Bubbles?, and other sources of sound on the ocean surface radiating in the ultragravity band (Farrell/Munk working paper)

W. E. Farrell October 23, 2012

Abstract

The source of deep sea sound in the ultragravity (ug) band is an enigma. This is a review of models of sources that have been proposed as generators of deep sea sound in the ugs, 5-30 Hz. A number of models are more than strong enough. Fewer have the flat spectrum that is observed.

1 Statement of Problem

We are convinced that Longuet-Higgins radiation from surface gravity waves explains deep sea acoustic signals in the gravities band. However, this mechanism fails to explain acoustic spectra in the ultragravities (Fig. 1), using accepted models of the wave field there (Elfouhaily, Viers-1). Thus, I survey other source theories in this paper.

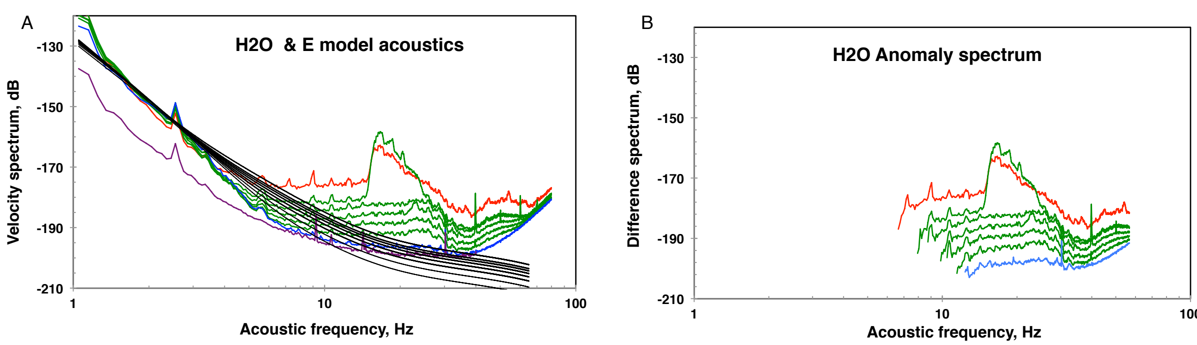

Figure 1: (Left) In the gravities ($f \lesssim 5$ Hz), wave spectra and bottom spectra are saturated for moderate and strong winds, and H2O vertical velocity spectra (colored) match velocity spectra calculated from the Elfouhaily ($\approx$ Phillips) model (black). In the ultragravities ($f \gtrsim 5$ Hz) wave spectra and bottom spectra are not saturated. For wind speeds between 6 and 12 m/s, observed spectra are much higher than model spectra. The right panel, anomaly spectrum, shows the difference between the E-model spectra and the observed spectra.

A model for the source of the acoustic field in the ugs must match not only the levels observed but the wind speed dependance (Fig 2). We are continuing to refine our methodology for estimating $F_P(U)$, and the current benchmark is plotted in the right panel of Fig. 2. The red line has the equation $\mathrm{dB} = -101 + 3.2U$, and is seen to be a reasonably approximation

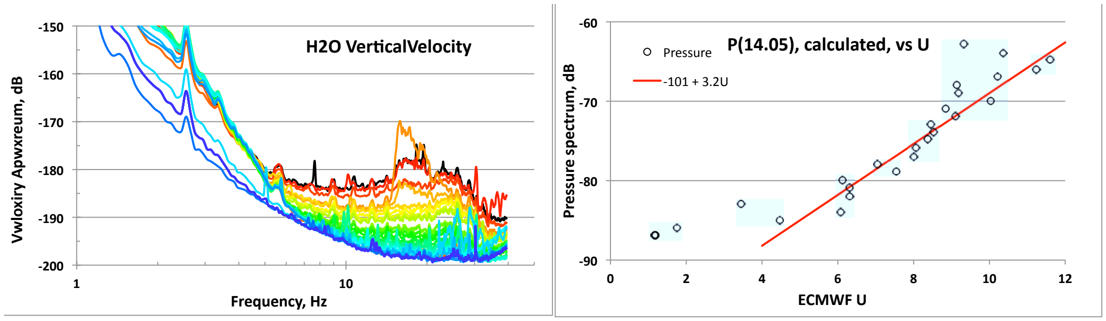

Figure 2: (Left) Thirty spectra of vertical velocity selected from data set 2001A and 2001 B (see Appendix A). (Right) Scatter plot of estimated pressure at 14.05 Hz against ECMWF U. Estimated pressures are calculated from observed horizontal velocity using an impedance-like transformation. Where the hydrophone SNR is above 1, the estimated pressure is the same as measured pressure.

for $5 \lessapprox U \lessapprox 12$. I consider it vital to get good acoustic data when the wind overhead is < 6.5 m/s, which is the value at the 50% point on the probability distribution function.

The importance of good acoustic data under low wind conditions is not a new idea. Crum made the point this way (Crum, 1995, p. 251)

> "examination of the Knudsen-Wenz curves indicates that ambient noise in excess of background is produced at wind speeds considerably below the threshold for whitecap production. ... Thus, there must be some noise source that is different from normal whitecapping. ... A likely source of this noise at low wind speeds is the production of bubbles by non-whitecap-producing breaking waves."

The term *microbreaking* for this phenomenon was already current.

This is contrary to the wisdom of just a few years before, when Prosperetti, citing work of Kerman and others wrote (Prosperetti, 1988a, p. 1042)

> "It is well known that at wind speeds between 7 and 10 m/s, which are typical of the onset of wave breaking, noise levels undergo a marked increase especially at frequencies of a few hundred Hz and above."

2 Background

The subject of the origin of ocean acoustics was exhaustively covered in the published proceedings of three NATO conferences held in Lerici (1987, Kerman, 1988), Cambridge (1990, Kerman, 1993), and Lake Arrowhead (1993, Buckingham and Potter, 1995). The results of each were more-or-less inconclusive, at least in the region of our interest. Amongst more than 2000 pages, in total, a tiny fraction (< 2% ?) are relevant. There is also Leighton's book, the *Acoustic Bubble* (Leighton, 1997). The 5 % on bubbles in the ocean, in which 110 references are cited, is mostly about the phenomenology of how and where bubbles occur and their properties, but has nothing of interest in their acoustic radiation.

Nearly 20 years have passed, and the issue is as open now as then. In the report of the first conference, the panel on Wave and Turbulence Noise, under the chairmanship of Kibblewhite, provided a convenient summary categorizing the various theories that have been proposed as sound sources (Kerman, 1988, p. 625):

1. Wave-wave interactions "believed to be dominant at frequencies less than 5 Hz and may be important to somewhat higher frequencies." See Section 3.

2. Atmospheric turbulence "may also be important in the range between 5 and 20 Hz, but neither [turbulence in atmosphere or ocean] appear to be viable mechanisms above 20 Hz because of their quadrupole nature." See Section 4.

3. Wave/atmospheric turbulence interactions "with its dipole nature and linear velocity dependence, remains a possible mechanism up to ... 100 Hz." See Section 5

4. Oceanic turbulence "may also be important in the range between 5 and 20 Hz, but neither [turbulence in atmosphere or ocean] appear to be viable mechanisms above 20 Hz because of their quadrupole nature." See Section 6.

5. Gross motions of the sea surface "has been identified as significant at very low frequencies, $<$ 0.1 Hz, but has not been invoked at higher frequencies." See Section 7.

6. Density discontinuities at the surface, Section 8

7. Bubble convection by turbulence, Section 9

8. Bubble cloud oscillations driven by hydrodynamic forces, Section 9

9. Soliton-like disturbances, Section 10

And they comment further, "The new mechanisms [6-9] ... have yet to be properly assessed as possible noise-generation mechanisms at low frequencies."

It would be remiss not to mention Carey and Evans (2011), a disappointing book, overall. As they note (Carey and Evans, 2011, p. 129) "the numerical representation of these sources [microbubbles, microbubble clouds, spray, splash, rain, and turbulence] as well as the description of the sonic radiation from the air-sea boundary interaction zone are still work in progress." The algebraic expressions for the various multipole source representations (Carey and Evans, 2011, p. 39-42) reflects that conclusion: the connection between the source models and observations, here and elsewhere, is weak.

For an executive summary of this working paper look at Figs. 1, 3, 6, 7, and 9. These show model spectra at various U for a number of Kibblewhite's source categories. Most model spectra are depicted sandwiched between the (obsolete) Wenz bounds, his synthesis of the limits of ocean measurements. The slopes of the model spectra are suspect, in detail, because various wave elevation assumptions have been folded in. But, more importantly, the levels are reasonable, indeed higher than needed, and the slopes are flatish. Other figures have plots of the published models on top of the H2O spectra.

3 Wave-wave interactions

We call this the Longuet-Higgins mechanism, because he was the first to calculate the effect of non-linear wave interactions. What was belief at Lerici in 1987 is pretty much proven now, for frequencies less than 5 Hz (Farrell and Munk, 2010, 2012; Duennebier et al., 2012; Kedar et al., 2008; Ardhuin et al., 2011, 2013). Data from only a handful of candidate stations have been properly examined. Having more would be nice. Recent efforts to pull in the score of PLUME stations have been plagued by uncertainties in hydrophone calibrations and self-noise.

3.1 Two approaches

Two approaches have been followed in deriving the acoustic radiation from wave-wave interactions. Most have followed the perturbation expansion pioneered by Longuet-Higgins, and most recently revisited by Guralnik et al. (2013). Alternatively, the derivation can start from Lighthill's "acoustic analogy" equations, the method followed by Goncharov (1970); Brekhovskikh and Goncharov (1972); Lloyd (1981); Guo (1987a); Cato (1991a,b). The first three authors appear to have done it right. Guo asserts he obtained the result of Hughes (Guo, 1987a, Eqn. 3.6) but I am unable to verify the result. Cato missed the right answer by 8π.

3.2 Pros

The theory is more than a half century old, but quantitative proof was long delayed by a paucity of good data. We've looked at Wake and H2O data, Fred D. has published on the ALOHA hydrophone, 100 km N of Ohau. The other references given above are concerned with frequencies less than 1 Hz.

Our ambitious proposal that the L-H mechanism explained bottom sound in the ultragravity band (Farrell and Munk, 2008), has pretty much been retracted (see above and Farrell and Munk, 2012). The ocean wave model required to fit the bottom acoustics conflicts with measurements of sea surface slope. The inferred slopes are too steep, and the inferred wind dependence is exponential, not linear.

3.3 Cons

Several authors, in assessing their own theories, have dismissed the L-H model as being too weak an acoustic radiator, even in the gravities. This was back in the days when the upper band of the Wenz model (See Appendix B) was thought to be relevant. It is now known that even the lower Wenz bound is too high above 3 Hz (see Fig 3), and the upper is 80 dB above ambient, in the deep sea, at 20 Hz (Fig. 10). Two prominent nay sayers are Kuryanov (Isakovich and Kuryanov, 1970; Kuryanov, 1993), and Guo (Guo, 1987a): their ideas are considered in Section 4, Atmospheric Turbulence.

4 Atmospheric turbulence

Turbulence in the atmosphere excites an acoustic wave in the water by beating down on the water surface. Half a century ago, Hasselmann concluded the "generation of microseisms by atmospheric turbulence is generally negligible" (Hasselmann, 1963, p. 198). Some subsequent work has reached the opposite opinion. I've not mastered any of the theories in their entirety, but give a synopsis in Section 4.1. In the following (Section 4.2), I look at Hasselman's equations, and, by a different analysis, show his conclusion applies to pressure in the ocean as well as seismic noise at a distance.

Klaus's result was either forgotten or ignored by Isakovich and Kuryanov and their followers. In view of the diversity of results, perhaps atmospheric turbulence is again in play. For this reason the theories abstracted below (Isakovich and Kuryanov, and Wilson, Section 4.3, Guo, Section 4.4, and others) may be relevant: it is possibly that their grossly exaggerated results are a consequence of an aggressive selection of model parameters in order to obtain unrealistically high spectral levels. Perhaps, by relaxing these parameters, closer agreement with better data can be achieved and be consistent with modern ideas on atmospheric turbulence.

An essential job has been untangling the wave spectrum for those theories involving the elevation spectrum of the ugs. The ideas about this spectrum current 30 or more years ago are of marginal interest today. The separation is crucial so we can distinguish between the physics of the acoustics field and the physics of ocean gravity waves.

4.1 Overview

Acoustic radiation into the water by turbulence in the atmosphere has by far the most complicated history with a plethora of unreconcilable theories. I start by collecting, with minimal comment, published results. Subsequent sections give a longer discussion.

This is a work in progress. The notation is being standardized. There may be errors in distinguishing between the speed of sound in air and water, both of which are constant, and the speed of water waves, which is not. I may also be muddled in places over using the dispersion relation linking frequency and wave number. There seem to be two views of the Mach number - either U/c or $\delta U/c$, where U is wind speed, δU is the turbulent variation about the mean, and c is the speed of sound in sea water.

4.1.1 Hasselman 1963

The following result is Hasselmann's (3.25), after integration with respect to wave number (see Section 4.2)

$$F_P(\omega) = \left[\pi\gamma\left(\frac{\rho_0}{\alpha_0 c}\right)^2\right] u_\star^8 \omega^{-1} \tag{H 3.25'}$$

In this expression ρ_0 and α_0 are the density and sound speed of air, c speed of sound in water, and the constant $\gamma \approx 1$ but may be two orders of magnitude up or down. With $\gamma = 1$ the constant evaluates to

$$[\,]_H = 1 \times 10^{-11} \tag{4.1}$$

and since this is expressed in friction velocity, which is typically much less than 1, the acoustic power is tiny.

Note the large wind exponent, absence of surface tension and f^{-1} frequency dependence.

4.1.2 Isakovach & Kuryanov 1970

Letting F_A be the spectrum of pressure acting on the water's surface, they first show that the radiated acoustic spectrum, F_P, is

$$F_P(\omega) = \frac{F_A(\omega)}{4\sqrt{2}} \left(\frac{U}{c}\right)^2 \tag{IK 12}$$

In this expression, U is the wind speed, c the speed of sound in water, and their ratio the Mach number. Also, the turbulence correlation lengths in the longitudinal direction (parallel to the wind) are assumed to be $x_0 = x_1 = U/\omega$ for the exponential and oscillatory parts, and similarly for the transverse turbulent correlation distance y_0. The measurement point is also taken to be far below the surface.

To get the spectrum of pressure acting on the water surface they assume it is related the the elevation spectrum of ug waves. After a complicated derivation they arrive at

$$\begin{aligned} F_A(\omega) &= \frac{4\rho^2\nu}{\pi g} U\omega^{11/3} \left[\frac{3g}{4}\left(\frac{\rho}{T}\right)^{1/3} \omega^{-4/3}\right] F_\zeta(\omega) \\ &= \frac{3\rho^2\nu}{\pi} U \left(\frac{\rho}{T}\right)^{1/3} \omega^{8/3} F_\zeta \end{aligned} \tag{IK 26, 27}$$

Putting this into the expression for the far field pressure gives

$$F_P(\omega) = \left[\frac{3\nu}{4\sqrt{2}\pi}\left(\frac{\rho}{T}\right)^{1/3}\left(\frac{\rho}{c}\right)^2\right] U^3\omega^{8/3}F_\zeta(\omega) \tag{IK 28}$$

Taking the molecular viscosity of water, the effective kinematic viscosity is $\nu = 10^{-6}$, although if a turbulent viscosity is more appropriate the value could be orders of magnitude larger. Take $T = 7.4 \times 10^{-2}$ for surface tension (SI units everywhere), then

$$[\,]_{IK} = 3.5 \times 10^{-6} \tag{4.2}$$

For the wave spectrum, the authors assume $F_\zeta \propto \omega^{-4.5}$, so that $F_P \propto \omega^{-1.8}$ (Isakovich and Kuryanov, 1970, p. 55).

4.1.3 Brekhovskikh & Goncharov 1972

In a very interesting paper in Russian (partially translated in Appendix C) Brekhovskikh and Goncharov, starting with the Lighthill equation, obtained results for a number of source models. One was turbulence in the air, beating on the ocean surface. Their result, in the ugs (see Appendix C.1.2) is

$$F_P(\omega) = \left[\frac{3\nu}{2\pi}\left(\frac{\rho}{T}\right)^{1/3}\left(\frac{\rho}{c}\right)^2\right] U^3\omega^{8/3}F_\zeta(\omega),\ f > 13.5 \tag{BG.WEF 15}$$

In this result,

$$[\,]_{BG} = 5 \times 10^{-6} \tag{4.3}$$

which is $2\sqrt{2}$ larger than (IK 28) above.

4.1.4 Wilson 1979, 1981

Wilson (1979) took three exceptions to the air-turbulence model of I & K: the assumption wave dissipation is due to molecular viscosity, the choice of the wave elevation model and the evaluation of an integral. As do they, he assumes, first, the far-field acoustic spectrum is related to the turbulent pressure, F_A beating on the ocean surface, and adopts I & K Eqn. (12).

$$F_P(\omega) = 0.175 F_A \left(\frac{U}{c}\right)^2 \tag{W 4}$$

($.175 = 1/(4\sqrt{2})$. Secondly, he also takes their assumption that the spectrum of turbulent pressure is related to the wave elevation spectrum:

$$F_\zeta(\omega) = \frac{F_A \omega}{U\rho^2} \int [\mathrm{W8}] \tag{W 7}$$

Using his equations (W8, W9), I get

$$F_A = 250 U \rho^2 \omega^2 F_\zeta A_{10}^{-1} \tag{4.4}$$

Where $A_{10} \approx .01$ is defined at equation (10) in his appendix. Using that value and combining these three equations gives

$$F_P(\omega) = \left[4.4 \times 10^{-5} \left(\frac{\rho}{c}\right)^2\right] U^3 \omega^2 F_\zeta(\omega) \tag{4.5}$$

In this equation

$$[\,]_W = 2 \times 10^{-5} \tag{4.6}$$

is ten times larger than the Russian's result. I believe this is primarily due to his assumption that the dissipation of wave energy, about ten times larger in his model, is by breaking, not viscosity. Equation (4.5) should probably be written in a form that shows the dissipation coefficient explicitly.

For F_ζ Wilson chose Toba's fit (W 1) to the data of Mitsuyasu and Honda (Mitsuyasu, 1977), taking which and using the dispersion relation for capillary waves, one gets $F_P \propto U^4 \omega^{-2/3}$.

4.1.5 Kuryanov 1993

Kuryanov (1993), responding to criticisms of Wilson, Cato, and Adair, revisited the problem and obtained a result somewhat different from the one obtained earlier in his collaboration with Isakovich. This was because of two modifications - the re-analysis of a certain integral expression and choice of a different wave elevation spectrum. In this work he adopted a wave spectrum, *in the ugs* with a slope “slower than ω^{-3},” basing this on evidence adduced by Mitsuyasu and Honda (Mitsuyasu, 1977), which had earlier been adopted by Wilson. In keeping with my approach here, this spectrum is factored out.

In his rebuttal, Kuryanov reiterated, as emphasized by others, the great difficulty in that “the characteristics of the turbulence near the surface are unknown and can essentially differ from ones for the free turbulence." For this reason, he throws doubts on the relevance of Goncharov (1970).

Most interesting is his new definition of the Mach number, for "Here $M = \delta U/c$ is the Mach number for fluctuations in the flow speed around the mean value of wind speed U." As I recall, we've seen from Bob Weller's buoy data that the fluctuating component of the wind, both transverse and parallel, is of the same order as the mean wind. Is the distinction important?

The new connection between the acoustic spectrum and the spectrum of turbulence beating on the ocean surface is

$$F_P(\omega) = \frac{F_A(\omega)}{2}\left(\frac{\delta U}{c}\right)^2 \tag{K 6}$$

The relation between the spectrum of turbulence and the spectrum of wave elevation, adopting his approximations for several terms, is

$$F_A(\omega) = \frac{12}{\pi}\rho c \nu T\left(\frac{\delta U}{c}\right)^3 \kappa^4 F_\zeta \tag{K 11}$$

yielding

$$F_P = \frac{6\nu T}{\pi}\left(\frac{\rho}{c^2}\right)\delta U^3 \kappa^4 F_\zeta \tag{K 12}$$

Take the dispersion relation for capillaries, $\omega^2 = T\kappa^2/\rho$. Then (K 12) is written

$$F_P = \left[\frac{6\nu}{\pi}\left(\frac{\rho}{T}\right)^{4/3}\left(\frac{\rho}{c^2}\right)\right]\delta U^3 \omega^{8/3} F_\zeta \tag{K.WEF 1}$$

Using the values quoted above for molecular viscosity and surface tension, the bracket evaluates to

$$[\,]_K = 3 \times 10^{-4} \tag{4.7}$$

This is $4/T$ time larger than 4.3.

In the ugs, $\kappa^3 \propto \omega^2$ so $\kappa^4 \propto \omega^{8/3}$. Conveniently, he adopts for the ug wave model the form $F_\zeta \propto \omega^{-8/3}$, so the frequency dependence falls out and

$$F_\zeta \propto \delta U^3 \tag{K 12.1}$$

4.1.6 Conclusions

The variety of functional forms is discouraging. This has not previously been so apparent, because authors melded in their favorite wave models, obscuring the source physics. We have separated them, obtaining what I call the "turbulence" term and the "wave" term. For the Hasselmann model, there is no wave term, so there must be a difference in the physics I've missed.

Ignoring the wind speed dependence of the wave term, the wind speed dependence of the turbulence term ranges from U^0 to U^8, although exponents of 2 and 3 predominate. The frequency dependence of the turbulence term ranges from ω^{-1} to $\omega^{8/3}$.

4.2 Hasselmann 1963

In the discussion of acoustic radiation arising from atmospheric turbulence, Klaus starts with the equations of motion and continuity, and immediately derives Lighthill's famous result (Hasselmann, 1963, 3.1, 3.2, and 3.3). In that sense there is an affinity between his work and that of Brekhovskikh and Goncharov. However, they don't cite Klaus, nor do any of the other papers on the acoustic radiation from atmospheric turbulence.

Skipping to the conclusion of the section, he obtains the following expression for the frequency and wave number spectrum of far-field pressure in the ocean due to turbulence in the air above:

$$F_{PT}(\vec{\kappa}, \omega) = \gamma \left(\frac{\rho_0}{\alpha_0} \right)^2 u_\star^8 \omega^{-3} \tag{H 3.25}$$

in which γ " is a constant that we can expect to be of the order of 1 within, perhaps, 2 orders of magnitude," ρ_0 and α_0 are density and sound speed of air, and $u_\star$ is the friction velocity. Note the extraordinarily large exponent on the friction velocity. Equation (H 3.25) is not at all similar to the result, I think for the same effect, obtained by Brekhovskikh and Goncharov (Appendix C, Eqn. 15). The difference in wind speed dependence is large.

To get the total pressure spectrum, the equation, which has no explicit dependence on wave number, must be integrated over frequency, up to the cutoff, giving the additional factor

$$\int d\vec{\kappa} = 2\pi \int_0^{\omega/c} \kappa d\kappa = \pi \left(\omega/c \right)^2 \tag{4.8}$$

Klaus's derivation of the L-H radiation, also in frequency and wave number space, stops at

$$F_{PLH}(\vec{\kappa}, \omega) = \frac{\rho_1^2 g^2 \omega}{2} F_\zeta^2(\omega/2) I \tag{H 2.15}$$

Upon completing the wave number integration (4.8), I have shown that (H 2.15) gives the usual result for the far field pressure (Farrell and Munk, 2012, A.13). Note that the wave frequency in (H 2.15) is half the acoustic frequency.

Taking the ratio of the two expressions, and noting that the wave number integrals cancel, gives

$$\frac{F_{PT}}{F_{PLH}} = 2\gamma \left(\frac{\rho_0}{\alpha_0 \rho_1 g} \right)^2 \frac{u_\star^8 \omega^{-4}}{F_\zeta^2(\omega/2) I} \tag{4.9}$$

Let the elevation spectrum be a Phillips spectrum, $F_\zeta = \beta g^2 \omega^{-5}$. This gives

$$\frac{F_{PT}}{F_{PLH}} = \frac{2\gamma}{I} \left(\frac{\rho_0}{\alpha_0 \rho_1 \beta g^3} \right)^2 \frac{u_\star^8 \omega^{-4}}{(\omega/2)^{-10}} \tag{4.10}$$

Let $I = (2\pi)^{-1}$. Then

$$\begin{aligned} \frac{F_{PT}}{F_{PLH}} &= \frac{\gamma}{\pi} \left(\frac{\rho_0}{\alpha_0 \rho_1 \beta g^3 2^5} \right)^2 u_\star^8 \omega^6 && (4.11) \\ &= 1 \times 10^{-16} \gamma u_\star^8 \omega^6 && (4.12) \end{aligned}$$

Klaus, making the comparison a different way concluded that the atmospheric turbulence contribution to microseisms, at $\omega = 0.6$, was 10^{-9} times as large as the L-H effect. My result is another million times smaller. The constant is so much smaller than his that my evaluation of the ratio needs to be checked.

4.3 Isakovich and Kuryanov and their successors

Unlike Hasselmann, Isakovich and Kuryanov (1970) concluded, in their abstract, "the direct action of wind on the surface of the ocean can yield a major contribution to the observed underwater noise levels." They followed a unique modeling approach. Using a velocity potential, the linearized boundary condition for the air/water interface included the effects of surface tension, the free surface displacement (η in their notation) and an external force (π) (Isakovich and Kuryanov, 1970, (13)). They relate the acoustic spectrum to the spectrum of air turbulence, and link the spectrum of air turbulence to the spectrum of wave elevation (see section 4.1.2).

The connection between acoustics and atmospheric pressure has a resonance term, such that there is infinite displacement for $g\kappa - T\kappa^2/\rho = \omega^2$. This smacks of the Miles mechanism, although they call it the "resonance mechanism of Phillips" (1957). John's first paper on the subject was published the same year.

The 1970 paper by Isakovich and Kuryanov spawned two decades of controversy (Wilson, 1979, 1981; Cato, 1981; Adair, 1987; Wilson, 1987; Copeland, 1993). At the Cambridge workshop Copeland gave a summary of the issues (Copeland, 1993). At the same meeting Kuryanov (1993) presented a new calculation in which he concluded the turbulence model still gave, in the region of 10 Hz, a spectrum of -50 dB (Kuryanov, 1993), with about the same wind dependence but shallower frequency droop. In this article, (summarized above in Section 4.1.5), he referenced the spectra to Pa^2/Hz, but neglected to correct the mislabeled axis in his earlier work, a mistake curiously missed by his critics as well.

4.3.1 Isakovich and Kuryanov, 1970

The essence of the paper is contained in their Fig. 5, copied in the left panel of Fig. 3. The description of Fig. 5, in the translation, says that the plot shows "the level of underwater noise in decibels relative to the zero level $p_0 = 2 \times 10^{-4}$ bar" (Isakovich and Kuryanov, 1970, p. 56 and Eqn. 32). This has to be a misprint for μbar, because a μbar is the same as a dyne/cm^2, and $p_0 = 2 \times 10^{-4}$ dyne/cm^2 is the normalization used by Wenz (see Appendix B). Thus, as shown in Appendix B, one adds 26 dB to change the abscissa to μPa^2/Hz.

The interesting curves in the left panel of Fig. 3 are the solid lines labeled by Beaufort speeds 1, 3, 5, and 8. These correspond to metric speeds of < 0.3, 3.5-5.5, 8-11, and 11-14. We are only interested in the branches for $f > 10$Hz. Their model introduced an artificial discontinuity there by ignoring the influence of surface tension for lower frequencies. The function they obtained (Isakovich and Kuryanov, 1970, Eqn. 28), using radian frequency, and after simplification by assuming $a = b = d = 1$ and taking the position to be far below the surface, is

$$F_P(\omega) = \left[\frac{3\nu}{4\sqrt{2}\pi}\left(\frac{\rho}{T}\right)^{1/3}\left(\frac{\rho}{c}\right)^2\right] U^3 \omega^{8/3} F_\zeta(\omega) \qquad \text{(IK 28)}$$

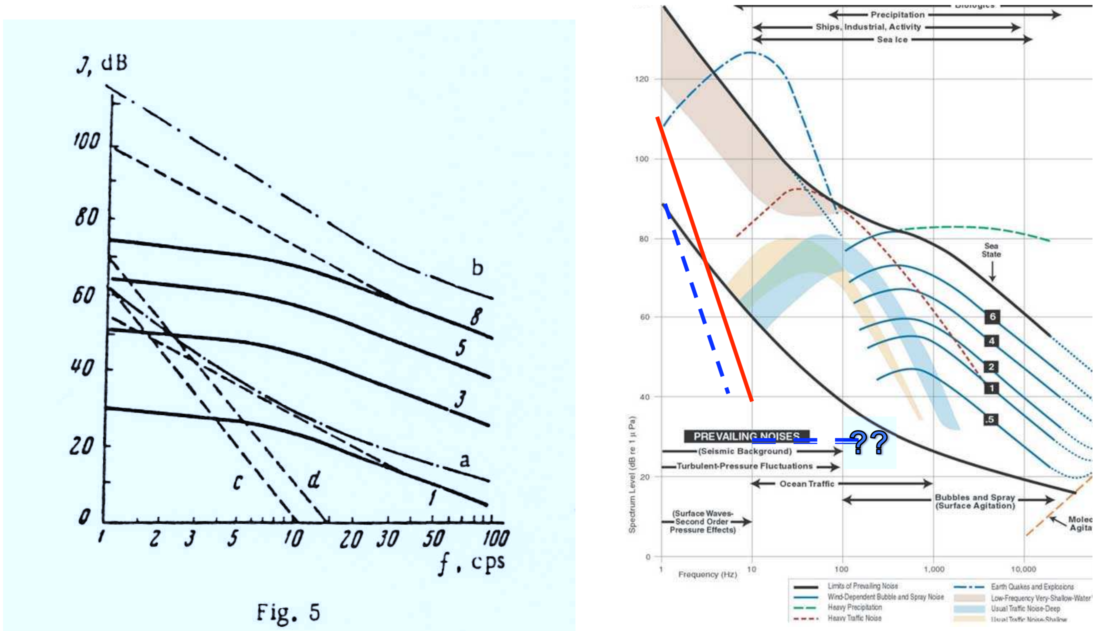

Figure 3: (Left) Isakovich and Kuryanov's Fig. 5. Dash-dot lines "a" and "b" are the boundaries of the Wenz model, shown in Appendix B and, using different units, the right panel. Dash lines "c" and "d" are the acoustic radiation from an *almost* Phillips spectrum, ($F_\zeta \propto \omega^{-4.5}$) for 1 and 10 m/s, and are roughly comparable to the dash blue and red lines in the right panel. Lines "1" through "8" show the pressure spectrum of atmospheric turbulence, with the labels indicating Beaufort wind speed. (Right) The infamous Wenz plot, redrawn so the abscissa has units $\mu\,\mathrm{Pa}^2/\mathrm{Hz}$, with H2O gravities spectra superimposed (saturated, red; bust, dash blue).

The authors, themselves, emphasize the relatively steep dependence on U.

To compare this model with H2O data, I read values from the plot at 20 Hz These values are plotted as circles in the left panel of Fig. 4. The solid line is an exponential model, with dB $\propto 3U$. For reference, H2O data yield a ug spectrum of about -60 dB for $U = 10$, so the I & K model is 20 dB above our best data.

These turbulence results are totally at variance with H2O deep sea spectra in the ultra-gravities (Fig 4, right). The turbulence spectra are much too high, and fall like f^{-4}, while ocean acoustic spectra are flat.

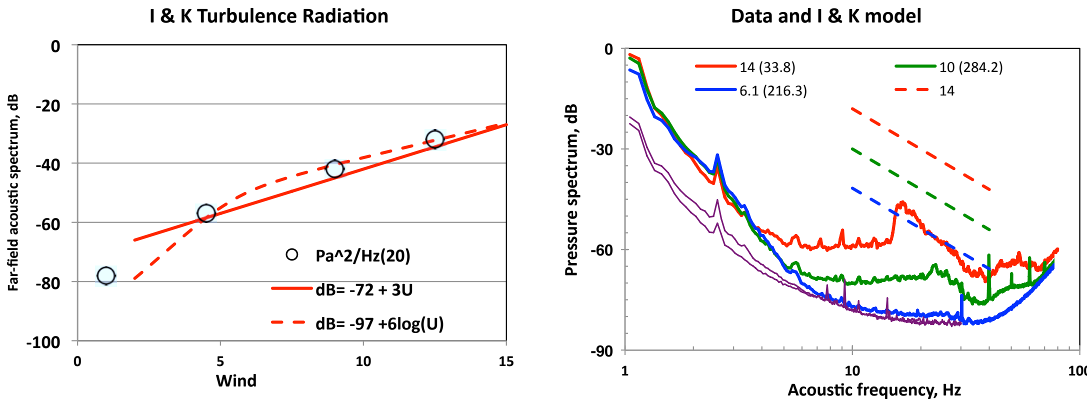

Figure 4: Left: Pressure for the I & K turbulence model at 20 Hz (circles) along with two functional approximations. Right: I & K model in the ugs (dash lines) and H2O vertical velocity converted to pressure using $Z^2 = 117$ dB. The respective wind speeds are close but not identical.

4.3.2 Wilson, 1979

I reworked Wilson's result in Section 4.1.4 above to show the wave elevation model as a separate factor. Here I recapitulate his approach, which had the preferred wave model embedded in the result. The final equation he actually obtained, using the adopted wave model, is (Wilson, 1979, Eq. 11)

$$F_P(\omega) = 5.27 \times 10^{-6} U^3 u_\star \left(\frac{\rho}{c}\right)^2 \frac{1}{\kappa A_{10}} \qquad \text{(W79 11)}$$

As previously explained, A_{10} is a function specified in the Wilson's Appendix which is about 0.01 and depends only weakly on frequency. The friction velocity, as well as the wave number, have been introduced through the adopted wave elevation model. This gives the bottom acoustics, a U^4 dependence on wind speed.

The top panel of Fig. 5 is Fig. 3 from Wilson's paper. The dash lines show the evaluation of equation (W79 11) for wind speeds between 5 and 50 knots. (The solid lines are the L-H radiation, for the indicated wind speeds, using the same wave model and the Hughes formula.) These are source levels, not far field pressures, and for a surface dipole layer the pressure is π greater than the dipole surface density.

Reading values from the top panel at 20 Hz, and adjusting by π, I get the plot shown in the lower left panel of Fig. 5. The values from the top panel and a range of frequencies are plotted in the lower right panel, along with H2O spectra. The green and blue data of the Wilson model are about 12 dB above the corresponding H2O data. Sensor noise obviates comparing the low wind model to data (purple).

4.3.3 Didenkulov's extension to Isakovich and Kuryanov, 1993

Didenkulov and Sutin (1993) also published a paper in the 2nd conference, which described an extension to the I & K theory. They assumed that the surface layer was bubbly, and found that scattering from the bubbles raised the radiated acoustic field in the ug band. They

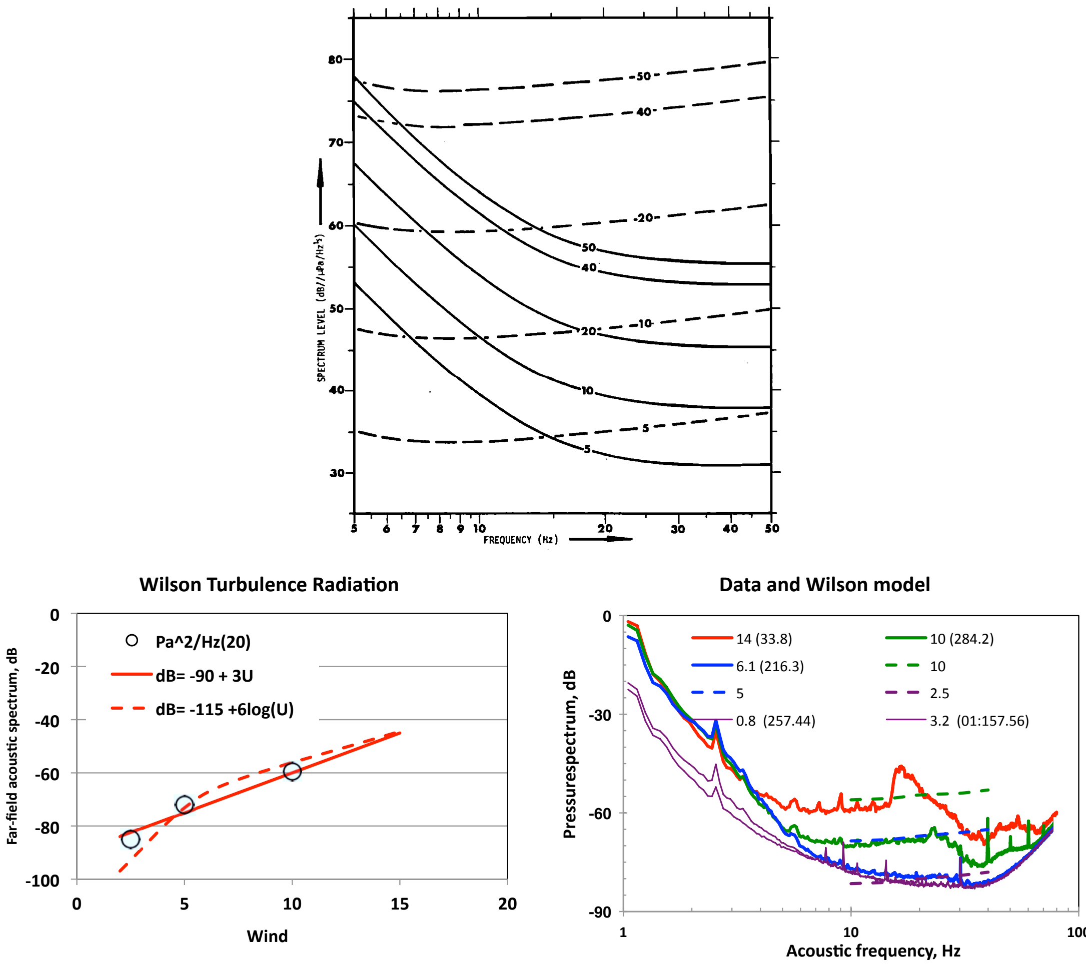

Figure 5: Top: Wilson (1979), Fig. 2. Bottom left: Acoustic power at 20 Hz, read from the dash curves of the top panel, with wind speed expressed in m/s, not knots. Bottom right: Wilson ug spectra plotted on H2O pressure data, estimated by subtracting 117 dB from the velocity spectra.

conclude, with the chosen set of parameters, the effect might double the far field pressure spectrum.

4.4 Ffowcs Williams and Guo

Guo, a student of Ffowcs Williams (hence, scientific grandson to Lighthill) wrote three papers spanning more than 50 pages in a single issue of JFM (Guo, 1987c,a,b). They also made presentations at the Lerici and Cambridge meetings. Guo's later career has been with Boeing, presently at their Huntington Beach facility. I've written but had no response.

4.4.1 Guo, 1987

The primary article, (Guo, 1987a), is an analytic tour de force which is beyond my comprehension. Starting with Lighthill's "acoustic analogy" in the air (2.1) and water (2.2), he purports to solve three problems:

1. the acoustic radiation from the waves by the L-H mechanism (3.6),
2. the wave field excited by the air flow (4.7); and
3. the acoustic field emitted into the water by the air turbulence (5.1);

He asserts his expression (3.6) agrees with Brekhovskikh and Hughes: this I have not confirmed. Despite the coverage of wave excitation by flowing air, Miles (1957) is not referenced.

The results are combined in three expressions for the "relative acoustic radiation efficiency of the turbulence sources and surface waves," (5.10, 5.11, 5.12). He concludes "the Brekhovskikh theory is probably not relevant in the natural ocean." Or, put more forcefully in the abstract "the weakly nonlinear mechanism proposed by Brekhovskikh is never an important source of sound in the real ocean."

4.4.2 Guo's error

This, of course, is not true, so where did Guo go amiss? Ffows-Williams had this to say in the proceedings of the second NATO conference (Ffowcs Williams and Guo, 1993, p. 324):

> That [analysis of interaction of sound with inhomegeneous surroundings] is what Guo (1987) did in providing the most robust description of ocean surface source processes yet available, robust in the sense that it is forgiving to approximation of the source terms and, being completely exact, is a secure basis for examining the source processes at work in the real ocean. Guo considered the sources distributed near the air/water surface of an unbounded ocean and proved that the Longuet-Higgis (1952) / Brekhovskikh (1966) model of second harmonic sound generation by weakly non-linear surface waves could *never* [emphasis added] be the dominant source mechanism for low frequency sound in the real ocean

On the other hand, in the proceedings of that very same meeting, Kibblewhite wrote this (Orcutt et al., 1993, p. 215):

> In their new analysis Kibblewhite and Wu (1990a) [published as Kibblewhite and Wu (1991)] have examined the inconsistency posed by Guo. They first establish the value of Guo's ratio in a real situation where the sea is developed and can be well described by one of the widely recognized forms of the ocean-wave spectrum. Using the Pierson-Moskowitz spectrum (Pierson, 1964), with appropriate parameter values, with Guo's Equation (5.4) to obtain p_t, they show that the ratio of the two pressures around the spectral peak will be
>
> $$\left(\frac{p_t}{p_s}\right)^{(1)} < 10^{-6}\omega U^2$$

This is obviously very small for the frequencies, ω, and wind speeds, U, of present interest and contrasts markedly with the ratio Guo calculated using his model [his Equation (5.11)],

$$\left(\frac{p_t}{p_s}\right)^{(2)} < 10^{10}\omega^{-5}U^{-2}L^{-1}$$

where L is fetch.

Years later (Kibblewhite and Wu, 1996, p. 16) they mentioned that Guo's error

"arises because it is tangential stress, rather than the fluctuating air pressure of turbulent air flow, that is primarily involved."

I have no idea what that means.

5 Wave/atmospheric turbulence interactions

The only result known to me is the formula obtained by Brekhovskikh and Goncharov (1972). The asymptotic form (see Appendix C.1.6) is

$$P_{WA}^2 \propto U^{10/3} f^{-3} \tag{29}$$

6 Oceanic turbulence

Goncharov (Goncharov, 1970) proposed that ocean gravity waves could interact with turbulence in the water to radiate an acoustic signal. There is some interesting physics here, because, unlike surface waves, there is no dispersion relation for turbulence. Thus, for any given wave vector of the ocean waves, there is guaranteed to be some turbulence energy at the same frequency but with oppositely directed wave vector.

I consider this theory in three parts, a summary of the two original works and recent correspondence with Goncharov mediated by V. Zavarotny at NOAA, Boulder.

6.1 Goncharov (1970)

Although this 1970 paper was superseded by his joint effort with Brekhovskikh (Brekhovskikh and Goncharov, 1972), the latter is in Russian, and its derivations are briefer, so Goncharov (1970) still has relevance.

He started with the Lighthill equation (Goncharov, 1970, (1)). Using S for surface waves and T for turbulence, he considers the pressure spectra arising from all three possible interactions, F_{SS}, F_{TT}, and F_{ST}. The results in this paper are only valid in the gravity band, because surface tension is neglected (Goncharov, 1970, (11)). For F_{SS} he obtains the Brekhovskikh formula for the L-H interaction (Goncharov, 1970, (12)), although, being restricted to the gravities, the "Brekhovskikh ratio" is absent.

For the ST interaction, a Pierson-Moskowitz spectrum for the wave field is assumed (Goncharov, 1970, (21)). I can not comment on his assumption for the spectrum of turbulence in the water (Goncharov, 1970, (22)).

He concludes (Goncharov, 1970, (23) and following text)

$$F_{ST} \approx 10^2 f^{-4} \text{ bar}^2/\text{Hz}, \text{or} \tag{6.1}$$
$$\approx 10^{12} f^{-4} \text{ Pa}^2/\text{Hz} \tag{6.2}$$

which implies absurdly large power spectra.

I believe there is the same confusion of units as happened with I & K, and the reference spectrum is in fact that adopted by Wenz, .0002 dynes/cm^2. The function I've called F_{ST} is named P_{ST} in the middle panel of Fig. 6. It has a value, at 1 Hz, of approximately 95 dB (viz. 6.1), and slopes like f^{-4}. The curve is neatly sandwiched between the upper and lower Wenz bounds (thick dash lines). Henceforth, I will assume that the correct representation of (Goncharov, 1970, 23) is the plot indicated.

It is notable that the frequency dependence, f^{-4} is the same as found by I&K (see Fig. 3), although Goncharov's result is only valid in the gravities, since surface.

The evaluation of the overlap integral for the case of a wind-wave field interacting with isotropic turbulence is interesting. Let H_W be the spread function of the wind waves, and $H_T = 1/(2\pi)$ the spread function of the turbulence. Then the overlap integral is

$$I = \int d\theta H_W H_T = \frac{1}{2\pi} \int d\theta H_W = \frac{1}{2\pi} \tag{6.3}$$

This result seems paradoxical: the overlap integral of and spread function and an isotropic function is identical to the overlap integral of two isotropic spread functions. However, it may be than turbulence theorists do not split the velocity field into a radial part and an angular part, an approach that implies $H_T = 1$

6.2 Brekhovskikh and Goncharov (1972)

Brekhovskikh and Goncharov (1972), examined a suite of five turbulence models, anchoring the analysis on the Lighthill equation. The paper is in Russian, but Appendix C has a translation of the most interesting parts, including relevant formulas. Here, just the culminating figure is (see Fig. 6, taken from Appendix C) which has three panels plotting model spectra on the Wenz axes. In all three panels the dash lines separated by 50 dB are the Wenz bounds, and the vertical dB axis uses Wenz units (see Appendix B). The Wenz bounds are way above contemporary deep-ocean acoustic observations (e.g. Figs. 3, 10).

Panel (a), top, shows the far field acoustic spectrum from turbulence in the air, P_A, and turbulence in the water, P_T. These evaluate the expressions given in C.1.1 and C.1.2. The asymptotic forms for these functions are given in Table C.2

Panel (b), middle, shows the spectrum of the L-H radiation, P_{BB} (Eqns. C.1, C.2, although the portion in the ug band has been cut from this panel). For the chosen wave model (taken from a 1969 Russian translation of Phillips' book), the formula evaluates to -12 dB (re. Pa^2/Hz). At 1 Hz, I read 100 dB, and adding 26 (correct for Wenz units), and subtracting 120 (μPa to Pa) gives 6 dB. The curve labeled P_{ST} is the radiation from the non-linear interaction of waves with ocean turbulence (Appendix C.1.4 and Table C.2).

In Panel (c), bottom, P_{BA} shows the acoustic spectrum radiated by the interaction of turbulence in the atmosphere and surface gravity waves. See also C.1.6 and Table C.2

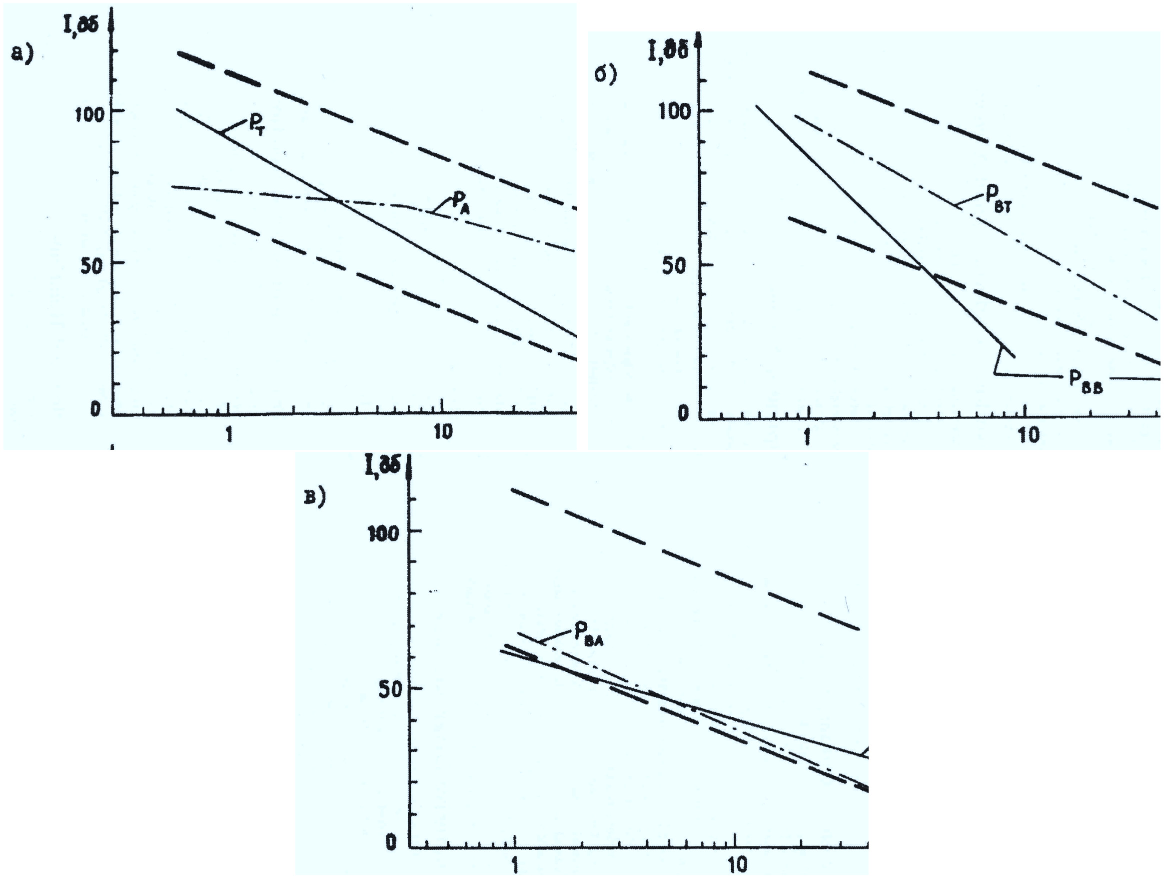

Figure 6: The far-field acoustic pressure for a variety of turbulence models. The vertical axis is exactly the same as that used by Wenz, so add 26 dB to get Pa^2/Hz. The slanting dash lines are the Wenz upper and lower bounds, separated by 50 dB (see right panel of Fig. 3). The other curves show the pressure spectrum for the models considered. All model results are much too large.

6.3 Recent contact

Seeking more recent information about this work, Valery Zavorotny (NOAA, Boulder), on my behalf, contacted Goncharov, in Russia, who wrote back in Russian. Here are excerpts of Valery's translation:

> "In short, it looks like the paper [Goncharov (1970)] is the only paper translated into English on the subject. There is also a paper, where main results of his PhD Thesis are presented [Brekhovskikh and Goncharov (1972)] ... The material of that paper was used by A. V. Furduyev for Part 9, "The noise of the ocean", paragraph 13, " Infrasonic noise caused by dynamic processes in the boundary layer of the ocean - atmosphere," pp. 676-681, of the book: L.M.Brehovskih (ed.), Ocean Acoustics. 1974, Moscow, Science, 695 p. ... There were several short papers with L. M. Brekhovskikh and others in the Proceeding of USSR Symposia (in Russian, not preserved) on similar topics between 1970 and 1972 but after that Goncharov never returned to this problem.

A couple of comments from Goncharov on the issue. According to him the main sources of noise in the ocean at frequencies above 5-10 Hz are technical noise (shipping, drilling rigs and other), as well as processes associated with breaking of high wind waves (noise of falling spray, sound emission by air bubbles, etc.). In a presence of the horizontal inhomogeneity of the medium, this noise can be captured by a sound channel and transmitted without significant losses over long distances.

At frequencies below 5 Hz, along with the noise caused by breaking waves, one may need to consider the noise described in [Brekhovskikh and Goncharov (1972)] ... But all the mechanisms of their generation, associated with turbulent fluctuations, are very difficult to confirm experimentally. This requires measuring the components of the spatio-temporal spectrum of turbulence either of those propagating faster than the speed of sound (linear mechanisms), or the corresponding surface waves (wave-turbulence interaction)."

Goncharov recommended two review articles by Kuryanov:

1. B. F. Kuryanov, "The development of notion of low-frequency noise in the ocean for 50 years," In the book: "Ocean acoustics," Proceedings of the School-Seminar of Acad. L. M. Brekhovskikh. Moscow, GEOS, 1998, pp. 116 -124.

2. B.F. Kuryanov. "Russian Investigations of Ocean Noise," in the book: "History of Russian Underwater Acoustics," Ed. O. A. Godin and D. R. Palmer, World Scientific, 2008, pp. 197-234

The first book has not been translated. The article in the second book , being an historical review and without any figures or equations, is most useful for the references.

7 Gross motions of the sea surface

It is not clear to me what work is categorized here. Whatever the cause, the Kibblewhite summary notes the effect is only "significant at very low frequencies, $f < 0.1$ Hz," well below frequencies that concern us.

8 Density discontinuities at the surface

I believe this is not a category of source physics, but rather an alternative mathematical method for evaluating acoustic radiation from sources on the ocean surface. In the case of the wave-wave interaction source, MLH, and most others, used a perturbative technique. An alternative approach has been to use the formulation for acoustic radiation from density discontinuities developed by Lighthill (1952) to model aerodynamic noise. The end result of both approaches is the same (modulo factors of 2 and π). The results obtained using this approach for LH radiation [Goncharov (1970); Brekhovskikh and Goncharov (1972); Lloyd (1981); Guo (1987a); Cato (1991a,b)] are discussed above (Section 3.1).

The Lighthill equations have also been used for assessment of acoustic radiation by turbulence, both in air and in water. This was pioneered in the excellent overview of Brekhovskikh and Goncharov (1972) (See Appendix C). Ffowcs Williams and Guo (1988) also started there, unaware of B & G's article, which appeared in an obscure Russian language journal, giving original credit to Powell and Curle (Curle, 1955; Powell, 1960). As discussed above (Section 4.4.2), their work has been discredited.

9 Bubbles

Mechanisms of acoustic radiation involving bubbles in the ocean boundary layer were comprehensively reviewed by Crum (1995). This included an overview of ideas at the time both of how bubbles were created, and their acoustical effect. Briefly summarizing the highlights, Ffowcs Williams (Ffowcs Williams, 1969; Crighton and Ffowcs-Williams, 1969), working with the Lighthill equation, and using continuum theory, showed that bubbles in a turbulent flow increased the radiated acoustic power by the factor $(c/c_m)^4$, where c is the speed of sound in pure water, and c_m the speed of sound in the mixture (Crum, 1995, p. 257). Although, at the time, Crum liked this idea (Crum, 1995, p. 269), such turbulence amplification is no longer thought Important, at least in the ugs (see below).

Prosperetti (Prosperetti, 1988a,b) applied his work on the physics of bubbles to noise in the ocean in the "range from a few Hz to 100-200 Hz." He recapitulated the turbulence theory, showed that individual bubbles radiated in the kilohertz range, and I believe, was the first to consider "collective bubble oscillation," although at that time "the actual occurrence of this process in nature remains of course to be proven" (Prosperetti, 1988b, p. 1052) The proof was shortly found in the laboratory (Nicholas et al., 1993; Lowen and Melville, 1994). However, neither of the measurements were made in the far-field, where the dipole moment dominates, and thus could not be applied to the deep ocean. ("we have, in fact, measured the near-field pressure fluctuations ... and that the observed signals may contain contributions from both the propagating and nonpropagating pressure fields" (Lowen and Melville, 1994, p. 1330).)

The energetics are no problem, at least for wind speeds sufficient for breaking. Lowen and Melville (1991) found that about 10^{-8} of the dissipated energy was lost acoustically. But how much of this reached the far field?

In summary, after 40 years of research on bubbles I have not found, in print, the most basic end product useful to us - a spectrum, from 5 to 50 Hz, of the far-field pressure due to sources involving bubbles. Such a figure has been fundamental throughout the development of wave-wave interaction theory and turbulence theories, but has never be achieved by the bubblers. This makes the comparison between bubble theories and H2O data hopeless, at present.

9.1 Naked bubbles

Individual bubbles are tiny, and their normal modes are in the kilohertz range. No one thinks that isolated bubbles contribute to the far field pressure in the ug band.

Deane and Stokes (2010) have explained the Knudsen spectrum "from a few hundred Hz up" as arising from bubble oscillations.

9.2 Bubble convection by turbulence

I believe this mechanism is the interaction between bubbles and a turbulent flow, first elucidated from the Lighthill equations by Ffowcs Williams (Ffowcs Williams, 1969; Crighton and Ffowcs-Williams, 1969). This model was also advocated by Kerman (1984), according to Pumphrey and Ffowcs Williams (1990, p. 273).

Prosperetti wrote me this on the topic.

> " Ffowcs-Williams & Crighton's theory addresses the issue of a turbulent flow containing bubbles. I don't think any more that this is the mechanism. I think that the main process is the creation of the bubble cloud by the breaking wave (be it spilling or plunging). Bubble clouds have their own normal modes the lower ones of which, I think, are excited when the cloud is formed. The higher modes are probably affected by the turbulence inside the cloud but their frequency lies above the range you mention."

Carey spent some time on bubbles (e.g. Carey and Browning, 1988), citing as his authority for the turbulence-bubble interactions Ffowcs Williams (1969). He also gave various JASA talks on the subject. He concluded this was not a viable mechanism (Carey and Evans, 2011, p. 40).

9.3 Bubble cloud oscillations

Bubble cloud oscillations are like the weather, everyone talks about it, but few do anything about it. An early study was by Omta (1987). The most applicable analysis I've found was done by Prosperetti's colleague Oguz (1994). There is a more recent calculation by Tkalich and Chan (2002). Unfortunately, both are focused on frequencies above 100 Hz.

The model adopted by Oguz is an infinite surface layer of incoherent bubbly hemispheres, of various sizes and randomly positioned - see Fig. 7, left panel. The right panel in Fig. 7, one of 6 cases considered, shows data (points) along with three far field spectra (curves). The models shown plunge steeply below about 100 Hz, as do all spectra in his paper.

The model spectra peak around 100 Hz but I've not determined which model parameters determine this or whether those parameters can be reasonably changed to give efficient radiation at lower frequencies. As noted above, the H2O floor, at 20 Hz and 15 m/s winds is about 50 dB, which is the very bottom of the y-axis.

Means and Heitmeyer (2001) developed a model of acoustic radiation from a bubble cloud that was consistent with at-sea measurements. The data were obtained from Flip (Schindall and Heitmeyer, 1996), and a spectrogram is shown in Fig 8.

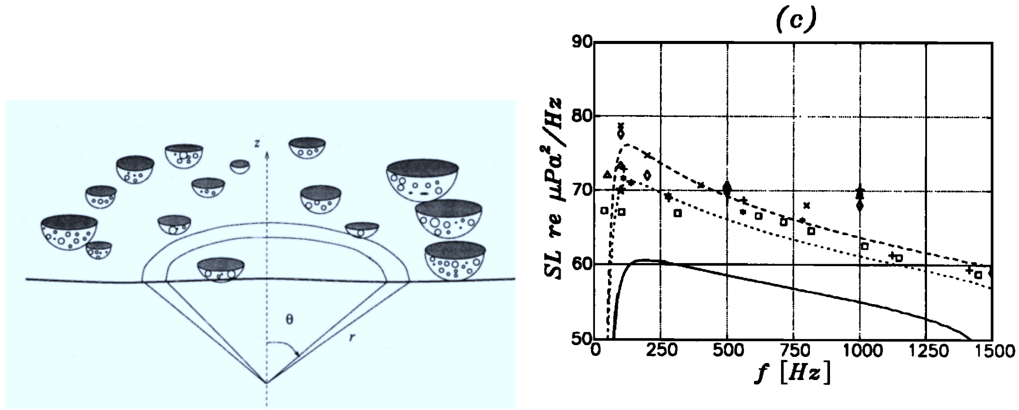

Figure 7: (Left) The model of a random distribution of hemispherical bubble clouds at the surface of the ocean (Oguz, 1994, Fig. 1). (Right) The far-field pressure for one bubble cloud model and 15 m/s wind (Oguz, 1994, Fig 12C). The isolated points are observations. The dash and solid lines are the spectra for three variations of the bubble cloud parameters.

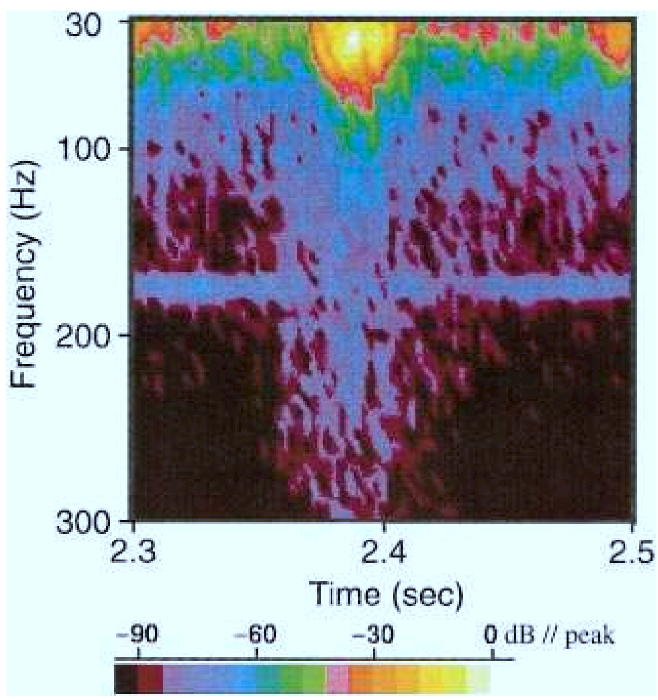

FIG. 3. Time-frequency surface obtained experimentally in at-sea measurements on the end-fire beam of an array deployed from aboard RP FLIP northeast of San Clemente Island. A single low-frequency peak in the spectra appears at ~40 Hz. Similar low-frequency peaks were observed in roughly $\frac{1}{3}$ of 221 analyzed spectra. The spectral line at 180 Hz is pump noise from the research vessel.

Figure 8: Bubble cloud spectrogram, showing a peak near 40 Hz, and duration of .02 sec.

10 Solitons

Mellen and Middleton (Mellen, 1985; Mellen and Middleton, 1988; Mellen, 1991) conducted the only work known to me on solitons, and Mellen and Middleton (1988) proposed that solitons, if they exist, could be an efficient acoustic source in the ugs. Their analysis of the acoustic radiation was actually a side effect of their main interest, which was effect of solitons as acoustic scatters. In particular, they sought to explain why "acoustic backscattering from surface waves is generally much greater than that predicted by gravity-capillary models." I do not know the state-of-the-art, then or now, in acoustic backscattering. But, as noted in the abstract, "Nonlinear acoustic radiation by wave-wave interaction [of colliding solitons] is also a potential mechanism for ambient noise."

They derive a formula for the far field pressure (opaque to me) from their model. The top panel if Fig. 9 is their Fig. 6. The convergence on the left is the merging of the soliton spectra with the L-H spectrum of the Phillips wave model. The soliton spectra dominate in the ugs, and are given for three wind speeds, 5, 7 and 15 Hz.

Mellen and Middleton stress that the model has a steep dependence on U. They take this to be a defect, believing that observation requires a small gradient. We believe this is a feature. To compare their model with H2O data, I first derive a wind rule, shown in the lower left panel. Circles are read from the top panel. The straight line is an exponential model, dB $\propto 3U$, which is a reasonable fit to the wind dependence at H2O and ACO. The dash line is of the form U^6. For simplicity I take the exponential.

The lower right panel compares the soliton model (black) to H2O data (colored). The figure is an adaptation of our prior model (Farrell and Munk, 2012, Fig 8), where the soliton spectrum has been substituted for the analytic ug spectrum.

Looks ok to me.

11 Discussion

It was not expected that this review would resolve the ug enigma. The scope of the field is huge. The best bubble cloud model I found does not go low enough in frequency, and bubble-turbulence interactions have lost favor.

I am attracted to interactions between waves and turbulence, and think Brekhovskikh and Goncharov (1972) a forgotten and neglected gem. It is notable that all their models emit acoustic radiation far stronger than is needed - assuming that H2O and ALOHA data are the proper benchmarks.

11.1 Atmospheric turbulence

A notable weakness in I & K, and their successors, is that the theory embraces, as a matter of course, a concept for how wind on the water makes waves. This seems like a hard problem all in itself.

There is a discrepancy between my massaging of Klaus's equations for the effect of atmospheric turbulence and his. Also, while Klaus dismisses air turbulence, the affect appears credible according to B & G. Needs to be revisited.

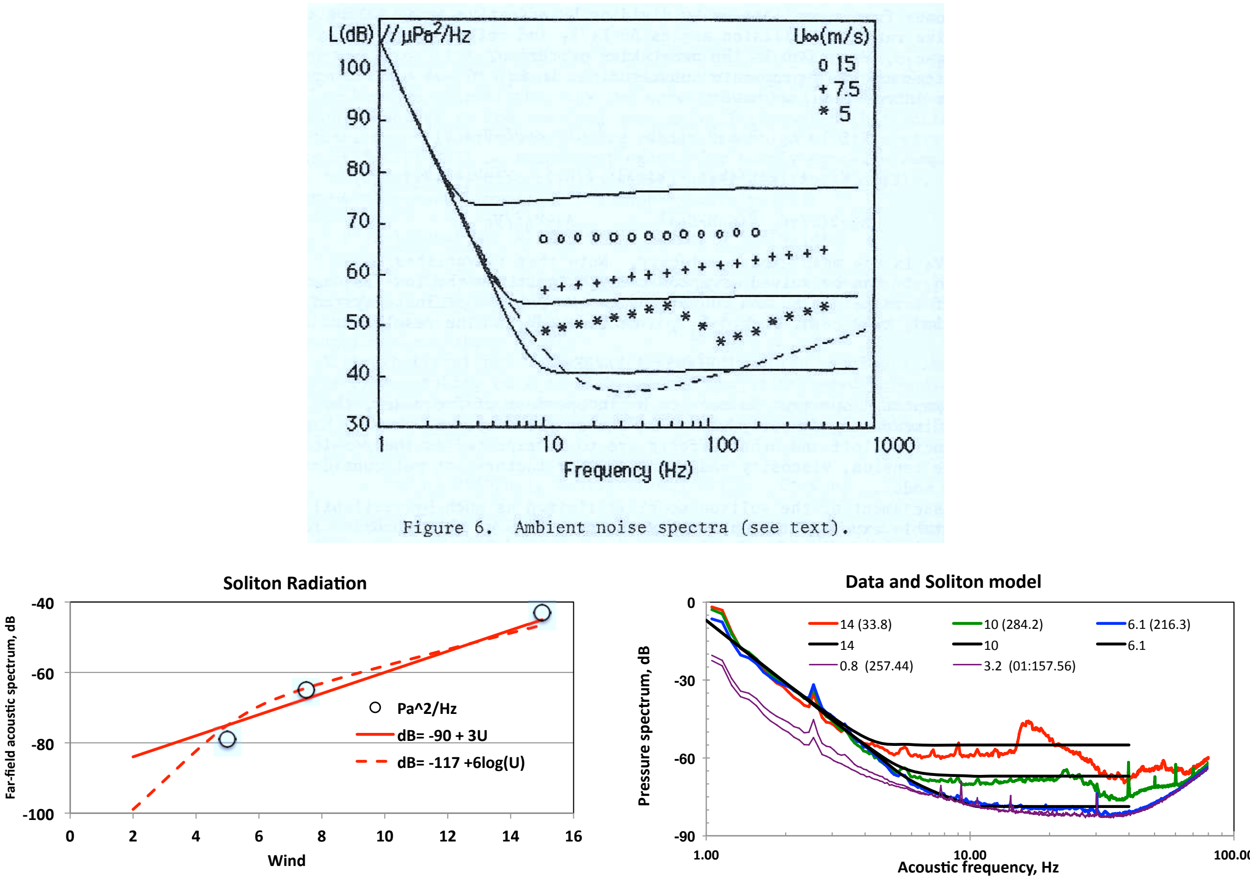

Figure 9: (Top) Spectra of the Mellen model (Mellen and Middleton, 1988, Fig. 6). The dash curve is the L-H radiation from the (saturated) P-M wave model and the Hughes formula. In the ugs, this is dominated by the unsaturated (wind speeds in the legend) almost white spectrum of soliton radiation. The points are measurement data, now pretty irrelevant. (Bottom left) Spectrum values at the three wind speeds plotted against U. (Bottom right) Soliton spectra overlaid on H2O spectra.

11.2 Turbulence in the ocean boundary layer

Source theories involving turbulence are most highly developed by Brekhovskikh and Goncharov, but, unfortunately, the derivations are sparse and the paper is in Russian.

With their assumed parameters, there is no problem getting a strong enough spectrum. But the frequency dependence disagrees with H2O observations. Most of the models have spectra falling like f^{-4} in the ugs. H2O spectra are essentially flat.

I also argue that the observation that the wind gradient of the spectrum is continuous through a speed $U = 6.5\,\mathrm{m\,s^{-1}}$ favors turbulence over bubbles, but maybe there is a discontinuity in the turbulence spectrum there, as well. Ken may have some ideas here.

Appendices

A Low wind spectra

Obtaining good spectra of ambient levels from H2O instruments for windows when the overhead wind is slight is not simple. This is because each of the instrument systems (hydrophone, Geospace geophone and Guralp seismometer) has a distinct frequency response and self-noise floor. Furthemore, the self-noise floor at high frequencies is determined by quantization noise, and this varied throughout the 3-year observation period as the operators changed the gain.

Here I consider just the hydrophone and Geospace geophone. The best hydrophone data were acquired between days 143 and 273 in 2001 and days 172-225 in 2002. During these intervals (130 days and 53 days, respectively) its gain was highest. The noise floor during those times was approximately -80 dB, but the wave-wave signal falls below this floor at about 4 Hz, and wind speed of ca. 1-3 m/s. Thus, the hydrophone itself is not helpful for low wind spectra in the ultragravities. An example of low-wind spectra of hydrophone data is shown below (Fig. 10). These are the 14 spectra with the lowest 5 Hz levels from among the subset 2001B.

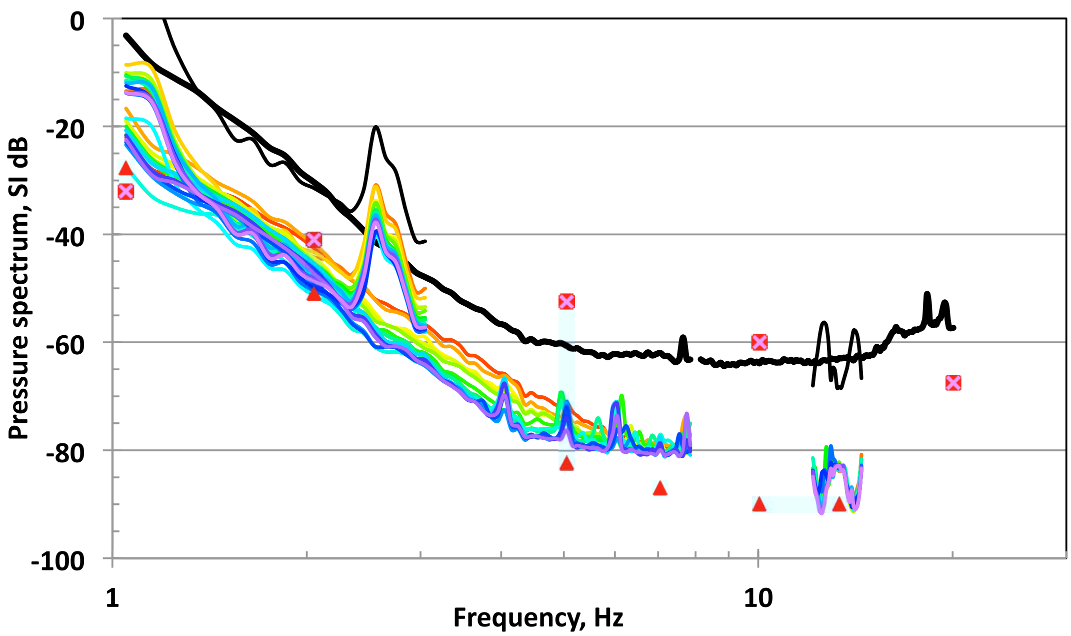

Figure 10: Pressure spectra for data set 2001B (high gain) for the 13 windows with the lowest power at 5 Hz (colored, extending to 8 Hz) are parallel to the saturation spectrum (black). Horizontal velocity data (colored and black with peak at 2.5 Hz) have been equalized to the pressure by an effective impedance $Z^2 = 112$ dB. There is a vertical spread of about 10 dB, which roughly corresponds to a 3 m/s range in wind speed. The actual ECMWF winds ranged from 0.83 to 3.5 m/s, but at these speeds the wind values have a relatively large error. Red squares are the lower bound of the Wenz model. Red triangles are the H2O noise floor model. The actual floor may be less, but requires scanning more data.

The geophone noise floor is controlled by two instrumentations factors, the front end amplifiers and the system gain, and one physics factor, the polarization. When the gain is high, digitizing noise is least, and the amplifiers set the floor from 5 Hz up. Under these conditions, the wave-wave signal is lost in noise *on the vertical component* for wind speeds less than about 7 m/s (Farrell and Munk, 2012, Fig 2). However, the polarization of the vector velocity makes a big difference. Due to the low shear velocity, the horizontal spectrum is, on average, 5 dB greater than the vertical. (In terms of the effective impedance, $Z_V^2 \approx 117$ dB, and $Z_H^2 \approx 112$ dB.) But, in addition, shallow velocity discontinuities support P-SV resonances, giving another 10 dB, or so, enhancement at specific frequencies (ref. Zeldenrust and Stephen). Thus, at the peak of a resonance, the horizontal spectrum is about 10 dB larger than the vertical, so the wind floor is dropped by about $10/3 = 3$ m/s. This is almost achieved in practice, as shown by Fig. 2.

A.1 Data set 2000

This set, along with the first 164 days in 2001, is the best data at the upper end of the ug band and into the capillaries because, here, the floor is set by the digitizer, and quantization noise is least when gain is highest. There are approximately 950 spectra with minimal ship interference

A.2 Data set 2001A

This set comprises the whole year, with excellent geophone data for the first 164 days, and excellent hydrophone data between 143 and 273. There are approximately 880 spectra with minimal ship interference. On the horizontal, the power at 14.05 Hz falls between $-194 < F_H(14.05) < 166$ dB. This implies a wind speed range of about 10 m/s. The ECMWF range is $0.83 < U < 12.5$ m/s

A.3 Data set 2001B

This set comprises days 143 to 273 only. Out of 1040 3-hour windows, 365 have minimal ship interference. The spectra in this set are distinguished because the hydrophone was operated at highest gain, giving it the lowest noise floor during these days

B Wenz scaling

The generic spectra devised by Wenz (1962) (see Fig. 11) were referenced to the unusual standard $P_0 = .0002\,\mathrm{dyne/cm^2}$. The appropriate adjustments to convert to other units are simple, but errors have been made.

The Wenz unit (see Fig. 11) is

$$\mathrm{dB_w} = 10\log\left(\frac{F_P}{P_0^2}\right) = 10\log(F_P) + 74$$

where F_P is measured in $(\text{dyne/cm}^2)^2/\text{Hz}$. For straight $(\text{dyne/cm}^2)^2/\text{Hz}$, the adjustment is

$$\text{dB}_\text{d} = \text{dB}_\text{w} - 74$$

Furthermore, $1\,\text{dyne/cm}^2 = 10^{-6}\text{bar} = 0.1\text{Pa} = 10^5\mu\text{Pa}$. This gives three more conversion factors

$$\begin{aligned}
\text{dB}_\text{b} &= \text{dB}_\text{d} - 120 = \text{dB}_\text{w} - 174 \\
\text{dB}_\text{Pa} &= \text{dB}_\text{d} - \ 20 = \text{dB}_\text{w} - \ 94 \\
\text{dB}_{\mu\text{Pa}} &= \text{dB}_\text{d} - 100 = \text{dB}_\text{w} + \ 26
\end{aligned}$$

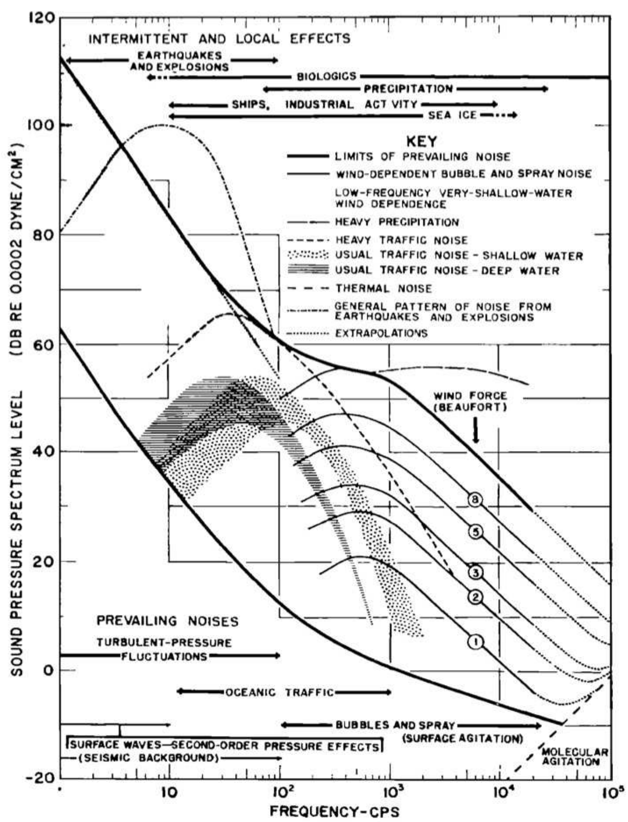

Figure 11: Wenz's composite spectra. The the heavy black curves are the important ones. These define the upper and lower limits of the acoustic spectrum, and intersect the left axis at approximately 112 dB and 62 dB, respectively.

C Brekhovskikh and Goncharov, 1972

Brekhovskikh and Goncharov (1972) published a brief but broad paper on ocean acoustics in an obscure journal which has not not been translated. It is a good summary of Russian results on how ocean surface processes (excluding bubbles) excite low frequency ocean acoustics.

Tthe Lighthill equation was their starting point. The derivations are sketchy. I give below the relevant formulas and a translation of the paper's summary. The full article probably merits translation.

C.1 Equations cited in the summary

The derivations are extremely sketchy. The following equations are shown because the paper's summary makes reference to them. The original equation numbering is retained. Brackets enclose my explanatory comments, everything else is them.

C.1.1 Acoustic spectrum due to turbulence in the water

Let ϵ be the mean specific dissipation of turbulent energy around wavenumber κ_{pm}, where κ_{pm} is the wave number of the peak in the gravity wave spectrum and let ω_κ correspond to the peak in the capillary wave spectrum [I am puzzled at the notion of a peak in the capillary wave spectrum].

$$P_T^2 = 2^{-7/2}\pi^{-5/2}(\rho g)^2\epsilon^{2/3}\kappa_2^{-2/3}\omega_k f^{-4},\ f > 10 \tag{BG 12}$$

In so much as

$$\epsilon \propto U^3,\ \kappa^2 \propto U^{-2}, \tag{BG 13}$$

where U is wind speed, so

$$P_T^2(f) \propto U^{10/3} f^{-4} \tag{BG 14}$$

C.1.2 Acoustic spectrum due to turbulence in the air

$$P_A^2 = \frac{2^5\pi^3\rho_1^2\nu}{gc^2}U^3 f^4\left[\frac{3g}{4}\left(\frac{\rho}{T}\right)^{1/3}(2\pi f)^{-4/3}\right]F_\zeta(f),\ f > 13.5 \tag{BG 15}$$

Φ [I've substituted F_ζ] is the frequency spectrum of the waves, ν the effective coefficient of viscosity, $\gamma = \sigma/\rho$, and σ [I've substituted T] is the coefficient of surface tension. [I believe ρ_1 is the density of air and the bracket encloses their function F for $f > 13.5$]

[Rolling in the bracketed expression and using radian frequency (the 2πs on each side cancel), I get

$$F_P(\omega) = P_A^2 = \frac{3\nu}{2\pi}\left(\frac{\rho_1}{c}\right)^2\left(\frac{\rho}{T}\right)^{1/3}U^3\omega^{8/3}F_\zeta(\omega),\ f > 13.5 \tag{BG.WEF 15}$$

Note that the bracket in (BG 15) is the same as I & K (27), but rest of (BG 15) differs from I& K (26)]

C.1.3 Wave-Wave interaction, eqn. 16

$$P_{WW}^2 = 1.5\times 10^{-7}\left(\frac{\rho g^3}{c}\right)^2 f^{-7},\quad 1 < f < 27 \tag{C.1}$$

$$= 4.6\times 10^{-3}\left(\frac{\rho\gamma}{c}\right)^2 f,\qquad 27 < f \tag{C.2}$$

C.1.4 Wave-turbulence interaction

$$P_{WT}^2 = 3 \times 10^{-5} \frac{\rho^2 g^{7/2}}{c^2} \epsilon^{2/3} \kappa_{pm}^{-7/6} f^{-4}, \ f > 1 \tag{BG 17}$$

[The subscript on κ_{pm}, here and elsewhere, is blurred in the photocopy, but we can tell from the context the reference is to the peak in the Pierson-Moskowitz spectrum (equation 26), defined by $\omega_{pm}^2 = g\kappa_{pm} = (g/U)^2$]

From here, using expression (13) we have

$$P_{WT}^2 \propto U^{13/3} f^{-4} \tag{BG 18}$$

C.1.5 Turbulence-turbulence interaction

$$P_{TT}^2 = \frac{8}{3} \pi^{-1/2} \frac{\rho^2}{c^2} \epsilon^{4/3} \kappa_0^{-10/3} \omega_0^{7/2} f^{-5/2} \tag{BG 21}$$

Taking into account expression (13) and the weak dependence of κ_0 and ω_0 on wind speed, we get

$$P_{TT}^2 \propto U^4 f^{-5/2} \tag{BG 22}$$

C.1.6 Wave-Atmosphere interaction

$$P_{WA}^2 = 2^{-1/2} \pi^{-3/2} 10^{-3} \frac{\bar{c} g^2}{c^2} \kappa_{pm}^{-2/3} \epsilon^{2/3} f^{-3} \tag{BG 28}$$

From which, considering expression (13), we get

$$P_{WA}^2 \propto U^{10/3} f^{-3} \tag{BG 29}$$

C.2 Analysis of Results

A comparison of our results with experimental data for low-frequency underwater sound in the ocean was complicated by the absence of simultaneous measurements of the wave height and turbulence in space and time. Moreover, calculation of the acoustic spectrum was made assuming the existence of a correlation between the velocity fluctuations in the waves and the turbulence at acoustic frequencies and for distances of the order of an acoustic wavelength (linear mechanism) and the order of the surface waves wavelength (nonlinear mechanism). Proving such a hypothesis experimentally is not yet possible. However it is still useful to evaluate the orders of magnitude of the intensity of the sound radiating by means of the processes shown above that permit us to determine approximately what frequency range the action of such a mechanism can contribute to low frequency ocean noise. Calculations were based on equations (12-28) with a constant wind speed of 15 m/sec. The parameters introduced in to the formulas shown were evaluated in the following way:

The value of κ_{pm} was calculated on the basis of the data introduced by Pierson and Moskowitz (1964) - $f_2 \approx 0.1$ Hz with $U = 15$ m/s; $f_k = \omega_k l/(2\pi) \approx 20$ Hz; the size of k_0 corresponded to a scale 100 meters, in the vicinity of which we could expect a transference of energy into turbulence from surface waves (cf. 1965 paper by Ozmidov (12)); the value of ω_0 was calculated based on the hypothesis of frozen turbulence and turned out equal to 0.01

Hz; the value of ϵ turned out differently for various mechanisms and in correspondence with the work of Venilov, (ref 13) lay within $10^{-3}\,\mathrm{cm}^2/\mathrm{sec}^3$ (turbulent component of the wave) to $10\,\mathrm{cm}^2/\mathrm{sec}^3$ (wind-turbulence interaction).

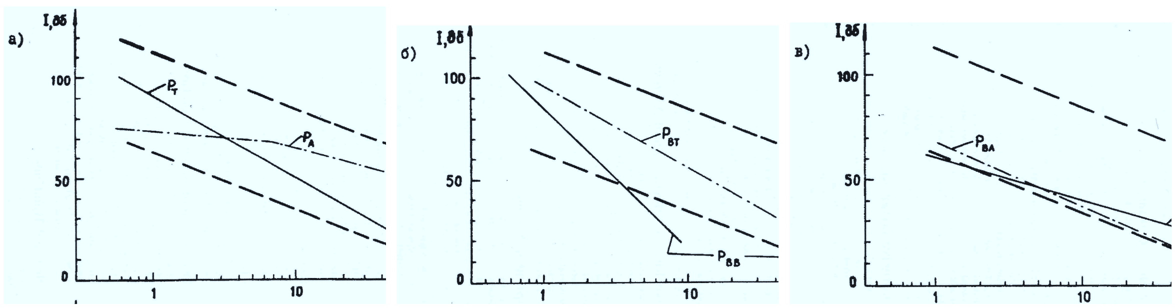

Figure 12: Dependency of intensity of radiated sound upon frequency for various generation mechanisms (— — — lines define the limits of the measured field observations of noise (taken from Wenz).

The results of the calculations are shown in Fig. 2 (here, Fig. 12), where along the abscissa axis on the logarithmic scale the frequency is displayed, and on the ordinate axis the intensity of the sound in decibels (relative to $I = 10\log(P^2(f)/P_0^2), P_0 = 2 \times 10^{-4}$).

Based on these calculations we have Tables 1 and 2 where we show the frequency range in which the given mechanism with determined wind speed may contribute significantly to ocean noise, and it shows the dependency of the spectrum on the frequency of the emitted sound and wind speed.

Table 1: Linear mechanisms of sound generation

Type of Mechanism	Frequency range in Hz	Dependency on wind speed and frequency
surface wave		
turbulent component of motion	from 1-2, to 100-200	$U^{10/3} f^{-4}$
atmospheric pressure variations	from 1-2 to 200-400	$U^{3.45} f^{-0.54}, f < TBD$ Hz $U^{3.45} f^{-1.9}, f < TBD$ Hz

Table 2: Non-linear mechanisms of sound generation

Type of Mechanism	Frequency range in Hz	Dependency on wind speed and frequency
WW interaction	below 100 and 100-200	$f^{-7},\ f<27$ $f,\quad f>27$
WT interaction	below 100-200	$U^{13/3}f^{-4}$
TT interaction	from 1-2 to 100-200	$U^{4}f^{-5/2}$
WA interaction	below 50	$U^{10/3}f^{-3}$
TA interaction	insignificant	insignificant

References

Adair, R. G., 1987: Comments on the infrasonic noise theory of isakovich and kuryanov and its modification by Wilson. *J. Acoust. Soc. Am.*, **81 (14)**, 1192–1195.

Ardhuin, F., L. Marie, J.-Y. Royer, J.-F. d'Eu, B. M. Howe, R. Lukas, and J. Aucan, 2013: A numerical model for ocean ultra low frequency noise: wave-generated acoustic-gravity and rayleigh modes. *J. Acoust. Soc. Am.*, submitted for special issue on deep ocean acoustics.

Ardhuin, F., E. Stutzmann, M. Schimmel, and A. Mangeney, 2011: Ocean wave sources of seismic noise. *J. Geophys. Res,*, **116 (C09004)**, 1–21, doi:10.1029/2011JC006952.

Brekhovskikh, L. M. and V. V. Goncharov, 1972: Sound radiation by the ocean-atmosphere boundary layer. *Sb. Morskoe Priborostroyenie, Ser. "Acoustics" (Marine instrument-making journal)*, **1**, 47–61, in Russian.

Buckingham, M. J. and J. R. Potter, (Eds.), 1995: *Sea surface sound '94*, World Scientific, New Jersey, pp. 494.

Carey, W. M. and D. Browning, 1988: Low frequency ocean ambient noise: Measements and theory. *Sea surface sound, natural mechanisms of surface generated noise in the ocean*, B. R. Kerman, Ed., Kluwer Academic Publishers, Netherlands, 361-376.

Carey, W. M. and R. B. Evans, 2011: *Ocean Ambient Noise.* Springer, Berlin.

Cato, D. H., 1981: Comments on "Very low frequency (VLF) wind-generated noise produced by turbulent pressure fluctuations in the atmosphere near the ocean surface". *J. Acoust. Soc. Am.*, **70 (6)**, TBD.

Cato, D. H., 1991a: Sound generation in the vicinity of the sea surface: Source mechanisms and the coupling to the received sound field. *J. Acoust. Soc. Am*, **89**, 1076–1095.

Cato, D. H., 1991b: Theoretical and measured underwater noise from surface wave orbital motion. *J. Acoust. Soc. Am*, **89**, 1096–1112.

Copeland, G. J. M., 1993: Low frequency ambient noise - generalised spectra. *Natural physical sources of underwater sound, Sea surface sound (2)*, B. R. Kerman, Ed., Kluwer Academic Pub., 17–30.

Crighton, D. G. and J. E. Ffowcs-Williams, 1969: Sound generated by turbulent two-phase flows. *J. Fluid Mech.*, **36**, 585–603.

Crum, L. A., 1995: Unresolved issues in bubble-related ambient noise. *Sea surface sound '94*, M. J. Buckingham and J. R. Potter, Eds., World Scientific, New Jersey, 243–269.

Curle, N., 1955: The influence of solid boundaries upon aerodynamic sound. *Proc. Roy. Soc. London*, **A231**, 505–514.

Deane, G. B. and M. D. Stokes, 2010: Model calculations of the underwater noise of breaking waves and comparison with experiment. *J. Acoustic. Soc. Am.*, **127 (6)**, 3394–3410.

Didenkulov, I. N. and A. M. Sutin, 1993: The influence of a subsurface bubble layer on wind ambient noise generation. *Natural physical sources of underwater sound, Sea surface sound (2)*, B. R. Kerman, Ed., Kluwer Academic Pub., 305–314.

Duennebier, F. K., R. Lukas, E. Nosal, J. Aucan, and R. Weller, 2012: Wind, waves, and acoustic background levels at Station ALOHA. *J. Geophys Res.*, **117 (C03017)**, 1–21, doi:10.1029/2011JC007267.

Farrell, W. E. and W. Munk, 2008: What do deep sea pressure fluctuations tell about short surface waves? *Geophys. Res. Let.*, **35 (L19605)**, 1–4, doi:10.1029/2008GL035008.

Farrell, W. E. and W. Munk, 2010: Booms and busts in the deep. *J. Phys. Oceanogr.*, 2159–2169, doi:10.1175/2010JPO4440.1.

Farrell, W. E. and W. Munk, 2012: Surface gravity waves and their acoustic signatures, 1-30 Hz, on the mid-Pacific sea floor. *J. Acoust. Soc. of America.*, in the press, this issue.

Ffowcs Williams, J. E., 1969: Hydrodynamic noise. *Annual Review of Fluid Mechanics*, W. R. Sears and M. Van Dyke, Eds., Ann. Rev. Inc., Palo Alto, Ca, Vol. 1, 197–222.

Ffowcs Williams, J. E. and Y. P. Guo, 1988: Mechanisms of sound generation at the ocean surface. *Sea surface sound, natural mechanisms of surface generated noise in the ocean*, B. R. Kerman, Ed., Kluwer Academic Publishers, Netherlands, 325-336.

Ffowcs Williams, J. E. and Y. P. Guo, 1993: Near surface sound mechanisms. *Natural physical sources of underwater sound -Sea surface sound (2)*, B. R. Kerman, Ed., Kluwer Academic Publishers, Netherlands, 315-327.

Goncharov, V. V., 1970: Sound generation in the ocean by the interaction of surface waves and turbulence. *Izv. Atmos. Ocean. Phys.*, **6**, 1189–1196.

Guo, Y. P., 1987a: On sound generation by weakly nonlinear interactions of surface gravity waves. *J. Fluid Mech.*, **181**, 311–328.

Guo, Y. P., 1987b: Sound generation in the ocean by breaking surface waves. *J. Fluid Mech.*, **181**, 329–347.

Guo, Y. P., 1987c: Waves induced by sources near the ocean surface. *J. Fluid Mech.*, **181**, 293–311.

Guralnik, Z., Z. Zabalgogeazcoa, J. Bourdelais, and W. E. Farrell, 2013: Wave-wave interactions and deep ocean acoustics. *J. Acoust. Soc. Am*, to be submitted to special issue on deep-ocean acoustics.

Hasselmann, K., 1963: A statistical analysis of the generation of microseisms. *Rev. Geoph.*, **1**, 177–210.

Isakovich, M. A. and B. F. Kuryanov, 1970: Theory of low-frequency noise in the ocean. *Soviet Physics - Acoustics*, **16 (1)**, 49–58.

Kedar, S., M. Longuet-Higgins, F. Webb, N. Graham, R. Clayton, and C. Jones, 2008: The origin of deep ocean microseisms in the North Atlantic ocean. *Proc. Roy. Soc. London*, **A464**, 777–793.

Kerman, B. R., 1984: Underwater sound generation by breaking wind waves. *J. Acoust. Soc. Am.*, **75**, 149–165.

Kerman, B. R., (Ed.), 1988: *Sea surface sound, natural mechanisms of surface generated noise in the ocean*, Kluwer Academic Publishers, Netherlands, pp. 639.

Kerman, B. R., (Ed.), 1993: *Natural physical sources of underwater sound -Sea surface sound (2)*, Kluwer Academic Publishers, Netherlands, pp. TBD.

Kibblewhite, A. C. and C. Y. Wu, 1991: The theoretical description of wave-wave interactions as a noise source in the ocean. *J. Acoust. Soc. Am.*, **89**, 2241–2252.

Kibblewhite, A. C. and C. Y. Wu, 1996: *Wave interactions as a seismo-acoustic source.* Springer, Berlin, 313 p.

Kuryanov, B. F., 1993: The theory of low-frequency noise generated by turbulence near the atmosphere-ocean interface. *Natural physical sources of underwater sound, Sea surface sound (2)*, B. R. Kerman, Ed., Kluwer Academic Pub., 255–262.

Leighton, T. G., (Ed.), 1997: *Natural physical processes associated with sea surface sound*, University of Southampton, Highfield, Southampton, pp. 278.

Lighthill, J. M., 1952: On sound generated aerodynamically: 1. general theory. *Proc. Roy, Soc. Lon.*, **A221**, 564–587.

Lloyd, S. P., 1981: Underwater sound from surface waves according to the Lighthill-Ribner theory. *J. Acoust. Soc. Am.*, **69**, 425–435.

Lowen, M. R. and W. K. Melville, 1991: Microwave backscatter and acoustic radiation from breaking waves. *J. Fluid Mech.*, **224**, 601–623.

Lowen, M. R. and W. K. Melville, 1994: An experimental investigation of the collective oscillations of bubble plumes entrained by breaking waves. *J. Acoustic. Soc. Am.*, **95 (3)**, 1239–1343.

Means, S. L. and R. M. Heitmeyer, 2001: Low-frequency sound generation by an individual open-ocean breaking wave. *J. Acoust. Soc. Am.*, **110 (2)**, 761–768.

Mellen, R. H., 1985: Wind-generated solitons: A potentially significant mechanism in ocean surface-wave generation and surface scattering. *IEEE J. Ocean Eng.*, **10 (4)**, 471–476.

Mellen, R. H., 1991: Experimental evidence for a proposed surface soliton mechanism in wind-wave generation and scattering. *J. Acoust. Soc. Am.*, **90 (2)**, 741–753.

Mellen, R. H. and D. Middleton, 1988: Ambient noise radiated by "soliton" surface waves. *Sea surface sound, natural mechanisms of surface generated noise in the ocean*, B. R. Kerman, Ed., Kluwer Academic Publishers, Netherlands, 325-336.

Miles, J. W., 1957: On the generation of surface waves by shear flows. *J. Fluid Mech.*, **3 (2)**, 185–204, doi:10.1017/S0022112057000567.

Mitsuyasu, H., 1977: Measurement of the high-frequency spectrum of ocean surface waves. *J. Phys. Oceanog.*, **17**, 881–891.

Nicholas, M., R. A. Roy, L. A. Crum, H. Orguz, and A. Prosperetti, 1993: Sound emissions by a laboratory bubble cloud. *J. Acoust. Soc. Am*, **95 (6)**, 3171–3182.

Oguz, H. N., 1994: A theoretical study of low-frequency oceanic ambient noise. *J. Acoust. Soc. Am.*, **95 (4)**, 1895–1912.

Omta, R., 1987: Oscillation of a cloud of bubbles of small and not so small amplitude. *J. Acoust. Soc. Am.*, **82**, 1018–1033.

Orcutt, J. A., C. S. Cox, A. C. Kibblewhite, and W. A. Kuperman, 1993: Observations and causes of ocean and seafloor noise at ultra-low and very-low frequencies. *Natural physical sources of underwater sound, Sea surface sound (2)*, B. R. Kerman, Ed., Kluwer Academic Pub., 203–232.

Pierson, W. J. and L. Moskowitz, 1964: A proposed spectral form for fully developed wind sea based on the similarity theory of S. A. Kitaigorodskii. *J. Geophys. Res.*, **69**, 5181–5190.

Powell, A., 1960: Aerodynamic noise and the plane boundary. *J. Acoust. Soc. Am.*, **32 (8)**, 982–990.

Prosperetti, A., 1988a: Bubble dynamics in ocean ambient noise. *Sea surface sound, natural mechanisms of surface generated noise in the ocean*, B. R. Kerman, Ed., Kluwer Academic Publishers, Netherlands, 151-171.

Prosperetti, A., 1988b: Bubble-related ambient noise in the ocean. *J. Acoust. Soc. Am.*, **84**, 1042–1054.

Pumphrey, H. C. and J. E. Ffowcs Williams, 1990: Bubbles as sources of ambient noise. *IEEE J. Ocean. Eng.*, **15**, 268–274.

Schindall, J. A. and R. M. Heitmeyer, 1996: Breaking wave noise measurements at frequencies below 400 Hz. *J. Acoust. Soc. Am.*, **100 (4)**, 2732–2732, abstract 3pUW5.

Tkalich, P. and E. S. Chan, 2002: Breaking wind waves as a source of ambient noise. *J. Acoust. Soc. Am.*, **112 (2)**, 456–463, doi:10.1121/1.1489436.

Wenz, G. M., 1962: Acoustic ambient noise in the ocean: spectra and sources. *J. Acoust. Soc. Am.*, **34(12)**, 1936–1957.

Wilson, J. H., 1979: Very low frequency (VLF) wind-generated noise produced by turbulent pressure fluctuations in the atmosphere near the ocean surface. *J. Acoust. Soc. Am.*, **66 (5)**, 1499–1507.

Wilson, J. H., 1981: Erratum: "Very low frequency (VLF) wind-generated noise produced by turbulent pressure fluctuations in the atmosphere near the ocean surface". *J. Acoust. Soc. Am.*, **69 (5)**, 1517–1518.

Wilson, J. H., 1987: Response to "Comments on the infrasonic noise theory of Isakovich and Kuryanov and its modification by Wilson". *J. Acoust. Soc. Am.*, **81 (14)**, 1195–1196.