bubble plumes.

The second and fourth conclusions are the most important differences between the present findings and those of NN01. However on closer inspection there is no real discrepancy. NN01 model one extra loss mechanism (scattering due to patchiness of the bubble cloud) and as a result predict higher total losses, without ruling out the possibility that rough surface scattering losses, enhanced by refraction, might suffice to explain the measurements. A potentially significant difference between the present methodology and that of NN01 is that here the propagation is assumed to take place in a surface duct, whereas NN01 assume an isovelocity wave guide with propagation via bottom-interacting paths. This assumption affects the angular distribution of energy and thus the attenuation rate in dB/km.

A remaining puzzle is the cause of the seasonal dependence in the measured data. If it is assumed that the surface roughness and bubbles are jointly responsible for *all* of the losses, and that the wave height spectrum is independent of season, then two possible explanations of the seasonal dependent losses are: seasonal variations in the wave direction; and seasonal variations in properties of the bubble population (such as void fraction for a given wind speed). For example, when the air is colder than the water, convective mixing occurs, carrying the bubbles deeper into the water, perhaps reducing the surface void fraction. This would increase the surface sound speed and hence decrease the scattering loss. This hypothesis would explain the higher surface loss observed in spring than in autumn.

7. ACKNOWLEDGEMENTS

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