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R Lee Culver
Pennsylvania State University - Main Campus

Thomas C. Weber
University of New Hampshire, Durham, thomas.weber@unh.edu

David L. Bradley
Pennsylvania State University - Main Campus

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THE USE OF MULTI-BEAM SONARS TO IMAGE BUBBLY SHIP WAKES

R. Lee Culver, Thomas C. Weber, and David L. Bradley

Applied Research Laboratory and Graduate Program in Acoustics, The Pennsylvania State University

Contact author: R. Lee Culver, ARL/PSU, PO Box 30, State College, PA 16804 (814) 865-3383 (w) (814) 863-7841 (fax) rlc5@psu.edu

Abstract: *During the past five years, researchers at Penn State University (PSU) have used upward-looking multi-beam (MB) sonar to image the bubbly wakes of surface ships. In 2000, a 19-beam, 5° beam width, 120° sector, 250 kHz MB sonar integrated into an autonomous vehicle was used to obtain a first-of-a-kind look at the three-dimensional variability of bubbles in a large ship wake. In 2001 we acquired a Reson 8101 MB sonar, which operates at 240 kHz and features 101-1.5° beams spanning a 150° sector. In July 2002, the Reson sonar was deployed looking upward from a 1.4 m diameter buoy moored at 29.5 m depth in 550 m of water using three anchor lines. A fiber optic cable connected the sonar to a support ship 500 m away. Images of the wake of a small research vessel provided new information about the persistence of bubble clouds in the ocean. An important goal is to use the MB sonar to estimate wake bubble distributions, as has been done with single beam sonar. Here we show that multipath interference and strong, specular reflections from the sea surface adversely affect the use of MB sonars to unambiguously estimate wake bubble distribution*

Keywords: *Multi-beam sonar, bubble imaging, ship wake imaging*

1. INTRODUCTION

For many years researchers have been seeking to understand acoustic propagation through and around surface ship wakes. Acoustic measurements made by the US in the 1940's showed that transmission loss (TL) through ship wakes depended upon whether the sound was transmitted across the wake or along the wake [1].   Measurements in the cross-wake

direction showed that TL increased with increasing ship speed (and thus wake depth and intensity) and with increasing frequency up to 40 kHz. However, measurements in the along-wake direction showed "anomalously low" TL induced by the wake.

At Penn State, an existing PE code has been modified to calculate TL between sources and receivers located inside a bubbly ship wake given the range- and depth-dependent sound speed and attenuation fields within the wake [2, 3]. The presence of bubbles significantly affects sound speed and acoustic attenuation in the ship wake; methods for calculating sound speed and attenuation from the bubble size distribution are well known [e.g. 4].

However, little is known about the size and spatial distribution of bubbles in ship wakes, and in particular, how they vary with ship operating conditions and the ocean environment. Two techniques have been used to place an acoustic measurement system under or inside the wake of a ship travelling at high speed: (1) fix the sensor and drive the ship over or beside it, thereby obtaining measurements of a single piece of the wake as it ages, or (2) put the sensor on a moving platform and obtain measurements of different parts of the wake. Since the bubble distribution in the wake varies with time and location, both types of measurements provide useful information. The size and spatial distribution of bubbles in the wake has been estimated by direct measurements of acoustic attenuation and by acoustic backscattering from the wake. Dumbrell [5] towed a multi-frequency attenuation measurement system and a single frequency backscattering system across the wake to obtain size and spatial bubble distributions in the *cross-wake* direction. Trevorrow et. al. [6] have used six single-beam transducers mounted looking upward on a freely-drifting platform to measure the bubble size distribution at somewhat random locations in the wake. Gallaudet and de Moustier [7] have towed a MB sonar behind a ship travelling at slow speed and measured backscatter from the bubbles at a fixed distance from the ship.

An upward-oriented MB sonar is well suited for measuring ship wake bubble distributions because each ping provides bubble backscatter in two spatial dimensions, and a sequence of pings provides a three-dimensional look at the bubble field. Laying a wake over a stationary MB sonar provides information about the time-evolution of the wake at a fixed point in space, although current can move the wake relative to the sonar field of view. Alternatively, mounting an MB sonar on a high-speed underwater vehicle provides a means of measuring the bubble field variability at a fixed distance astern of the ship. In both cases, we have found that multipath and specular scatter from the ocean surface can limit the usefulness of the MB sonar for ship wake bubble field characterization.

2. MARCH 2000 SHIP WAKE MEASUREMENT

In March 2000, an opportunity was presented to measure the spatial distribution of bubbles in the wake of a large US Navy ship. It was decided to use a MB sonar built by Penn State in 1988 because it provided water column data and was integrated into an autonomous underwater vehicle (AUV) capable of speeds up to 28 kts. The sonar is shown in Figure 1.

2.1. Penn State multi-beam sonar description

The Penn State MB sonar is completely contained in two 53 cm diameter cylindrical shell sections that are a total of 71 cm long. It was integrated into ARL/Penn State's autonomous test vehicle, which allows for its use in the upper 200 m of the world's oceans. Five piezoelectric transmit elements spaced around the shell provide 200 dB source level over a 120° sector. Seventeen 2" diameter polyvinylidene fluoride (PVDF) elements, each with a 5°

conical beam, were spaced at 7.5° intervals to cover the 120° sector. Operating at 250 kHz, received signals were bandpass filtered, basebanded, log-amplified, and sampled at about 4 kHz. The receiver has a dynamic range of 100 – 200 dB re 1 uPa. The pulse length is 1 ms, and the transmit rate is variable.

- Transmit: 5 Tonpilz elements
  - 120° Coverage
- Receive: 17 - 2" dia. PVDF sensors
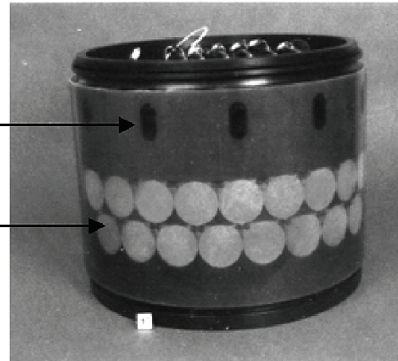 - 5° beamwidth (each element)
  - 120° total coverage

Fig.1: Penn State multi-beam sonar, fully-contained in a 53 cm dia. 71 cm long shell.

2.2. Measurement approach

With the MB sonar pointed upward, the AUV ran a pre-programmed course that crossed under the ship wake multiple times because the MB sonar data could not be processed in real time to generate steering commands and keep the vehicle under the wake. The AUV was launched toward the ship as it passed by; it ran at 6.2 m/s and at a depth equal to twice the ship draft. The ship has two propellers; ship speed was 9.3 m/s. The AUV moved toward the ship wake and just prior to reaching it, executed a 75° turn to the left and began a sequence of turns designed to cross under the wake at angles of 15° to 22° between the vehicle heading and wake axis. This course was selected over a straight trajectory directly under the ship wake because a small error in vehicle launch direction would have translated into an error in vehicle heading after the left turn, possibly causing the vehicle to miss the ship wake entirely. It turned out that the vehicle launch direction was excellent and the vehicle crossed under the wake eight times. Unfortunately, an electrical problem in the vehicle stopped MB sonar data acquisition at the end of the third crossing.

2.3. Wake data

Figure 2 shows levels received from a pulse transmitted prior to the sonar arriving under the wake, and illustrates a common problem with MB data: leakage of the specular reflection from the surface into all beams. The vertical axis in Fig. 2 is depth normalized by the draft of the ship; the horizontal axis is cross-track distance normalized by the beam of the ship. The gray scale is echo strength. The location of the MB sonar is the bottom-center of the plot. The light patch at the surface in the center beam is the surface echo. However, all of the beams show echo energy at the same distance from the sonar as the surface. Fig. 2 shows that the receive beam response falls off relatively smoothly to about –40 dB at 60° away from the main lobe. This would generally be considered very good control of side lobe levels, but is a problem for the MB sonar because the specular surface reflection coming in through a

side lobe can be stronger than echoes from bubbles in the main lobe. In Fig. 2, echoes from above the sea surface are multipath due to specular reflection from the sea surface combined with bubble scattering. This will be discussed in more detail shortly.
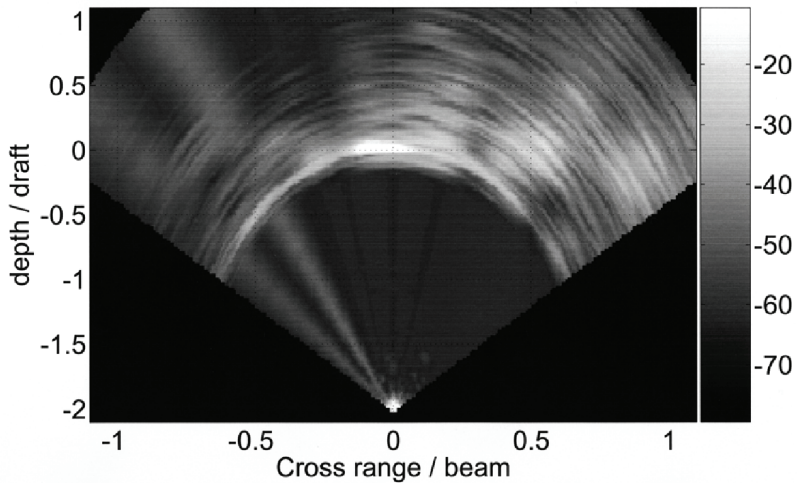

Fig.2: Multi-beam sonar echo with no wake present, showing surface specular reflection leakage into all beam.
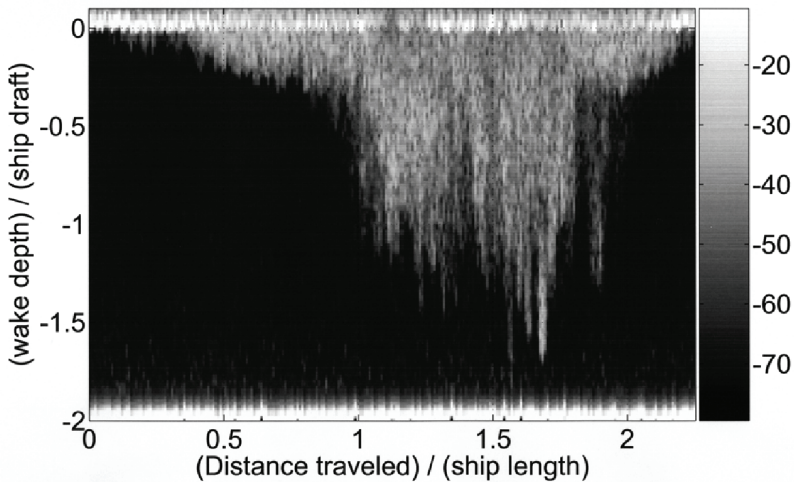

Fig.3: Data from center beam only as the sonar passed under the ship wake.

Fig. 3 shows received levels from the only the beam which is pointed directly upward for a sonar crossing under the wake. The plot vertical axis is the same as in Fig. 2; the horizontal axis is distance travelled divided by the length of the ship. The angle between the AUV heading and that of the ship was about 15°. The intermittent line across the upper part Fig. 3 is the surface echo. Note that it is strong when the sonar is not under the wake, but attenuated when the sonar is under thicker parts of the wake. Backscattering from the water volume very close to the sonar is responsible for the line across the bottom of the plot. The wake in Fig. 3 is composed of two bubble masses that extend downward to 1 to 2 times the draft of the ship. The two masses are probably associated with the ship's two propellers.

Fig. 4 shows the estimated depth of the wake during the crossing. It was obtained by taking the range in each beam and ping at which the gradient of the echo becomes large. The plot vertical axis is distance travelled in the cross-wake direction, normalized by the beam of the ship, and the horizontal axis is distance travelled along the wake normalized by the length of the ship. The gray scale is depth normalized by the ship's draft; black indicates a wake depth of nearly twice the draft. Leakage of the surface specular return into side-looking beams has been removed from the data, and as a result, values are not plotted in Fig. 4 for every ping and beam. Cross-wake structures protruding downward are called *wake curtains*; they indicate turbulence caused by velocity shear at the lower boundary of the wake.
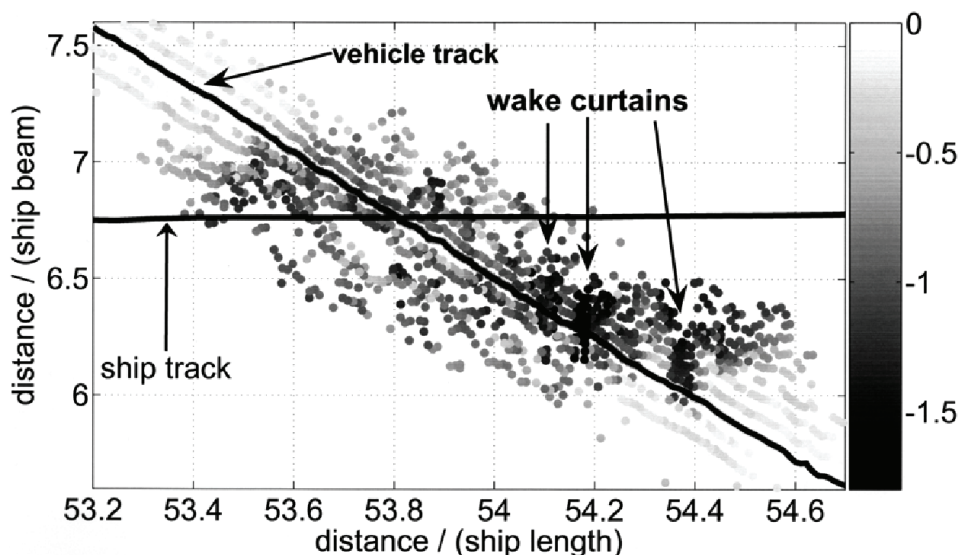

Fig.4: Estimated wake depth divided by ship draft from one wake crossing. The vehicle and sonar travelled from upper left to lower right. The ship travelled from left to right. Wake curtains indicate turbulence caused by velocity shear at the wake lower boundary.

3. AUGUST 2002 SHIP WAKE MEASUREMENT

The March 2002 ship wake measurement provided useful information about the bubble spatial distribution in the along-wake direction. However, the resolution of the data was limited by the 5° beam width of the sonar (the diameter of a 5° beam 25 m from the sonar is 2.2 m). In 2001, the US Navy supported purchase of a Reson 8101 MB sonar that provided much higher resolution. In August 2002, an opportunity was provided to measure the spatial distribution of ship wake bubbles at a site approximately 2.5 km east of San Clemente Island, which is about 80 km off the southern California coast.

3.1. Sonar description

The Reson 8101 sonar utilizes separate transmit and receive arrays to produce 101 1.5° degree beams spanning a 150° swath. The processor and display are connected to the wet end

array via a coaxial cable limited in length to about 100 m, or alternatively, a fiber optic cable that allows a much greater separation distance. A roll and pitch sensor and compass package provided MB sonar heading and attitude. A pressure vessel was constructed to house a power supply, a fiber optic media converter, and other communication electronics.

The 8101 features a variable length (21-225 μs) 240 kHz pulse transmitted by a line array projector, and backscattered signals are received on an orthogonally-oriented cylindrical array of elements. Maximum range is 300m. Reson provided an engineering software package called the "Snapshot" program, which runs on a PC residing on the same local area network (LAN) as the 8101 processor. The program allows the user to record amplitude and phase data for all samples on each of the 101 beams, out to the maximum range set by the user. Each of the 101 beams are sampled at 15k samples/second, and the ping repetition rate (PRR) is 1-20 seconds, depending upon the maximum range setting. This PRR is significantly slower that that achieved by the sonar in the bathymetric mode of operation, the rate being limited by the time required to transfer data across the LAN.

Webber [8] calibrated the Reson 8101 transmit and receive arrays in the cross- and along-track directions at ranges of 2-12 m. The transmit beam is reduced 6 dB in the main direction in order to reduce leakage of specularly-reflected energy leakage into other beams.

3.2. Measurement description

The measurement approach used in August 2002 was to mount the sonar on a buoy deployed in a stable 3-point moor, and use a fiber optic cable to control the sonar and upload data in real time. The sonar was pointed 30° down from the vertical rather than directly upward in an effort to reduce specular surface reflection contamination in all beams. The M/V Independence[1], a 61 m, 1798 ton research support boat ran over the top of the array several times, steering a course aligned with the main axis of the MB sonar. M/V Independence has a 12.2 m beam and a 4.1 m draft, and is driven by two 2.2 m diameter propellers. The propellers turn outboard; rotational speed during the runs was 288 rpm on both shafts; ship speed was 12 kts. Environmental conditions at the time were benign, with surface current less that 0.1 m/s and significant wave height about 0.25 m. The wind speed was 5 – 10 kts, but the measurement site was in the lee of San Clemente Island and the waves were fetch-limited. The sound speed profile featured a mixed layer down to about 7 m, and a thermocline below that extending to about 100 m depth.

3.3. Wake data

Fig. 5 shows a sequence of three MB sonar images projected onto a vertical plane containing the sonar and approximately perpendicular to the wake axis. The gray scale indicates echo level in dB relative to an arbitrary reference. The sonar is located at the origin and the ocean surface is marked with a dashed line. The top image was made before the ship passed over the sonar. In addition to a strong echo from the ocean surface (coincident with the dashed line), there is a line of echoes about 20 m long, parallel to the surface but about 4 m below it, which is due to specular reflection from the surface directly over the sonar. The surface above the sonar has been ensonified through a transmit side lobe at approximately 30° from the main lobe that is -19 dB down [8]. Note that both the specular surface reflection
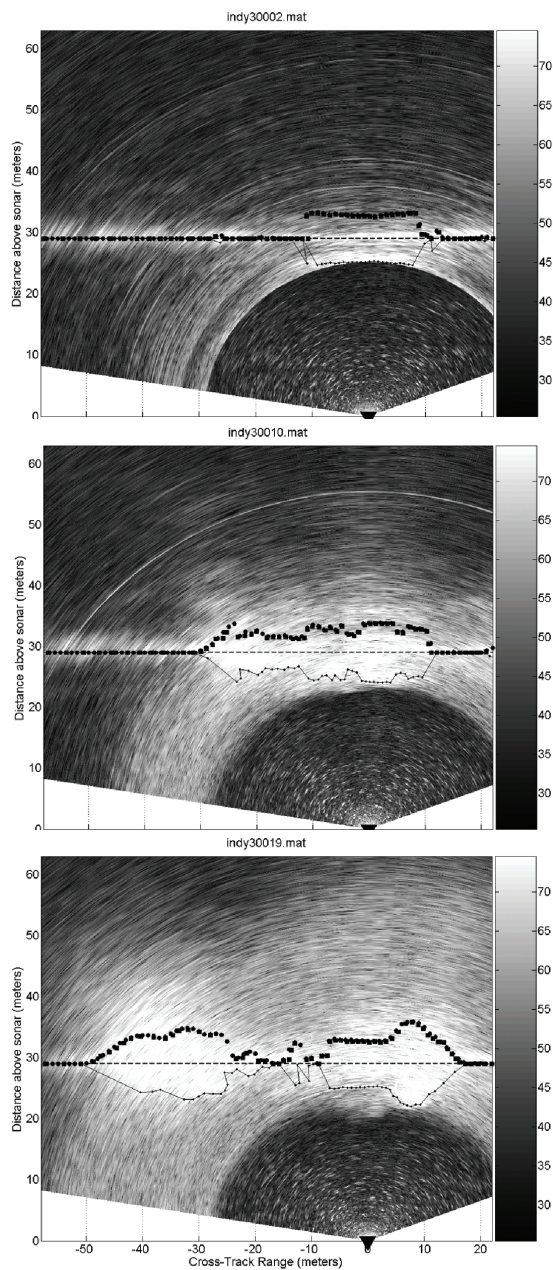

Fig. 5: Top: image made before the ship crossed over the array; middle: 20 s after M/V Independence passed over; Bottom: 200 s after ship passage.

and the off-specular surface echo contribute energy, indicating side lobe interference like that seen in the March 2000 data. Finally, a wake edge detection algorithm based upon the gradient of the echo energy produced the line connecting black dots.

The second image was made about 20 seconds after M/V Independence passed over the sonar. Echo strength is uncompensated for attenuation by the wake. Judging by where the echo is strong, the wake is about 35 m wide and centered about 8 m to the left of directly over the sonar. A semicircular band of energy extending across all beams is due to energy scattered by the wake entering through the side lobes of most of the receive beams. In many beams, it is difficult to distinguish between wake echo and leakage from the specular surface return directly over the sonar. The wake image extends above the surface. To understand this, the length of the path through the transmit main lobe to the surface, specularly reflected back to the wake edge, and scattered back along the same path was calculated. Most of the echo above the surface is within the boundary of this multipath. The multipath calculation assumed straight-line propagation and did not take into account refraction due to the sound speed profile, which is a possible reason for the wake echoes that are outside the multipath boundary.

The third image was made about 200 seconds after the second image. It shows that the center of the wake has drifted about 10 m to the left and that the two lobes have expanded outward. There is wake echo energy outside of the multipath range boundary, particularly at large receive beam angles. Using ray tracing rather than straight-line propagation to calculate the multipath boundary would extend the boundary outward, perhaps far enough to encompass the entire wake echo above the surface.

There are at least two other multipaths that can occur, considering only ensonification through the transmit main lobe. They are:

- Transmit array –> bubble scatter –> specular reflection at the surface –> receive array.
- Transmit array –>specular reflection at the surface –> bubble scatter –> receive array.

The first type always arrives at the receive array before the echo from the surface and thus interferes with echoes from the bubbles. The second type can arrive just prior to or just after the echo from the surface, and thus also interferes with the direct path echo.

4. CONCLUSIONS

Multi-beam sonars offer the obvious advantage of higher coverage rate relative to single beam sonars, and as such have proved quite useful for hydrographic applications. Their use for water column investigations has likewise yielded valuable information, but there are issues with multipath and surface specular returns through side lobes that must be addressed before MB sonars can provide unambiguous estimates of bubble distribution. Multipath energy must be accounted for, and even with the transmit beam pointed away from the surface, specular and near-specular echoes still get into all receive beams. The following suggestions are offered:

- Employ a baffle near the transmit array to attenuate the specular surface return.
- Use a longer transmit array that is shaded to reduce side lobe levels.
- Provide an option to record receive element levels so that the user can steer nulls or trade off receive beam width and side lobe levels.

5. ACKNOWLEDGEMENTS

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