3D Sonar Measurements in Wakes of Ships of Opportunity

Alex Soloviev[1], Chris Maingot[1], Mike Agor[2], Lou Nash[3], Keith Dixon[3]

[1]Nova Southeastern University Oceanographic Center, Dania Beach, Florida
[2]Coda Octopus Products Inc., Lakeland, Florida
[3]Measutronics Corporation, Lakeland, Florida

Corresponding author address and email:
Alex Soloviev
8000 North Ocean Drive,
Dania Beach, Fl 33004
soloviev@nova.edu

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Abstract

The aim of this work is to test the potential capabilities of 3D sonar technology for studying small-scale processes in the near surface layer of the ocean, using the centerline wake of ships of opportunity as the object of study. The first tests conducted in Tampa Bay, FL with the 3D sonar have demonstrated the ability of this technology to observe the shape of the centerline wake in great detail starting from centimeter scale, using air-bubbles as a proxy. An advantage of the 3D sonar technology is that it allows quantitative estimates of the ship wake geometry, which presents new opportunities for validation of hydrodynamic models of the ship wake. Three-dimensional sonar is also a potentially useful tool for studies of air-bubble dynamics and turbulence in breaking surface waves.

1. Introduction

The problem of ship and ship wake detection from space using synthetic aperture radar (SAR) has attracted attention since the launch of the NASA SEASAT satellite in 1978 (Fu and Holt 1982; Peltzer et al 1992, Reed and Milgram 2002). Monitoring of ships and ship wakes from satellites is a useful tool for fishing and pollution control, navigational safety, and global security.

The problem of ship detection involves a variety of topics including ship and ship wake hydrodynamics, wind-wave conditions, surface films, radar imaging, image processing, and pattern recognition (Hyman 2000; Benilov 2001; Reed and Milgram 2002; Crisp 2004; Zilman 2004; Vachon 2006; Soomere 2007; Soloviev et al. 2008).

A typical ship wake consists of a bow Kelvin wave, stern Kelvin wave, transverse Kelvin wave, centerline wake, and a turbulent region adjacent to the ship (Pichel et al., 2004). The centerline ship wake usually appears in SAR images as a dark scar. The dark appearance of the centerline wake is associated with the reduction of surface roughness due to the suppression of short (Bragg-scattering) surface waves by surfactants, wave-current interactions, and turbulence in the wake. The centerline wake can sometimes be traced for tens of kilometers behind the moving ship (Fig. 1a). In some cases, however, the wake is not prominent in SAR (Fig. 1b).

Recent advances in satellite technology have improved the capabilities of SAR for identifying sea surface features including ships and ship wakes (Brusch et al. 2010; Soloviev et al. 2010). In addition to SAR, infrared and optical imaging has been implemented in ship wake studies both in the field and laboratory (Garrett and Smith

1984; Munk et al. 1987; Brown et al. 1989; Zheng et al. 2001; Gilman et al. 2011; Voropayev et al. 2011).

Hydrodynamic models of the centerline wake attuned to remote sensing techniques provide a new insight into the problem of ship and ship wake detection from space (Fujimura et al. 2010; 2011). These models, however, require validation with in-situ measurements. Unfortunately, direct measurement of the velocity field in far wakes with conventional current-measuring technologies is difficult due to the relatively small velocity magnitudes and significant distortions from the orbital velocities of surface waves. One approach to validating these numerical models is through the use of sonar systems to provide an underwater view of the wake.

The presence of bubbles within the wake allow for imaging of the wake with sonar, which responds to a certain bubble size depending on the sonar frequency (Weber et al 2005). Bubbles within the wake are also believed to be an important factor in the visibility of the ship wake in SAR due to the scavenging of surfactants and transporting them to the sea surface. The surfactants suppress short gravity capillary waves, which makes the wake visible in SAR (Peltzer et al 1992). Soloviev et al. (2010) reported a case study that observed a correlation between the visibility of the centerline ship wake in SAR and in sonar, using bubbles, which provides additional evidence of the role of bubbles in remote sensing of ship wakes.

In this paper we present the results of ship wake imaging with 3D sonar using the shape of the air bubble clouds as a proxy for the turbulent wake. In Section 2, we provide a brief description of the 3D sonar technology and its application for measurements in ship wakes. Section 3 is a comparison of our results to other available laboratory and field data and numerical models on the 3D structure of the centerline ship wake. Section 4 is the discussion, and Section 5 summarizes the main results of this work.

2. 3D sonar and measurements in ship wakes

For tests in the wakes of ships of opportunity, we have employed a real-time 3D imaging system, Coda Octopus Endoscope™-UIS™ (Underwater Inspection System). The sonar has a working frequency of 375 kHz with a 128x128 (16,384) array of beams, which provide an angular coverage of 50°x50° and a beam spacing of 0.39°. The maximum range is 150 m with a range resolution of 3 cm, and ping rate of 12 Hz. More technical details about the sonar can be found at http://www.codaoctopus.com/echoscope-uis/.

The 3D aspect allows high resolution visualization to be performed from multiple perspectives (so-called mosaic view). Three dimensional images are formed through combining multiple 2D fragments taken from different angles due to the motion of the object with respect to the sonar. The addition of an attitude and positioning system allows the data to be located accurately in 3D space and referenced to the Earth's coordinate system. In order to determine the 3D shape of the wake, we have used the edge detection mode of the sonar.

The tests have been conducted in Tampa Bay, Florida with the help of Measutronics Corporation (http://Measutronics.com). The sonar was attached to the survey vessel "A Nickel More" using a retractable mount (Fig. 2). During the tests, local ships were tracked using an automatic information system (AIS). This system allowed us to identify the approaching ships and also record information about speed, heading, length, and other parameters.

Figure 3 demonstrates the sonar data during the passage of a tugboat in the Tampa Bay Port Channel. The survey vessel equipped with the sonar system was moving on an opposite course at a 5 knot speed. A view of the tugboat from the video camera is shown in Figure 3a. The sonar image of the tugboat wake is shown in Figure 3b.

A segment of the tugboat wake visualized with the 3D sonar is shown in more detail in Figure 4. This image displays a strong intermittency of the wake shape, while turbulent features are resolved starting from centimeter scale. Note that surface reflections have been removed from Figure 4, whereas they are still present in Figure 3b.

Figure 5 shows a snapshot taken from the video record of the cargo ship *Alert* above the water surface with synchronous 3D sonar image below the water surface. Data from the AIS for this vessel gives a length of 128 m, a beam of 21 m, a draught of 7.3 m, and a heading of 85° at 11.2 knots during the time of the survey. This cargo ship has a bulbous bow. For this example, we can trace the origin of the bubble curtain around the hull to the bulbous bow breaking wave and bow breaking wave.

Figure 6 shows the ship stern and wakes produced by the hull and propeller in 2D view. Due to the relatively slow propeller rotation rate, it is possible to see even the propeller on these sonar images.

The side view of the ship wake in mosaic mode is shown in Figure 7. The ship wake has red/orange color and the bottom blue/green color, which is due to different distances from the sonar. As illustrated in Figure 7, the mosaic mode allows the possibility of quantitative estimates of the ship wake geometry.

A bird's eye view of the *Alert's* wake is shown in Figure 8. Note that in edge detection mode, we can only image the outer face of the wake. The image in Figure 8 displays the latter portion of the wake, showing the fragmentation and gradual dissipation of the bubble clouds associated with the wake.

3. Comparison to laboratory, field, and modeling results

In this section we compare the results of the 3D sonar field tests with recent laboratory, field, and modeling results on ship wake dynamics. A review of the previous research for studying ship wakes can be found in Reed and Milgram (2002) and Soloviev et al. (2010).

a) Laboratory Results

Voropayev et al. (2011) performed a series of laboratory experiments to study the surface signatures of ship centerline wakes. The experiment was conducted in a tank with temperature stratified water. The wake was created with a self propelled ship model. An infrared camera registered the signature of the wake in the temperature field on the water surface. The experiments were conducted with distilled water to minimize surfactant effects. From these experiments the temperature signature of the wake revealed meandering, instability, and fragmentation increasing with distance from the model ship. After re-scaling, these laboratory results are consistent with the wake observations made with the 3D sonar system in our experiments in Tampa Bay.

b) Dye Release Experiment

Woods Hole Oceanographic Institution (WHOI) conducted an experiment using an airborne Light Detection and Ranging instrument (LIDAR) to map fluorescent dye released in the centerline wake of Florida Atlantic University's research vessel, *R/V Stephan* (Ledwell and Terray, private communication). In this experiment, conducted in the Straits of Florida, the airplane flew back and forth over the centerline ship wake, measuring the wake structure with the LIDAR instrument. Data collected by LIDAR showed meandering, instability, fragmentation, and disappearing of the ship wake over time. Although the environmental conditions in the Straits of Florida are different from those in Tampa Bay, our results from the 3D sonar experiment in ship wakes are qualitatively consistent with the WHOI dye release experiment.

c) 3D Ship Wake Numerical Simulation

Fujimura et al. (2011) conducted high-resolution numerical experiments with the computational fluid dynamics (CFD) software ANSYS FLUENT on the dynamics of centerline ship wakes in the presence of near-surface stratification and wind stress. The ship wake model was initialized using a model of a ship hull and propellers. The modeling results reveal characteristic features of the centerline wake (meandering, instability, fragmentation, and dissipation). Our 3D sonar measurements provide qualitative validation for the modeling results. Quantitative validation is beyond the scope of this paper.

4. Discussion

The above mentioned laboratory, field, and numerical results are qualitatively consistent with our experiments with 3D sonar in wakes of ships of opportunity. The 3D sonar technology greatly enhances the capabilities in studying ship wakes. The application of 3D sonar has provided spatial structure of the ship wake in great detail starting from a centimeter scale using air bubbles as a proxy. It should be noted that the air bubbles in the wake may not exactly characterize the velocity field in the wake due to their rising to the surface or dissolution. However, the bubbles bring surface active materials to the surface, which suppress short gravity capillary waves thus providing a link between the wake's visibility in sonar and in space born SAR.

Three dimensional images obtained during our measurements of a large cargo vessel's wake (Figs.5-8) have elucidated the process of air entrainment by the ship's hull. The relatively slow revolution rate of the propeller of this ship has also allowed us to visualize the propeller jet in great detail. The air entrainment for this type of hull and propulsion system, however, occurs predominately at the bow of the ship and along the hull sides.

Our experiments with 3D sonar have also revealed intermittency in the ship wake similar to that previously observed in the numerical model, laboratory experiments, and field dye release experiment. With the 3D sonar technology, we have been able to explore the subsurface features of the wake in the field in three dimensions and in great detail. The mosaic mode allows the possibility of quantitative estimates of the ship wake geometry and visualization of the wake's generation, fragmentation, and disappearance. The 3D sonar technology provides a new insight into ship wake dynamics. These observations are useful for validation of hydrodynamic models, with application to remote sensing of ship wakes. The 3D sonar technology using edge detection of bubble clouds may also provide important insight into the mechanism of surface wave breaking and upper ocean turbulence generation.

5. Conclusions

In this article, we have demonstrated the application of 3D sonar technology to study fine scale processes in wakes of ships. Sonar responds to air bubbles in the wake; the bubbles in the wake also contribute to the wake's visibility in SAR by bringing surfactants to the surface and suppressing short (Bragg scattering) gravity capillary waves. The first application of 3D sonar has made the spatial structure of the ship wake observable in great detail starting from a centimeter scale using air bubbles as a proxy. The tests in Tampa Bay, FL in wakes of ships of opportunity suggest that 3D sonar technology will be useful for validation of hydrodynamic models with application to remote sensing of ship wakes. The 3D sonar technology may also be helpful in quantifying turbulence in air-bubble clouds, such as breaking surface waves.

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Figures

Fig. 1. ALOS PALSAR images taken in the Straits of Florida with (a) prominent and (b) almost invisible wakes behind moving ships.

Fig. 2. The CodaOctopus Endoscope™-UIS™ (Underwater Inspection System): (a) survey vessel “A Nickel More”, (b) the real time kinematic GPS system and video cameras, (c) 3D sonar transducer.

Fig. 3. (a) Tugboat and (b) its wake in 3D sonar. Distance to the object is color coded.

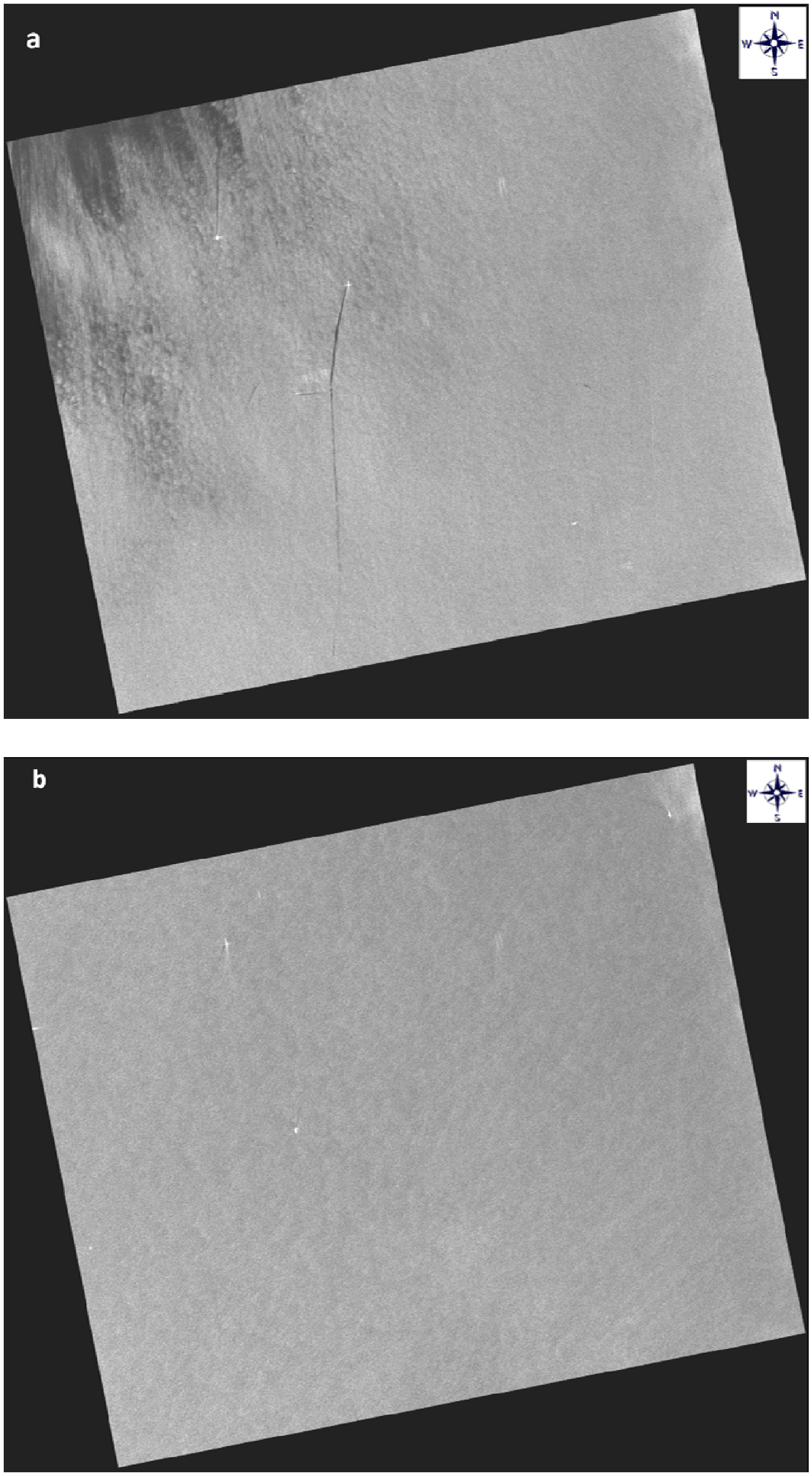
Fig. 4. Tugboat wake in 3D sonar image in more detail. The image is color coded by distance from the sonar.

Fig. 5. Bubble cloud around *Alert’s* hull.

Fig. 6. Bubbles in *Alert’s* hull and propeller wake (2D view).

Fig. 7. Wake geometry of the cargo ship *Alert*.

Fig. 8. Aerial view of *Alert’s* wake in 3D. The ship wake has brown color and the bottom blue color, which is due to different distances from the sonar.



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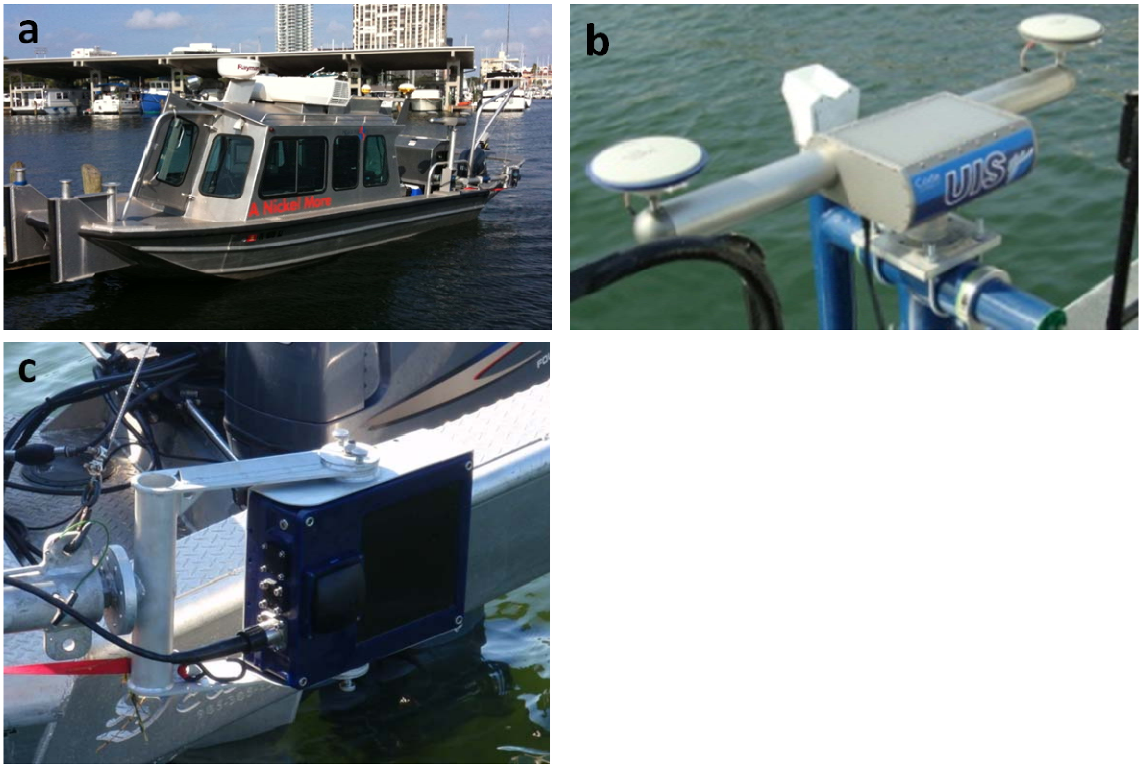

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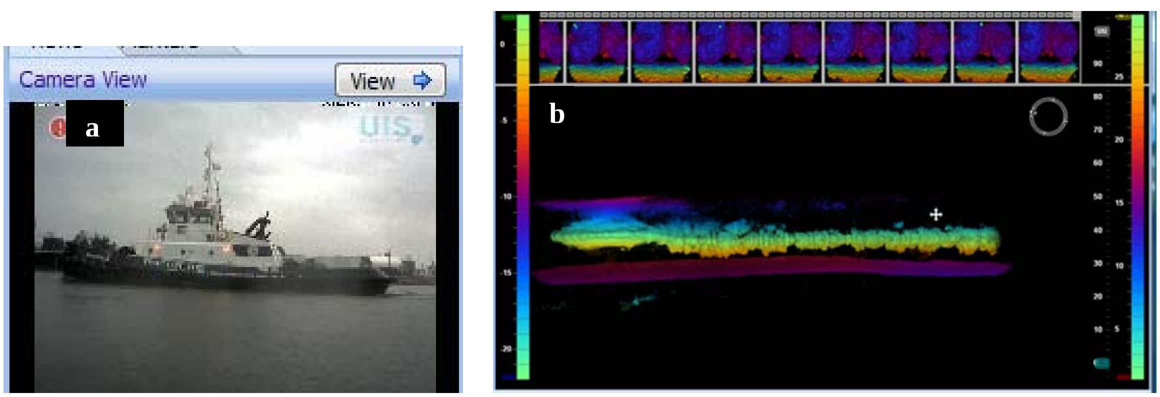

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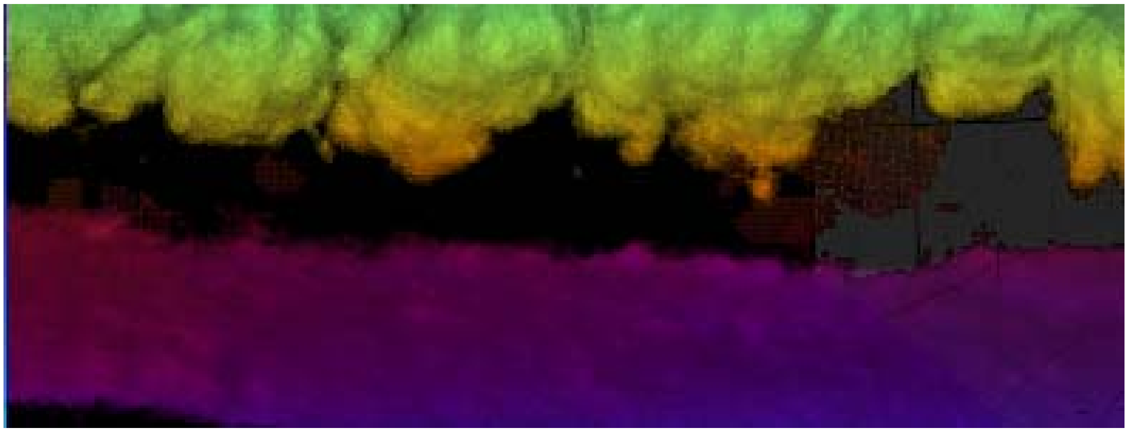

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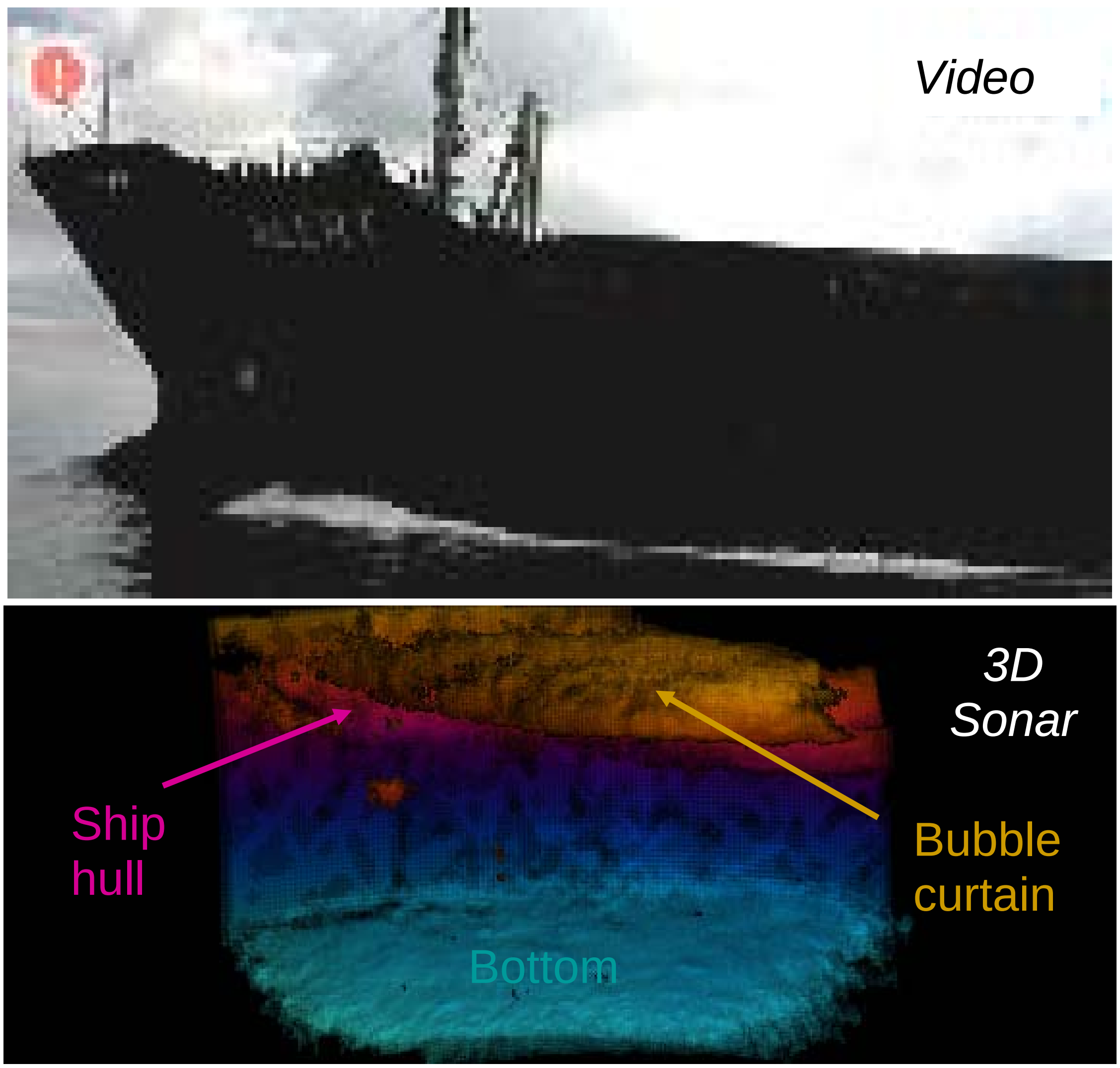
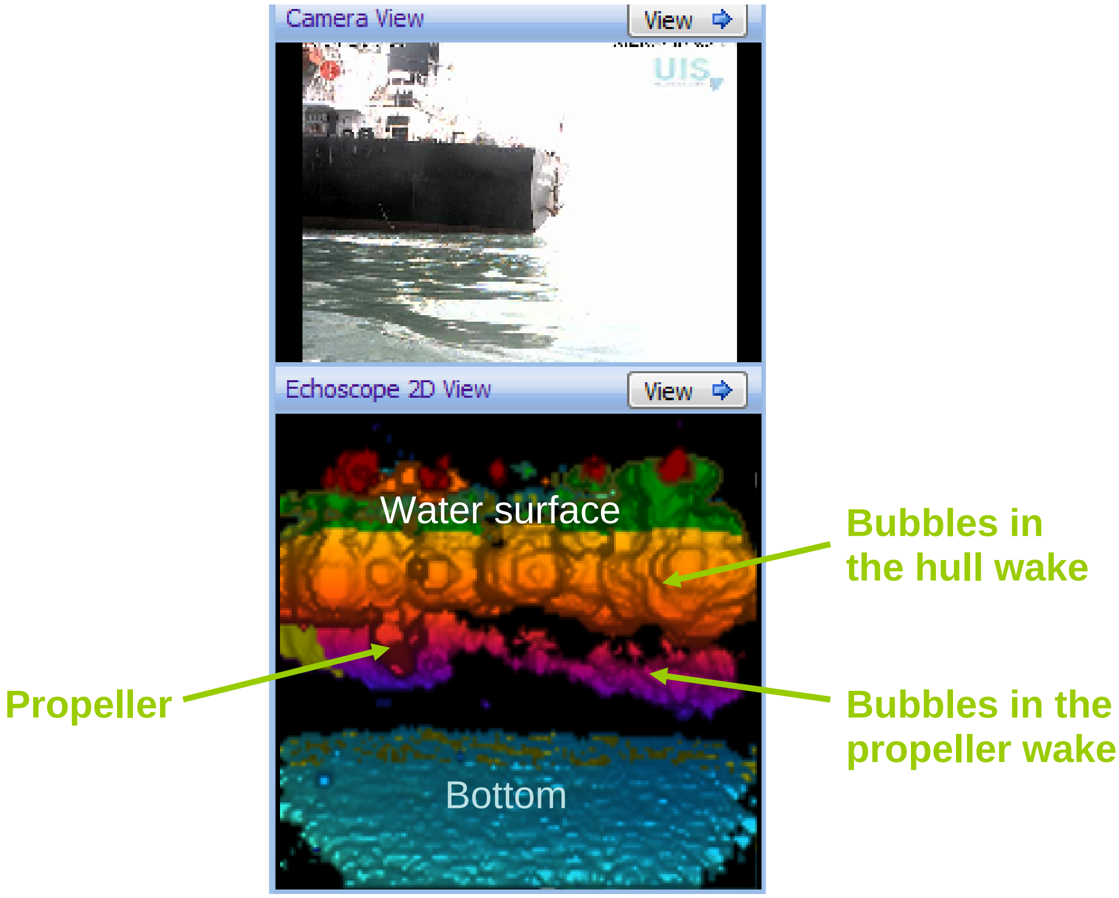


Fig. 5. Bubble cloud around *Alert's* hull.



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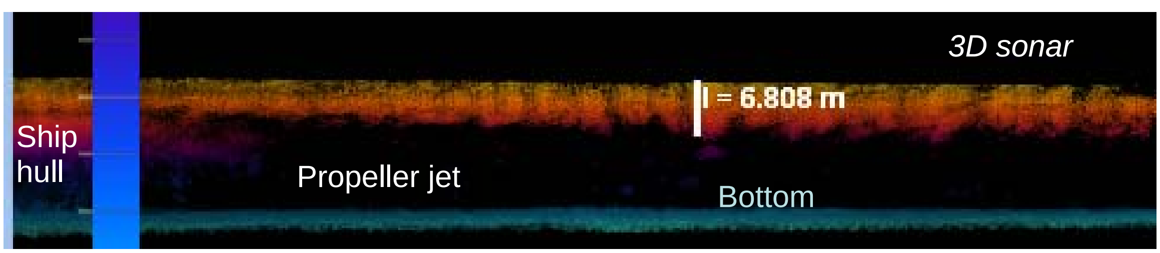

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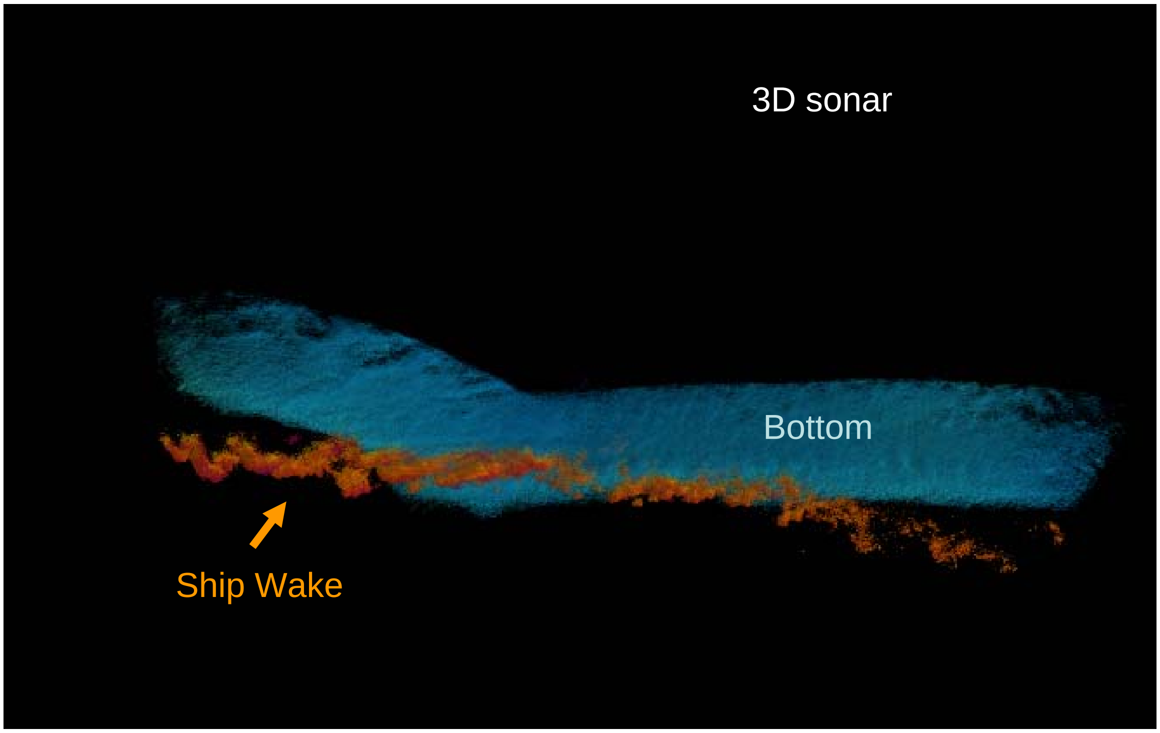

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