Bubble number densities in the wake of a propeller and a pump jet ship

Steve Stanic[1], Russell Dahlburg[2], and Jerald Caruthers[3]

[1]Naval Research Laboratory
Stennis Space Center, MS 39529

[2]Naval Research Laboratory
Washington DC 20375

[3]University of Southern Mississippi
Stennis Space Center, MS 39529

Abstract

Bubbly wakes generated by a surface ship are generally the result of cavitation generated by its propulsion system, and air being entrapped along the water line as the ship moves through the water. As this turbulent wake decays, bubbles of different sizes coalesce, break up, and rise at different rates. This results in changing horizontal and vertical bubble distributions that are a function of ship's speed, wake depth, and age. The changing vertical and horizontal distributions have a time and frequency dependent effect on acoustic signals that creates an excess attenuation. A series of acoustic attenuation measurements were taken across the wake of a propeller driven ship using NRL's acoustic wake characterization system. These measurements were taken over a broad range of acoustic frequencies (30 kHz to 140 kHz), ship speeds (18 and 22 knots), wake depths (3 m to 6 m), and wake age (4.5 to 9.7 minutes). The acoustic attenuations across the wake due to varying bubble-size densities were determined experimentally. Using these measured average acoustic attenuations across the wake and the resonant bubble approximation, estimates of the average bubble number densities in the wake of the propeller driven ship were derived. These bubble number densities are compared to those obtained for the wake of a similar sized pump jet ship, (**Stanic et al JOE v34, Jan 2009)**. Results show that the bubble number densities for the propeller driven ship (18 knots) and the pump jet ship (15 knots) at a wake depth of 3 m were very similar. These bubble number densities were also seen to decrease with wake depth and age. As the propeller ship's speed increased, the bubble number densities for the propeller driven ship were lower than those for the pump jet ship at a speed of 15 knots. These results also showed that in general the wake of the propeller driven ship was not as intense and not as persistent as the wake of the pump jet ship at wake depths greater than 3 m and at all ship speeds.

I. Introduction

Bubbly wakes generated by a surface ship are generally the result of cavitation generated by its propulsion system, and air being entrapped along the water line as the ship moves through the water. As this turbulent wake decays, bubbles of different sizes coalesce, break up, and rise at different rates. This results in changing horizontal and vertical bubble distributions that have a time and frequency dependent effect on acoustic signals. These bubble number densities vary and depend on hull design, speed through the water and local oceanographic conditions.

Some of the earliest acoustic measurements taken of surface-ship wakes are documented in Wildt [1]. In this1949 treaties, which are still an excellent starting point for surface ship-wake characterizations studies, Wildt presents an in-depth discussion on acoustic probing of a wide range of ship wakes. Since then, there have been numerous measurements made of acoustic propagation through time dependent bubble clouds generated by surface ships. Extensive bibliographies can be found in Stanic *et al.* [2], King [3], and Lamatte and Melville [4]. Two recent measurements on surface-ship wakes were done by Trevorrow *et al*. [5, 6]. These papers, reported on a series of measurements taken on three different surface ships using fixed-upward-looking, high-frequency sonar systems. These systems measured the acoustic backscatter from these wakes at six frequencies. Trevorrow found that the volume-scattering cross section was roughly constant within the top 5-6 meters of the wake, suggesting a roughly homogeneous bubble distribution. However, differences in the volume backscatter did show an increased concentration of larger bubbles (> 100 microns) in the center of the wake. In a series of backscattering measurements from a small motorboat, Vagle and Burch [7] were able to use an acoustic-inversion technique to estimate the low-frequency sound-speed profile in an upward-refractive bubble layer. Stanic *et al*. [2] used a portable acoustic wake tracking system to estimate the average excess attenuation across the bubbly portion of a surface ship wake. Using the resonance bubble approximation, the bubble number densities were calculated as a function of wake age and frequency for a pump jet class ship.

In this paper we will present several main points in the theory of sound propagation through bubbly seawater. We will briefly describe a method of measuring the average across-wake acoustic excess attenuation. Using the resonance bubble approximation, we calculate estimates of the bubble number densities as a function of wake age, speed, and depth for the wake generated by the propeller-powered ship, Athena. These bubble number densities are compared with a series of bubble number densities calculated for the pump-jet driven ship, Neptune that were taken at a depth of 3 m. [2].

II. Theory of acoustic propagation in a bubbly fluid

An outline of the theory of propagation in a bubbly medium is given in Stanic [2]. Briefly, the theory, primarily developed by Medwin [8, 9] and Clay and Medwin [10], gives an expression for the excess attenuation $\beta(\omega)$ in a bubbly fluid:

$$\beta(\omega) = \frac{2\pi}{k_0}\int_0^\infty \frac{a\delta n(a)da}{\left(\frac{a^2}{a_r^2} - 1\right)^2 + \delta^2} \quad (1)$$

Where k_0 is the wavenumber in ambient water, δ is the damping constant, a is the bubble radius, a_r is the radius of the bubbles that resonate at the angular frequency ω, and $n(a)$ is the bubble number density. An approximate relationship between angular frequency and the radii of the bubbles that resonates at that frequency is given by $a_r = \sqrt{3\gamma P}/\omega$, where γ is the ratio of specific heats of the bubble gas and P is the ambient pressure. It should be noted that $\beta(\omega)$ is measured in nepers/m in Eq. (1), but when plotted or discussed here attenuation is given in dB/m. Although attenuation, as given in Eq. (1), is a positive number, transmission loss as we use it, is a negative number. Techniques introduced by Commander and McDonald [11], Caruthers *et al*. [12], and Elmore and Caruthers [13] have developed for formally inverting equation (1). An approximation, based on the recognition that the greatest contribution from the integral occurs when $a=a_r$, and is found in [1, 8, 11, 12, 14, 15]. This approximation results in

$$n(a) \approx \frac{4.6\times10^{-6} f^3}{1+0.1z}\beta(f) \quad (2)$$

where z is depth and f is the frequency. In Caruthers *et al*. [12] this approximation is referred to as the resonant bubble approximation (RBA). The constant coefficient in Eq. (2) contains a factor that converts $\beta(f)$ in Eq. (2) to dB/m.

III. Measurements and Discussion

The data presented in this paper were taken across the wake generated by the propeller driven ship, Athena. This ship is a twin screw powered ship with a top speed greater than 30 knots. Athena is 50 m long, has a beam of 7.3 m and a draft of 1.7 m. The measurements were taken using NRL's acoustic wake measurement system, covered the frequency range from 30 kHz to 140 kHz, and extended over the length of Athena's wake (~ 1.5 km). The measurement system and measurement techniques are outlined in Stanic *et al.* [2]. Figure 1 shows a photograph of Athena and a schematic of the wake measurement configuration.

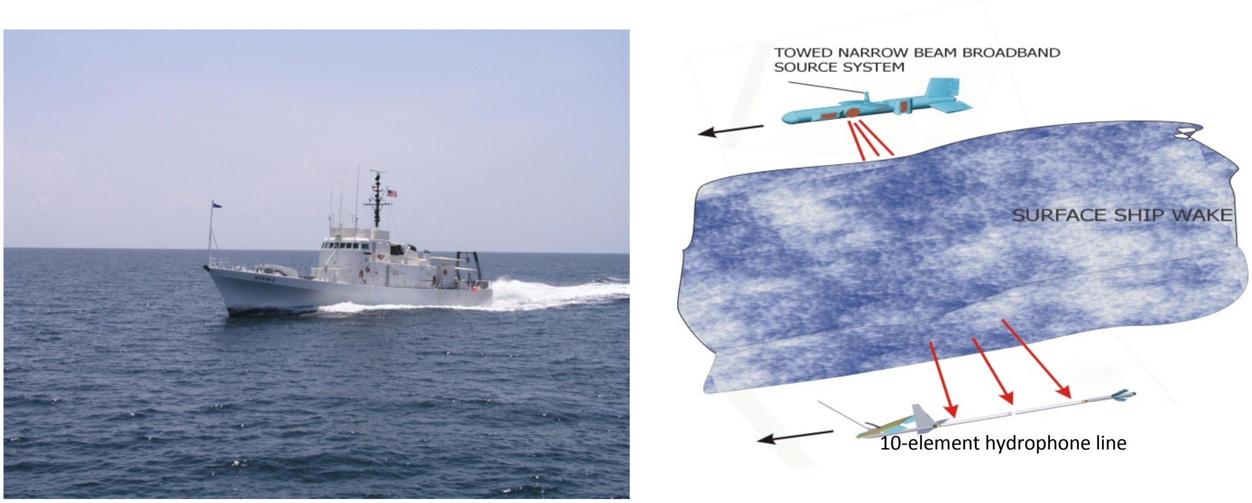

Fig. 1. Athena and a schematic of the wake measurement configuration

The average across-the-wake acoustic transmission loss measurements were taken for ship speeds of 18 and 22 knots. The data was taken in an area 10 miles south of Panama City, FL in a water depth of 50 m. Three pulse sequences were transmitted from the towed source system to a towed ten-hydrophone line located on the other side of Athena's wake. Each acoustic pulse sequence included four 0.5 ms long CW pulses that were separated by 1.0 ms. The frequencies in the first pulse sequence ranged from 30 kHz to 60 kHz, the second sequence ranged from 70 kHz to 100 kHz, and the third sequence from 110 kHz to140 kHz. Each CW pulse was separated by 10 kHz and the three pulse sequences were activated sequentially each second. The down-wake distance traveled by the measurement systems between each pulse sequence was approximately 2.5 m and each pulse sequence was repeated every 7.5 m of travel down the wake. The distance between the transmit and receive systems was 150 m and was monitored using a laser range finder. Source to receiver separation was plus or minus 2 m.

The cross-wake acoustic transmissions began several minutes before Athena passed between the two measurements support ships and provided signal levels in the bubble-free water. Each of the ten-hydrophone channels was band-passed filtered, and sampled at 1MHz. For each hydrophone, ping sequence, and transmitted frequency within the sequence, an envelope intensity level, and a 1024-point power spectral density (PSD) function were calculated. By comparing the frequency dependent signal intensity levels before and after the passage of Athena, direct estimates of the frequency-dependent excess attenuation due to changing bubble densities across the turbulent portion of wake were obtained from:

$$\beta_{dB}(f) = \mathrm{TL}_{excess} = \mathrm{TL}_{bubbly\ water} - \mathrm{TL}_{bubble-free\ water}$$

Using the RBA, the bubble-size densities are estimated as a function of bubble size, ship speed, and wake age. The bubble number densities were calculated for hydrophones 2, 4, 6, 8, and 10 and the results averaged.

A. Results for an 18-knot wake

Shown in fig 2 is a representative series of bubble densities versus range for bubble radii of 52, 46, 41, and 37 μm. This corresponds to bubble resonance frequencies of 70, 80, 90, and 100 kHz. These data are for a ship's speed of 18 knots and a hydrophone line depth of 3.0 m. The zero point on the wake age scale is when the acoustic transmissions first encountered the ship's wake. At this point, bubble densities increased rapidly for about 600 m and rapidly decreased as the wake aged, turbulence diminished, and the bubbles rose to the surface before fully dissipating at a range of about 1400 m behind Athena.

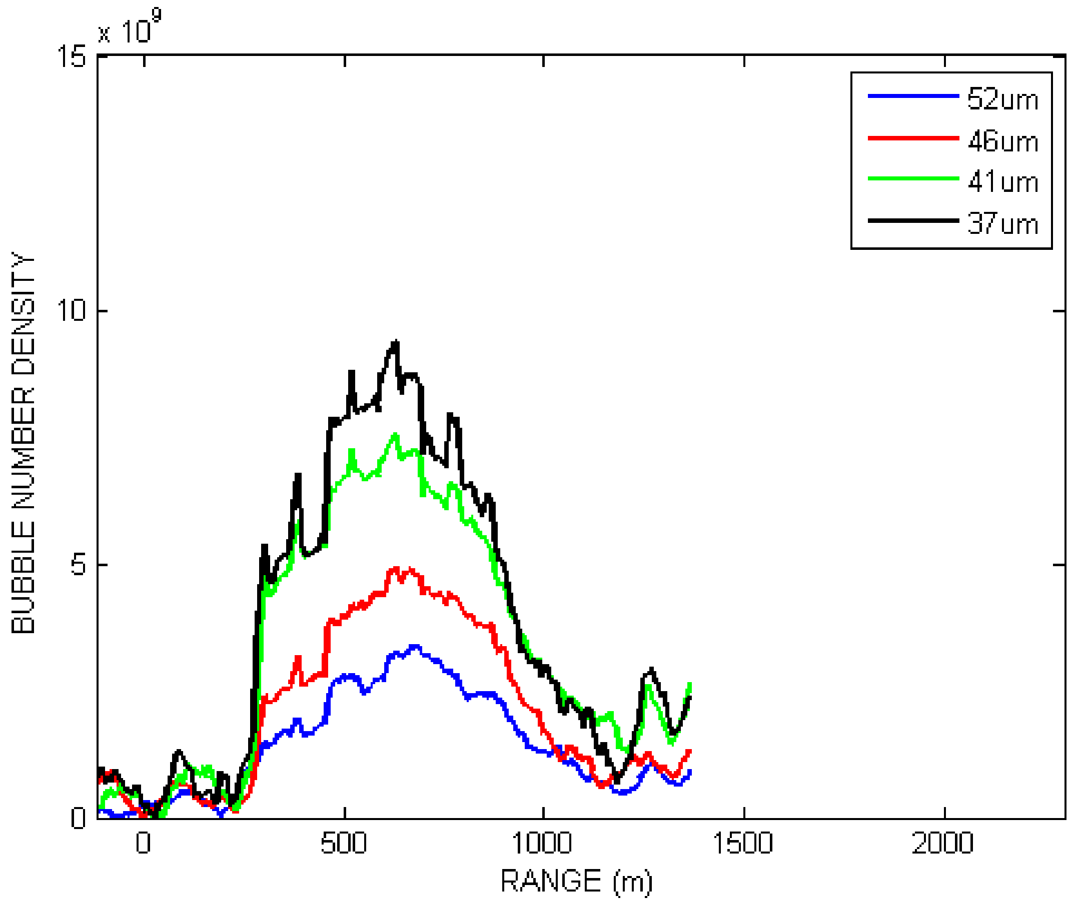

Fig. 2. Bubble densities vs wake age for a ship's speed of 18 knots.

Figures 3, 4 and 5 show the calculated average bubble densities using the RBA as a function of wake age and hydrophone depth for the 18-knot wake generated by Athena. The results are for wake ages of 4.5, 6.4, and 9.7 minutes and measurement depths that ranged from 3.0 m to 6.0 m. Shown in figures 3 are the corresponding bubble number density results for the pump jet ship Neptune [2].

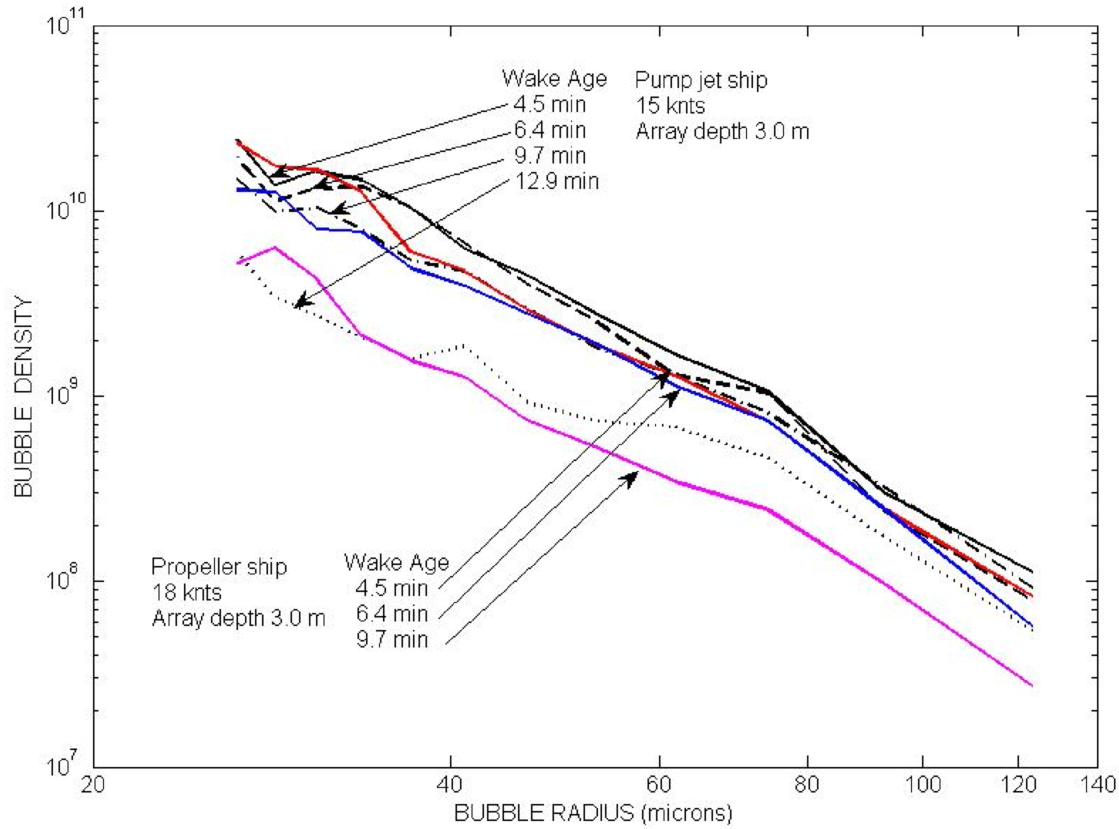

Fig. 3. A comparison of bubble number densities between Athena (18 knots) and Neptune (15 knots) as a function of wake age for a hydrophone depth of 3.0 m.

At a depth of 3.0 m, the bubble number densities for Athena, at a speed of 18 knots and at wake ages of 4.5 minutes and 6.4 minutes are comparable to Neptune's results at wake ages of 6.4 and 9.7 minutes (fig 3). The small changes in bubble number densities generated by Athena at these wake ages indicate that most of the bubbles over these wake age ranges likely remained entrapped by the wake turbulence. At a wake age of 9.7 minutes, the bubble number densities for Athena showed that, except for a small increase in the number of small bubbles, there were fewer bubbles than in Neptune's wake at 12.9 minutes. The maximum bubble densities for the smaller bubbles ranged from 2.0×10^{7} m^{-4} at a wake age of 4.5 minutes to 6.0×10^{9} m^{-4} at a wake age of 9.7 minutes. The minimum levels for the larger bubbles were below 2.0×10^{10} m^{-4}. These results suggest that the wake of Athena was not as persistent nor as turbulent as the wake generated by Neptune, even though Athena was travelling 3 knots faster. In the wake of Athena, turbulence at the higher wake ages may be dissipating more quickly, thus allowing smaller bubbles to dissipate and leave the wake earlier.

The data in fig. 4 shows a comparison of the bubble number densities for Athena's wake at depths of 3.0 m and 4.5 m. These curves show a decrease in the bubble number densities at the 4.5 m depth. At this depth, the maximum bubble densities for the smaller bubbles ranged from 2.0×10^{9} m^{-4} at a wake age of 4.5 minutes to 1.0×10^{9} m^{-4} at a wake age of 9.7 minutes. The minimum levels for the larger bubbles were below 1×10^{7} m^{-4}. These results show that at a depth 4.5 m and at a wake age of 4.5 minutes there are slightly larger bubbles above

40 microns than there were at a depth of 3.0 m and at a wake age of 9.7 minutes. The levels at the 4.5 m depth and at a wake age of 6.4 minutes were generally the same as the levels at a depth of 3.0 m and wake age of 9.7 minutes. The levels at a wake age of 9.7 minutes were the lowest for all bubble sizes.

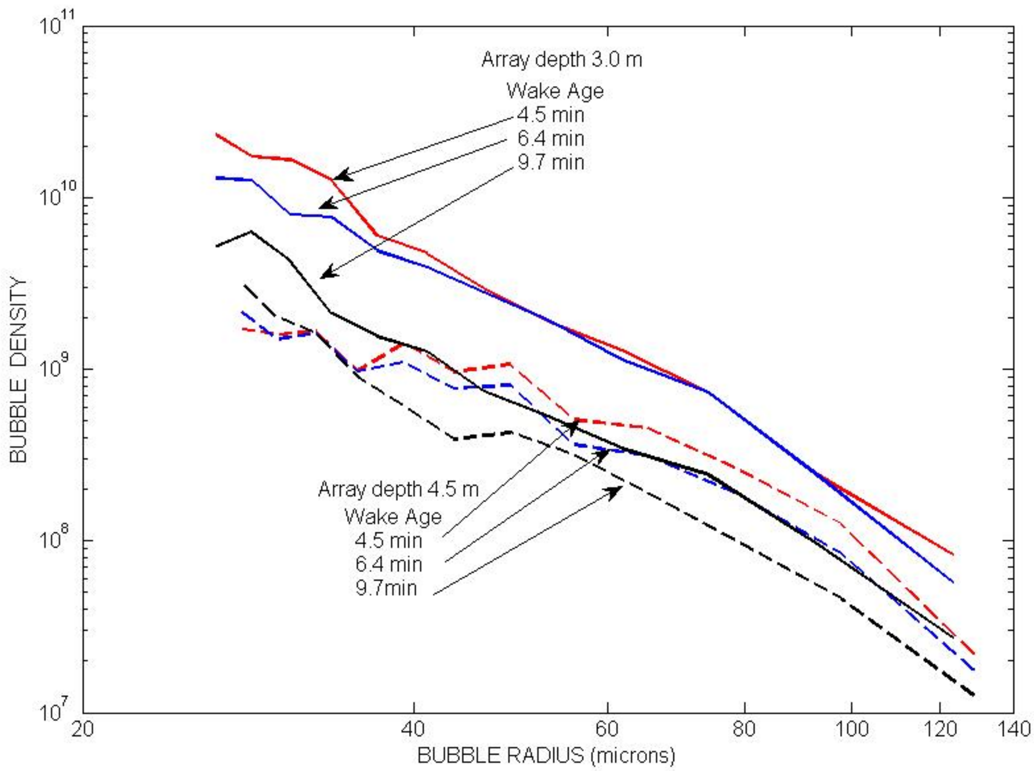

Fig. 4. A comparison of the bubble number densities for Athena's wake (18 knots) at depths of 3.0 m and 4.5 m. These results are shown as a function of wake age.

Fig. 5 shows a comparison of the bubble number densities at hydrophone line depths of 3.0 m and 6.0 m. At a depth of 6.0 m, there was a general decrease in the bubble density levels at all wake ages when compared to the results at 4.5 m. At the 6.0 m depth, the maximum bubble densities ranged from about 4.5 x10^9 m^{-4} at a wake age of 4.5 minutes to 2.0 x 10^9 m^{-4} at a wake age of 9.7 minutes. The minimum levels for the larger bubbles were on the order 10^7 m^{-4}. There was a slight increase in the number of small bubbles and general decrease in the number of larger bubbles at the 6 m depth. This may be due to the breakup of the larger bubbles and the entrapment of these small bubbles in the ship's wake turbulence at this depth. At a depth of 6.0 m, the results at the two early wake age results are quite similar, however, the densities at 9.7 minutes are lower.

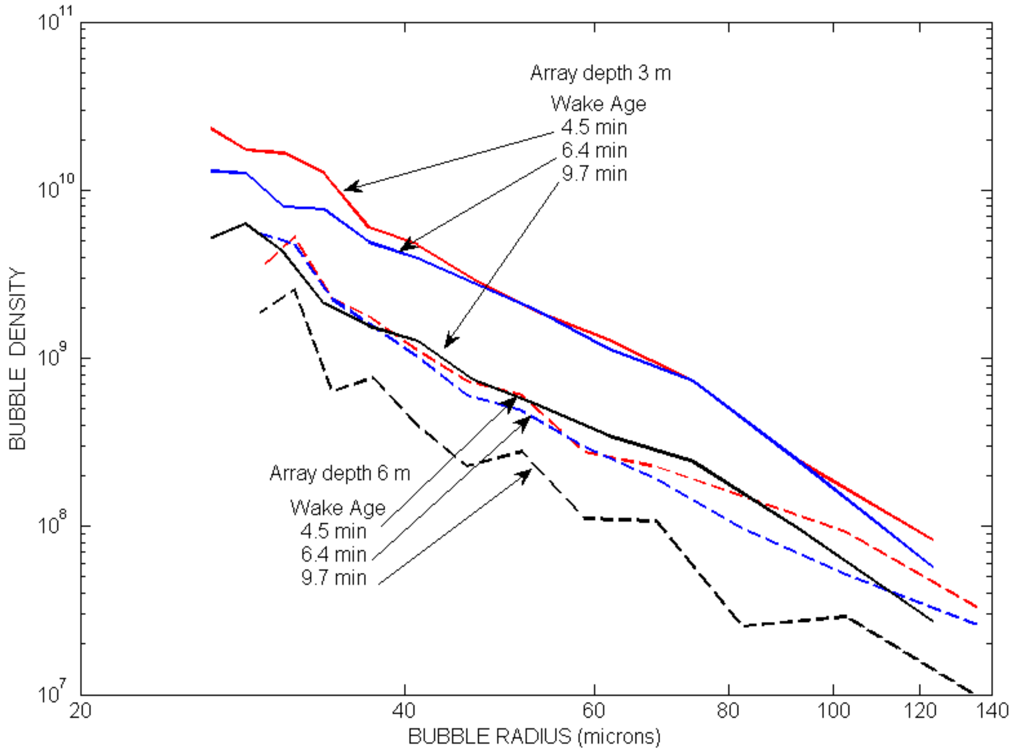

Fig. 5. A comparison of the bubble number densities for Athena's wake (18 knots) at depths of 3.0 m and 6.0 m. These results are shown as a function of wake age.

B. Results for a 22-knot wake

Acoustic excess across wake attenuation measurements were also taken when Athena was travelling at 22 knots. Figures 6, 7, and 8 shows the bubble number densities at depths of 3.0, 4.5, and 6 m. The results shown in fig. 6 are for a hydrophone line array depth of 3.0 m. The bubble number densities for Neptune at a depth of 3.0 m are again shown for comparison. At a wake age of 4.5 minutes the bubble number densities for Athena are very similar to Neptune's densities at a wake age of 9.7 minutes and at a speed of 15 knots. As Athena's wake aged, the bubble number densities at 6.4 minutes were comparable to Neptune's results at 12.9 minutes. As Athena's wake age approached 9.7 minutes the bubble number densities were generally much lower than Neptune's results at a wake age of 12.9 minutes, even though Athena was travelling 7 knots faster than Neptune. This shows that Athena's wake appeared to be not as intense; this was collaborated by visual observations. At 22 knots and at a depth of 3.0 m, the bubble densities for Athena ranged from about 10^{10} m^{-4} for a wake age of 4.5 minutes to 3.0 x 10^9 m^{-4} for a wake age of 9.7 minutes. The minimum levels for the larger bubbles was below 3.0x 10^7 m^{-4}.

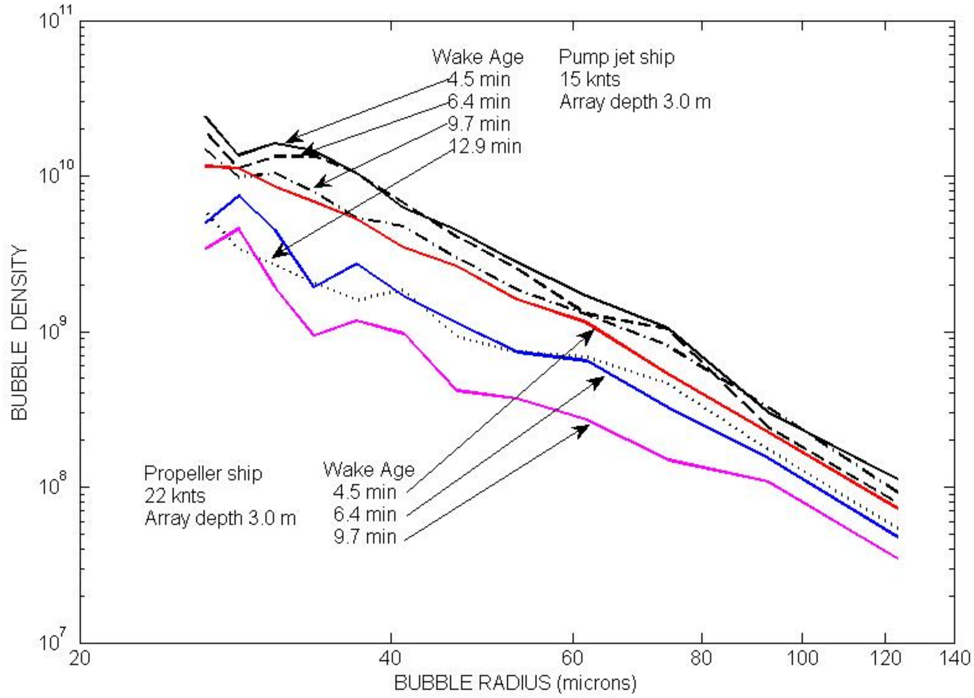

Fig. 6. A comparison of bubble number densities between Athena (22 knots) and Neptune (15 knots) as a function of wake age for a hydrophone depth of 3.0 m.

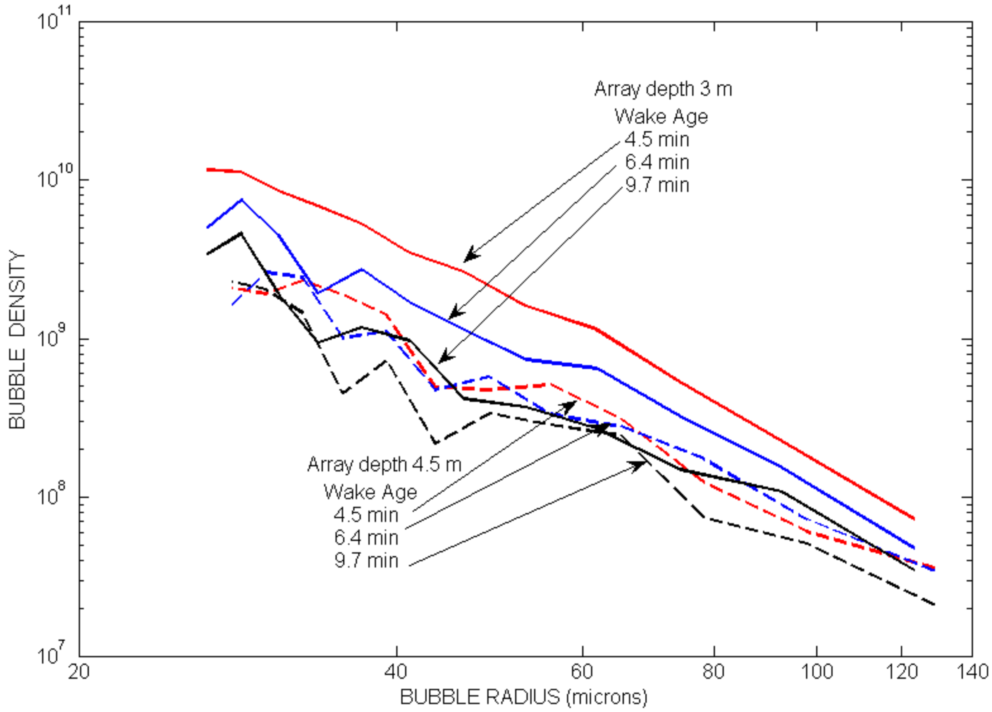

Fig 7. A comparison of the bubble number densities for Athena's wake (22 knots) at depths of 3.0 m and 4.5 m. These results are shown as a function of wake age.

Fig. 7 shows the bubble number density levels calculated for Athena's wake at a depth of 3.0 m and 4.5 m. At the 4.5 m depth, the bubble number densities at 4.5 minutes and 6.4 minutes are comparable to the levels in Athena's wake at a depth of 3.0 m and at a wake age of 9.7 minutes. At a depth of 4.5 m and for a wake age of 9.7 minutes the bubble number densities are generally the lowest. At 22 knots and at a depth of 4.5 m the small bubble densities for Athena ranged from about 2.0×10^9 m^{-4} for a wake age of 4.5 minutes to 1.0×10^9 m^{-4} for a wake age of 9.7 minutes. The minimum levels for the larger bubbles were below 2.0×10^7 m^{-4}. These bubble number densities were slightly higher than the corresponding levels at 18 knots.

The data shown in fig. 8 compare the results at hydrophone line depths of 3.0 m and 6.0 m. At a depth of 6.0 m and at wake ages of 4.5 minutes and 6.4 minutes, there is a slight increase in the number of small bubbles that may be the result of the breakup of some of the larger bubbles, and the smaller bubbles being entrapped by the turbulence generated by Athena's propellers. At a wake age of 9.7 minutes, the number of bubbles in Athena's wake are lower than the levels at 4.5 minutes and at 6.4 minutes. At a depth of 6.0 m and at a speed of 22 knots, the small bubble density levels for Athena ranged from about 8.0×10^9 m^{-4} at a wake age of 4.5 minutes to about 1.0×10^9 m^{-4} at a wake age of 9.7 minutes. The minimum levels for the larger bubbles were below 1.0×10^7 m^{-4}.

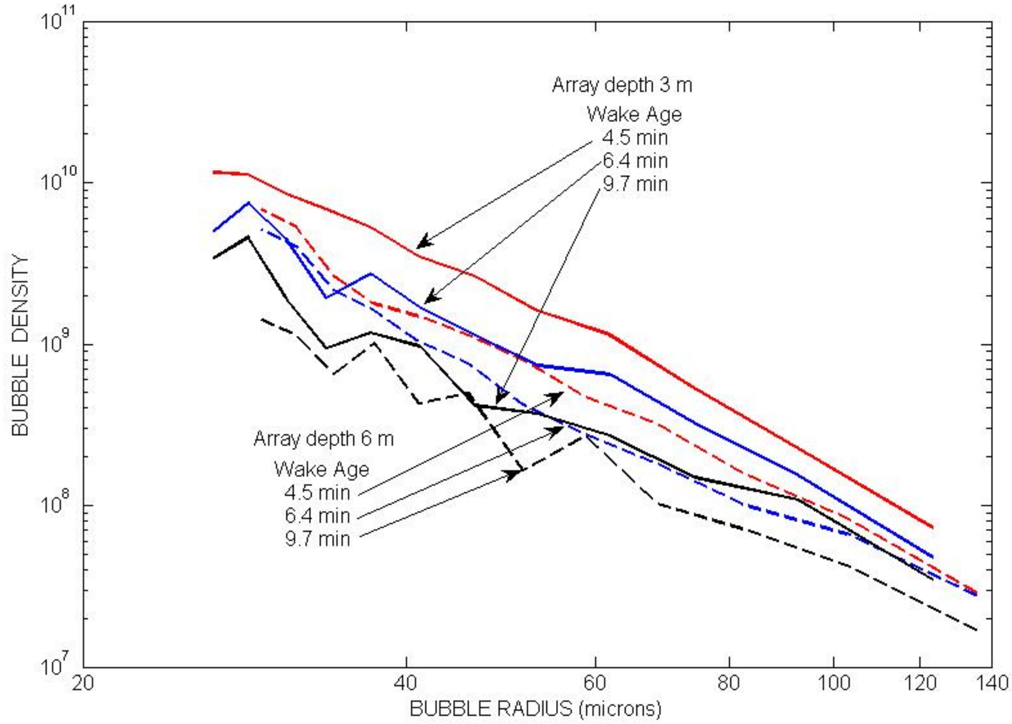

Fig. 8. A comparison of the bubble number densities for Athena's wake (22 knots) at depths of 3.0 m and 6.0 m. These results are shown as a function of wake age.

IV. Summary and Conclusions

In this paper we have presented the results of a series of acoustic across-the-wake excess attenuation measurements for the wakes generated by the propeller driven ship, Athena. The measurements were taken using a 10-element hydrophone line, and were conducted for ship speeds of 18 knots and 22 knots. Bubble size distributions were measured at wake ages of 4.5, 6.4, and 9.7 minutes and were taken at depths of 3.0 m, 4.5 m, and 6.0 m. The bubble number densities were calculated using the RBA; and the results at a depth of 3.0 m compared with the results derived from the corresponding measurements taken across Neptune's wake at a depth of 3.0 m. The results for Athena were also compered as a function of depth, speed, and wake age.

A comparison of Athena's wake and Neptune's wake at 18 knots and 15 knots respectively, showed that the wake generated by Athena appeared to be not as intense, even though Athena was travelling 3 knots faster. This was also observed visually, and was most likely due to Athena's stream-lined hull. These lower levels were also evident in the bubble number densities for the wake of Athena at a speed of 22 knots. Even though Athena was travelling 7 knots faster, the corresponding levels for Athena's wake were lower than the corresponding levels for Neptune's wake at a depth of 3.0 m. At this higher speed, Athena appeared to be travelling in a planing configuration which may have resulted in less air being entrapped by the hull.

At the wake depth of 4.5 m and speed of 18 knots, there appeared to be fewer small bubbles and more large bubbles in Athena's wake at all wake ages. At ship speeds of 18 knots and 22 knots, the bubble number densities appeared to be generally clustered around the levels at the 3.0 m depth and at the 9.7 minute wake age. At a ship's speed of 22 knots and at depths of 4.5 m and 6.0 m the bubble number density levels were very similar for all wake ages. The lowest level of bubble number densities was for the 18 knot wake at a depth of 4.5 m and at a wake age of 9.7 minutes.

These results show the difference between the two types of ship propulsion systems. In these experiments, it is suggested that the wake generated by the propeller system and hull of the Athena appeared to be not as intense nor as persistent as the wake generated by the pump jet propulsion system and hull of Neptune, even though Athena was travelling faster that Neptune.

V. Acknowledgements

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VII. References

[1] R. Wildt (editor), *Physics of Sound in the Sea*, National Defense Research Committee, Div. 6. Summary Tech. Rep. Vol. 8, 1949. Reprinted as *Physics of Sound in the Sea*, pp.460-477 Peninsula Publishing: Los Altos, CA (1989).

[2] Steve Stanic, Jerald W. Caruthers, Ralph R. Goodman, Edgar Kennedy, and Robert Brown, "Attenuation Measurements Across Surface -Ship Wakes and Computed Bubble Distribution and Void Fractions," *IEEE J. Oceanic Engr*., **34,** 83-92, (2009).

[3] W. F. King, "Sound propagation in wakes," *J. Acoust. Soc. Am.*, **54,** 735-745 (1973).

[4] E. Lamatte and W. K. Melville, "Void-fraction measurements and sound-speed fields in bubble plumes generating by breaking waves," *J. Acoust. Soc. Am.*, **95**, 1317-1328 (1994).

[5] M. V. Trevorrow, S. Vagle, and D. M. Farmer, "Summary of acoustical measurements of microbubbles within ship wakes," Institute of Ocean Sciences, DREA CR/93/435 (1993).

[6] M. V. Trevorrow, S. Vagle, and D. M. Farmer, " Acoustical measurements of microbubbles within ship wakes," *J. Acoust. Soc. Am*., **95,** 1922-1930 (1994).

[7] S. Vagle and H. Burch, "Acoustic measurements of the sound-speed profile in the bubbly wake formed by a small motor boat," *J. Acoust. Soc. Am.*, **117**, 153-163 (2005).

[8] Medwin, H. "Acoustical determinations of bubble-size spectra," *J. Acoust. Soc. Am*., **62**, 1041-1044 (1977).

[9] Medwin, H. "In situ acoustic measurements of microbubbles at sea," *J. of Geophy. Res*., **82**, No. 6, 971-976 (1977).

[10] C. S. Clay and H. Medwin, Acoustical *Oceanography: Principles and Application* Wiley-Interscience, New York, 1977.

[11] Commander, K.W. and McDonald, R.J. "Finite-Element solution to the inverse problem in bubble swarm acoustics," *J. Acoust. Soc. Am*., **89,** 592-597 (1991).

[12] J.W. Caruthers, P.A. Elmore, J.C. Novarini and R.R. Goodman, "An iterative approach for approximating bubble distributions from attenuation measurements." *J. Acoust. Soc. Am*., **106,** 185-189 (1999).

[13] P.A. Elmore and J.W. Caruthers, "Higher order corrections to an iterative approach for approximating bubble distributions from attenuation measurements," *IEEE J. Oceanic Engr*., **28,** 117-120 (2003).

[14] Medwin, H. "In situ acoustic measurements of bubble populations in coastal ocean waters," *J. Geophy. Res*., **75,** 599-611 (1970).

[15] N. Breitz and H. Medwin, "Instrumentation for *in situ* acoustical measurements of bubble spectra under breaking waves," *J. Acoust. Soc. Am*., **86,** 739-743 (1989).