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Characterization of the Bubble Flow and Transom Wave of the R/V Athena I

by

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14. ABSTRACT
The bubble flow and transom wave associated with the naval research vessel Athena I was characterized during a field experiment conducted in June 2005 by several research groups. The bubbly flow around the passing ship was documented by stationary divers using underwater cameras. The free surface behind the ship was characterized in the near field using Quantitative Visualization, a laser-imaging technique developed and used by the Naval Surface Warfare Center, Carderock Division. The far-field transom wave was quantified using LIDAR instrumentation operated by the Scripps Institution of Oceanography. Results from the near and far-field measurements in the stern, along with images of from underwater video, are given in the report. The overall objective of the current experiment was to obtain full-scale qualitative and quantitative breaking wave field data of the naval combatant surface ship for use in CFD code development and validation.

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Abstract

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Administrative Information

The work described in this report was performed by the Maneuvering and Control (Code 5600) and Resistance and Powering (Code 5200) Divisions of the Hydromechanics Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD), the Scripps Institution of Oceanography, San Diego, California, and the Chemical Engineering Department at the University of California, Davis, California. This work was funded by the Office of Naval Research, contract number N0001405WX20449. Dr. L. Patrick Purtell is the program manager.

Acknowledgements

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Introduction

The flow around a ship as it moves through the water is a complex, unsteady, three-dimensional hydrodynamic phenomenon made up of breaking waves, bubbly flows and spray. The characteristics of this flow depend not only on the ship's forward speed and geometry but also on the ship's motion and on the incident seaway and ambient water chemistry. While there has been an accumulation of data on bow waves at both model and full scale (1, 2), much less is known about the fine temporal and spatial scale of free surface fluctuations in the transom region of wet transom ships. During the 2004 Athena cruise, preliminary LIDAR data were taken and demonstrated that

Ship Speed (kt)	Ship Speed (m/s)	Fr_L	Fr_D
6	3.1	0.14	0.6
9	4.6	0.21	0.8
10.5	5.4	0.24	1.0
18	9.3	0.42	1.7
26	13.4	0.60	2.5

Table 1. Test Conditions

high resolution information could be obtained using scanning laser techniques. In the current 2005 test, detailed transom data were taken along with underwater video of the *Athena*.

The overall objective of the current experiment is to obtain full-scale qualitative and quantitative breaking wave field data of a naval combatant surface ship for use in CFD code development and validation. The experiment allows for the investigation of source mechanisms of bubble generation and bubble entrainment, as well as the investigation of the effect of field conditions, including ambient waves, on the transom wave. To achieve these goals, researchers obtained flow visualization of the bubbly flow close to the hull, as the *R/V Athena* passed a stationary observer, and characterized the free-surface elevation of the transom wave just astern of the *R/V Athena* at several speeds in calm water (minimum ship motion) and ambient waves.

Field Experiment Description

In this field experiment, conducted in June 2005, measurements of the free surface in the transom region of the *R/V Athena* were made at various speeds. Table 1 lists the test conditions; not all measurements were taken at all speeds. The sections below describe the test platform as well as the various measurements.

Test Platform

The *R/V Athena I* is a converted PG-84 class patrol boat built in 1969 and converted to a research vessel in 1976 (Figure 1). She has an aluminum hull and an aluminum and fiberglass superstructure. Measurements and details for the *R/V Athena* are listed in Table 2. Figure 2 shows the vessel profile and layout.

Quantitative Visualization (QViz) of Free Surface

Technique Description

A non-intrusive optical technique, Quantitative Visualization (QViz), has been used to measure the free-surface disturbances occurring in regions commonly inaccessible to more traditional measurement methods, i.e. near wake flows, bow sheets and breaking waves. These regions are generally difficult to quantify due to the multiphase aspect of

Figure 1. *R/V Athena* photograph.

Table 2. *R/V Athena* Details

Length Overall	50.3 m (165 ft)
Extreme Beam	7.3 m (24 ft)
Draft	3.2 m (10.5 ft)
Propulsion	Twin screw, twin diesel (low speed) Gas Turbine (high speed)
Speed	12 knots (diesel) 35 knots (turbine)
Range	2300 n.m. at 13 knots

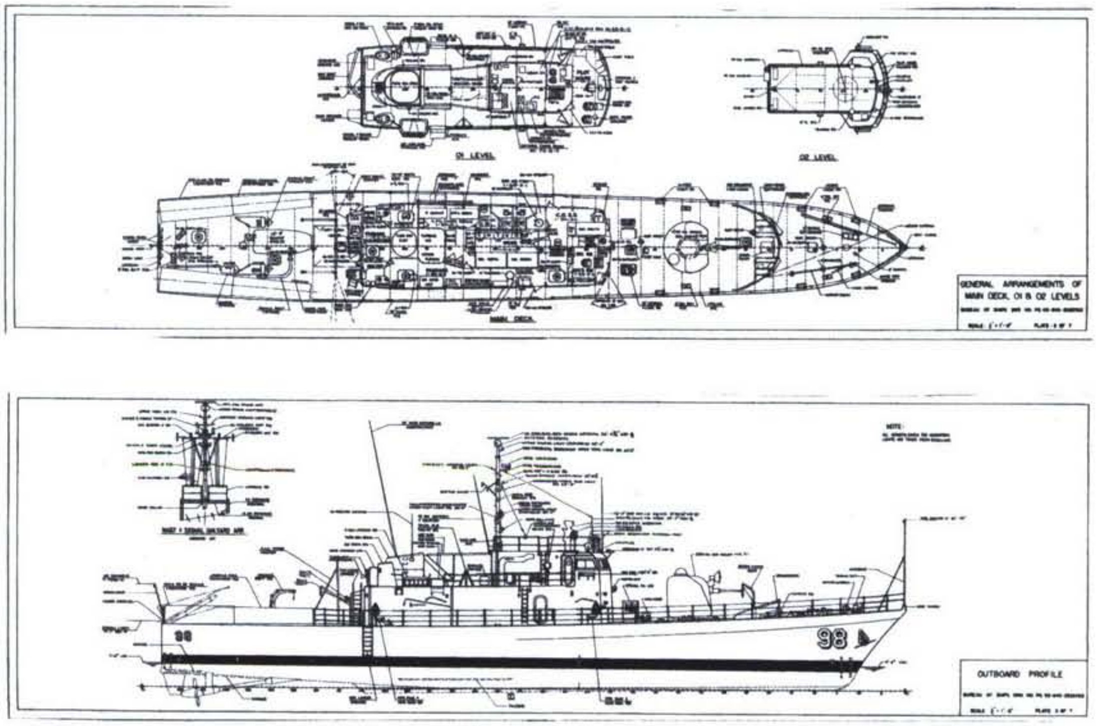

Figure 2. *R/V Athena* profile and layout.

the flow as well as their very unsteady nature. However, the unsteady surfaces, droplets and bubbles in these regions are effective scatterers and allow for optical imaging of the deformations in the surface. With a laser sheet and digital camera, the QViz system illuminates the surface of interest and collects digital images representing instantaneous cross sections of the spray envelope and surface profiles (3).

Setup

In the current experiment, QViz was used to determine the free-surface height close to the stern at ship speeds of 6, 9, and 10.5 knots (3.1, 4.6, and 5.4 m/s). A laser light sheet was projected onto the water surface perpendicular to the transom and moved incrementally from port to starboard to cover the transom area. The light sheet was generated by a diode-pumped, solid-state YAG laser, with an output of 2.5–3.5 W at 532 nm (Model MLM-0532 by Melles-Griot), and a scanning mirror. Two progressive scan video cameras were mounted next to each other off of the stern, facing the laser sheet, and angled down 45 degrees towards the water. They captured images of the laser sheet reflection off of the water surface. The two cameras were 43 cm (17 in) apart; their views overlapped so that they both captured the free surface at the center of the light sheet. The cameras initially faced starboard, and were moved outboard (in the starboard direction) in conjunction with the laser to capture data at various lateral positions. After capturing images at five laser sheet positions, the

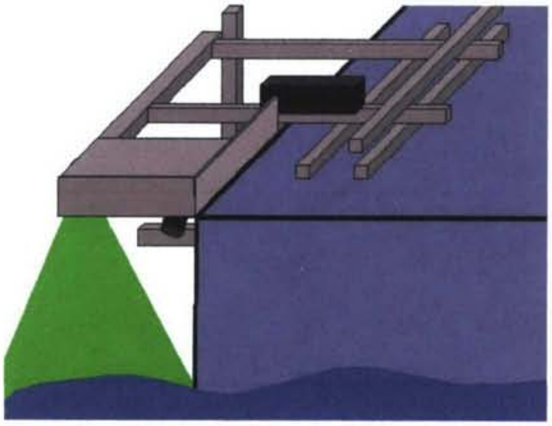

Figure 3. Illustration of the Quantitative Visualization (QViz) setup off the stern of the *R/V Athena.*

system was reversed so that the cameras were facing port and images were captured at five additional positions.

The coverage area for the QViz system was 2.3 m (7.6 ft) (lateral) x 1.7 m (5.7 ft) (axial). The laser sheet was 1.7 m (5.7 ft) wide and incremented laterally at 30 cm (12 in) spacing. Two minutes of data were taken at each position, at 30 frames per second, resulting in 3600 frames at each of ten locations. Figures 3 and 4 are diagrams of the QViz setup on the transom.

Digital images from the video cameras were collected at 30 frames per second using a National Instruments frame-grabber board and a personal computer. An image analysis program was developed using the Mathworks Matlab Image Processing Toolbox to extract the surface profile information. Images were analyzed using image filtering and search routines to identify the boundary of the free surface. The image size was 640×480 pixels, covering a viewing area of approximately 1.2×0.9 meters. Thus the lowest possible uncertainty (approximately one pixel) was equal to 0.2 cm. The resulting wave profiles were averaged to generate the free-surface profiles shown in the Results section.

Calibration

Distortion due to camera placement and viewing angle was corrected using an image of a calibration grid with equally spaced points and a calibration algorithm written using Matlab. The largest error in the system was introduced by the camera placement and the calibration method. For example, error in the calibration would result if the calibration grid was not held perfectly square and at the correct distance relative to the camera. A plumb bob was used as a reference to a known location relative to the ship; an image of the plumb bob was used to calibrate the free-surface location. Error in this system resulted from motion in the ship and the plumb bob. It is estimated from the

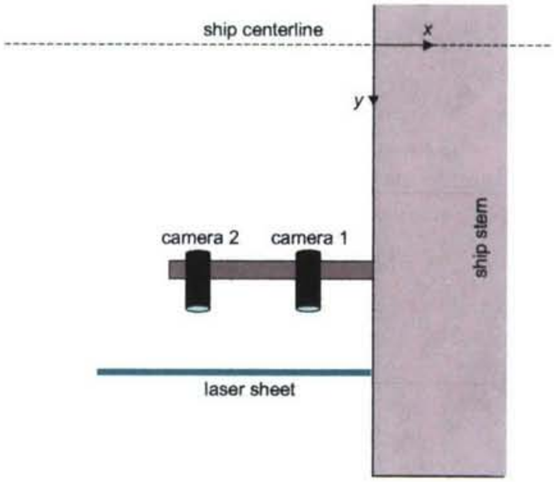

Figure 4. Schematic diagram of the Quantitative Visualization (QViz) cameras and laser light sheet.

calibration and plumb bob images for the two cameras that the maximum error on the location of the free-surface elevations is ± 3 cm. However, this is an error affecting the determination of the absolute horizontal location of the free surface. The error in the free-surface measurement in the vertical dimension is estimated at ± 0.5 cm. This is because the reference used for the vertical dimension was the laser sheet itself in calm water, which was a more accurate measurement.

LIDAR Measurement of Far-Field Free Surface

The Scripps Scanning Laser Altimeter System is designed for rapid and accurate measurement of the water's free surface. The system is composed of a Riegl LMS-Q140I-80 lidar unit, an electronically controlled pan/tilt unit, a 6-DOF motion package, a tower-based mounting system, cabling, a bore-sited camera and a data acquisition and recording unit. The scanning laser is classified as CLASS 1 eye safe.

The unit was mounted as shown in Figure 5 on the Athena transom. The coverage area for the LIDAR system was 6.1 m (20 ft) (lateral) $\times$ 0.3 cm (0.01 ft) (axial). Spatial resolution and accuracy was ± 2.5 cm (± 1 in), the sampling rate was from one to forty scans per second. Sixty seconds of data were taken at each speed for 900 frames.

Flow Visualization (Underwater Video) of Underwater Bubbles

Standard frame rate (30 fps) digital video was used to record the wetted hull surface from bow to stern. Flow visualization was performed approximately 20 nautical miles south of Pass entrance to ensure high water clarity and was done near mid-day to maximize ambient light levels.

Images at 30 frames per second were taken by an underwater diver, fixed in space, as

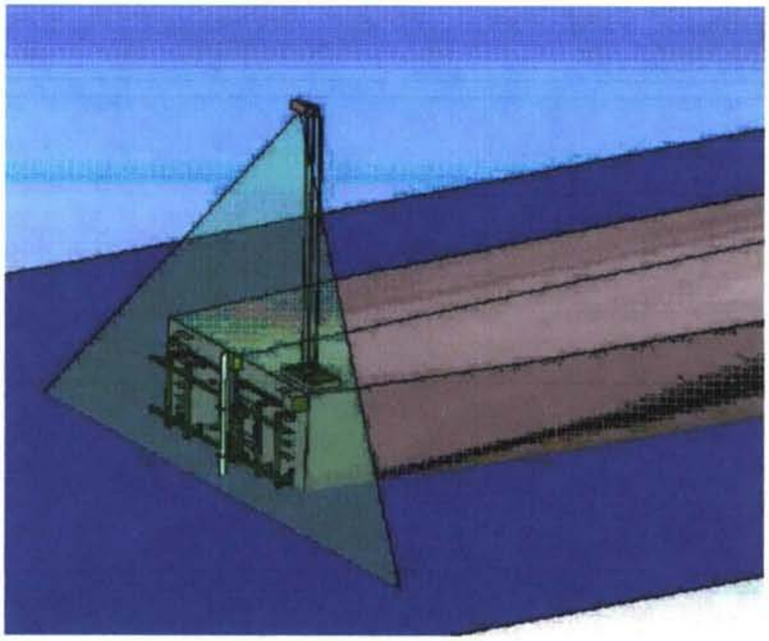

Figure 5. Diagram of LIDAR setup on the stern of the *R/V Athena*.

the ship passed nearby. A frame shown in Figure 6 was deployed prior to the runs, along with divers at that location, which remained constant. The ship then passed, at speed, between the buoys at the top of the frame. Video of the entire ship passage was recorded at each ship speed, documenting bubble generation and entrainment surrounding the ship.

Results

This section presents the results from QViz measurements and examples of the LIDAR measurements, in addition to images taken using the underwater video flow visualization.

Quantitative Visualization (QViz) of Free Surface

Free-surface profiles generated using data from the Quantitative Visualization (QViz) experimental technique are presented in Figures 7 through 9. The profiles show free-surface elevations in centimeters, referenced to the still water level, from immediately behind the stern of the ship to approximately 1.7 m behind the stern. Profiles generated from images taken while the cameras were facing port are slightly shorter, because the field of view was smaller. The lateral y location for each profile is specified to the left of the graphs, and is given in meters from the centerline. Data were only taken on the starboard side of the centerline.

The profiles were generated by averaging the free-surface profiles from every image frame taken from the camera at a given y location, regardless of head or following seas.

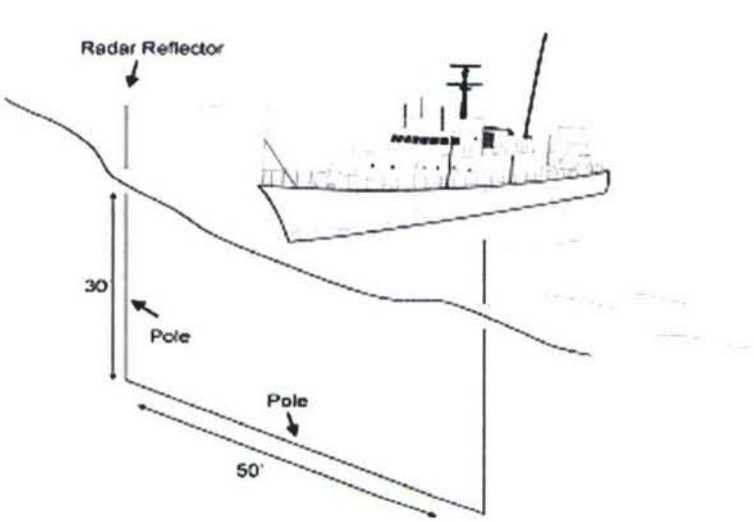

Figure 6. Flow visualization operational diagram.

The mean profiles from each of the two cameras were then averaged to generate the complete profile. The profiles from the two cameras overlapped between approximately 0.3 and 1.1 m aft of the stern.

It can be seen in the free-surface profiles (Figures 7 through 9) that transom submergence decreases with speed. Figure 10 shows the mean free-surface height (with the mean taken over all the transverse, or y, positions) at the transom ($x \approx 0$); this figure illustrates more clearly that the water level at the transom decreases with speed. This observation agrees with the qualitative observation that the transom becomes dry around 12 knots, or Fr=0.28. Figure 10 also shows the peak-to-trough amplitude of the transom wave, averaged over all the transverse locations, illustrating the substantial increase in the amplitude of the transom breaking wave with speed. Also, the free-surface profiles (Figures 7 – 9) illustrate the increased unsteadiness of the breaking compared to the non-breaking regions, as it manifests itself as the small fluctuations in the mean profiles versus the smoother portions of the profiles. In the future we will attempt to characterize these free-surface fluctuations, both spatially and temporally.

LIDAR Measurement of Far-Field Free Surface

Figure 11 shows a contour plot of the free surface behind the stern of the *R/V Athena* at 26 knots, generated by the LIDAR data obtained in this field experiment. Figure 12 shows mean wake profiles and standard deviation approximately 2.8 m aft of the stern in following seas, while Figure 13 shows a pseudo-color time-series of wave elevation at the stern in head seas; both are at a ship speed of 10.5 knots.

Flow Visualization (Underwater Video) of Underwater Bubbles

Images from video taken by divers are shown in Figure 14 at three locations as the ship passed. This video provides some qualitative insight into air entrainment and

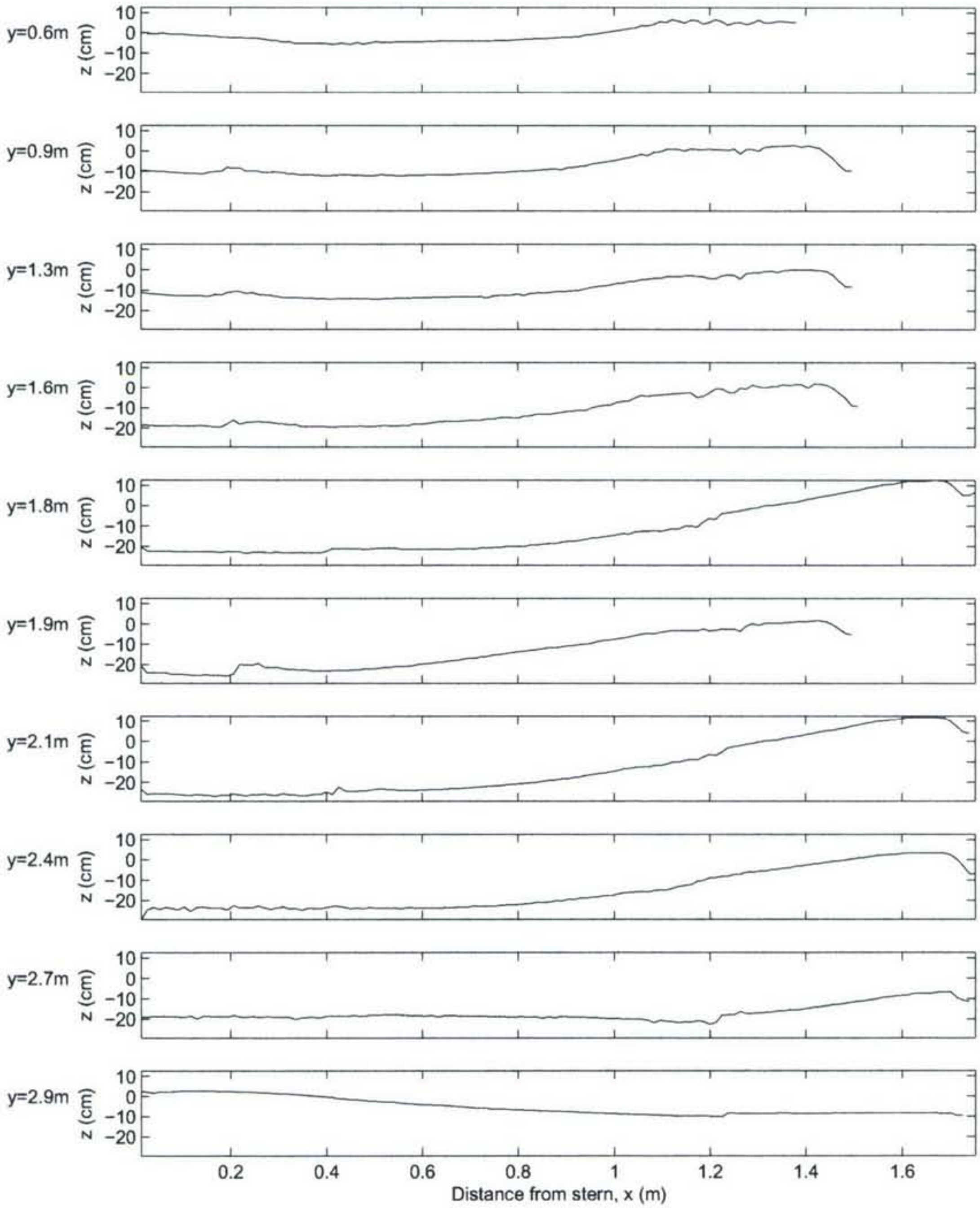

Figure 7. Profiles of free-surface elevations at 10.5 knots (5.4 m/s) at each of ten locations behind the stern.

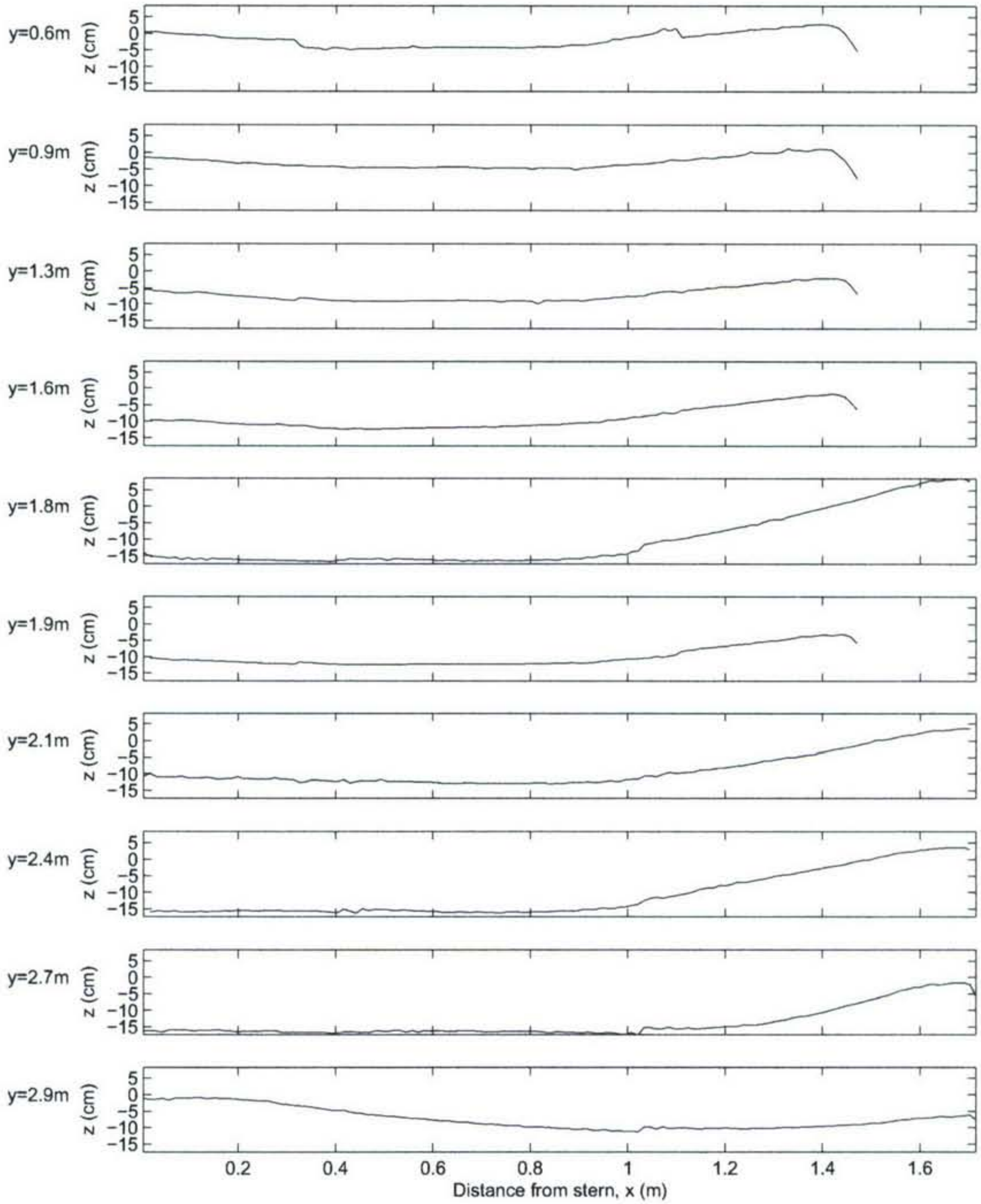

Figure 8. Profiles of free-surface elevations at 9 knots (4.6 m/s) at each of ten locations behind the stern.

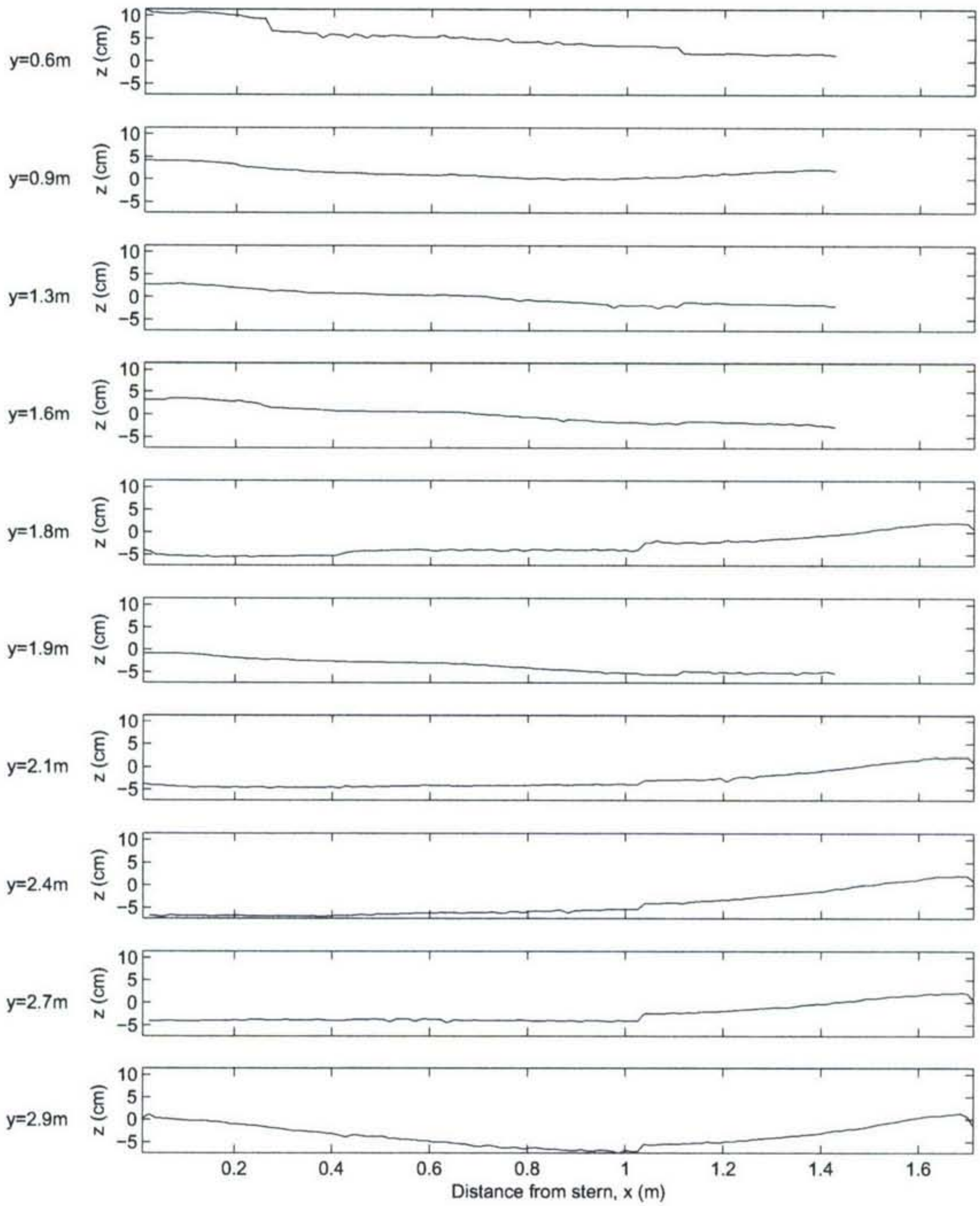

Figure 9. Profiles of free-surface elevations at 6 knots (3.1 m/s) at each of ten locations behind the stern.

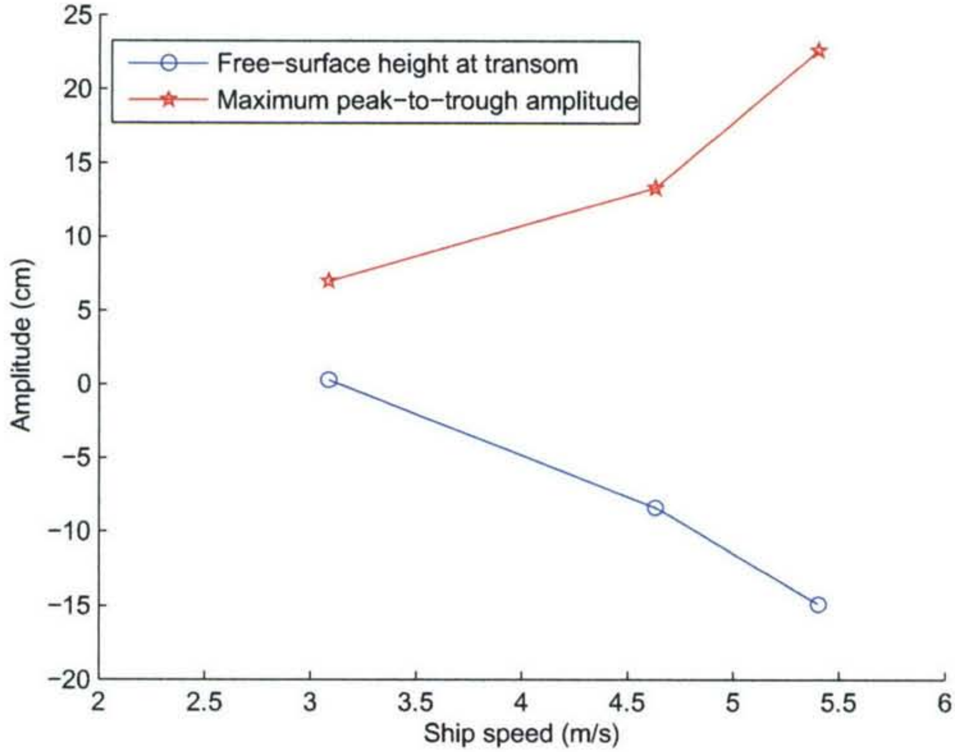

Figure 10. The free-surface height at the transom and the maximum peak-to-trough amplitude averaged over all transverse positions, as a function of ship speed.

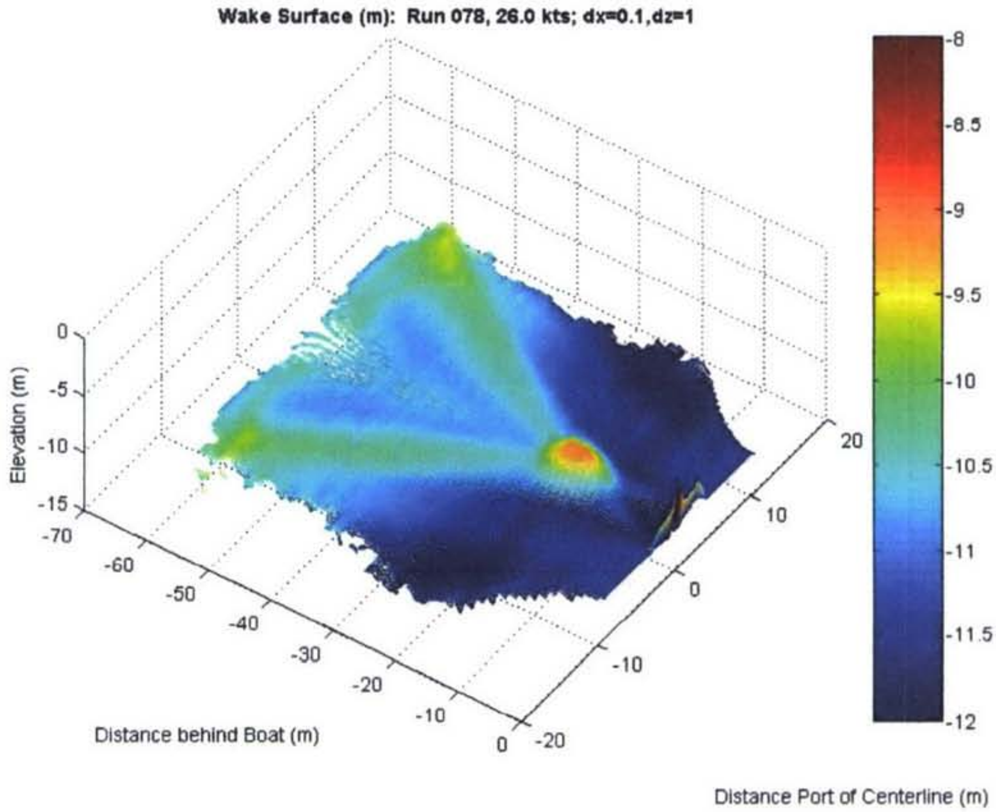

Figure 11. Sample result from LIDAR measurement, showing contours of free-surface height in the transom region.

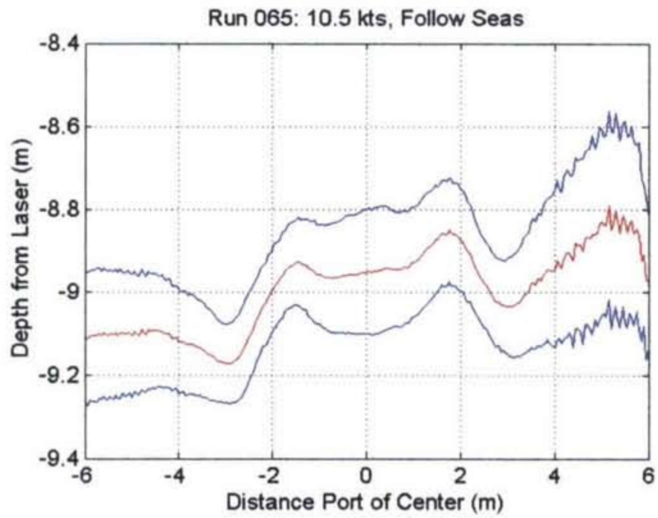

Figure 12. Mean wake profiles (red) and standard deviation (blue) approximately 2.8 m aft of the stern at 10.5 knots (5.4 m/s) in following seas.

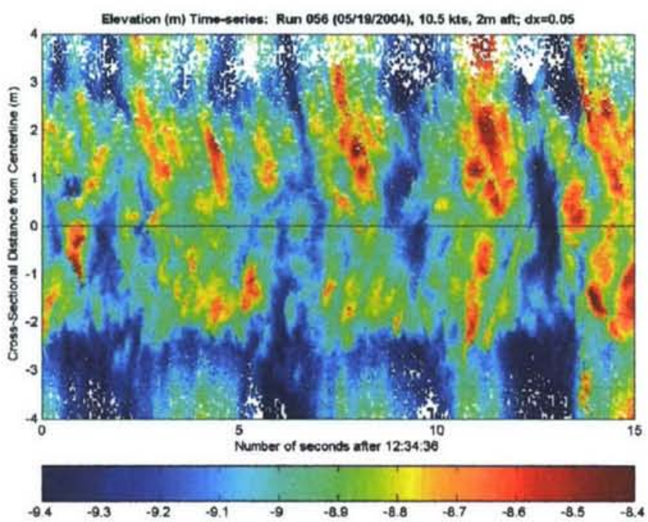

Figure 13. Pseudo-color time-series of wave elevation at the stern of the *R/V Athena*. Ship speed is 10.5 knots (5.4 m/s), heading is head seas.

bubble generation by a passing ship.

Conclusions

While high-resolution measurements of full-scale bow waves and low-resolution measurements of transom breaking waves have been made in the past, this was the first set of high resolution (approximately 0.2 cm spatially at 30 hz) measurements of the breaking transom wave of a full-scale ship. It again demonstrates the ability of the Quantitative Visualization (QViz) system to work successfully at full-scale in the field.

The data taken at 6, 9, and 10.5 knots in calm field conditions complement NSWC model 5365 data taken in the tow tank at similar Froude scaled speeds. Figures 15 through 18 show images taken from above-water video of the transom of the *R/V Athena* at model and full-scale. These figures show frames from the video of the transom at 10.5 (fully wet transom) and 18 knots (fully dry transom). The images confirm that the transom transitions from wet to dry between these two speeds. They also provide a useful qualitative comparison between model scale and full scale. The current test data will allow for continued CFD development, by providing free-surface elevation data sets of the transom region at full scale.

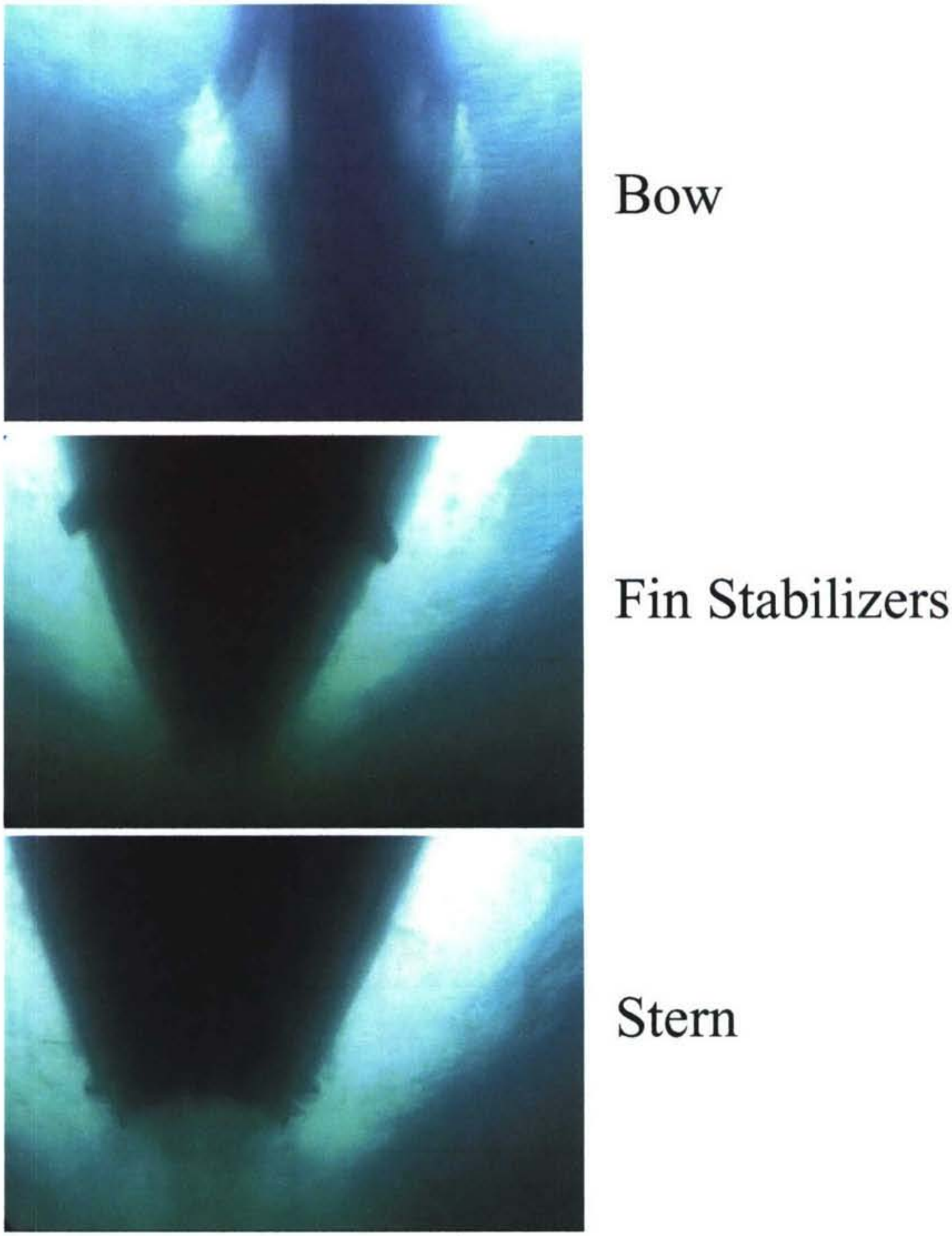

Figure 14. Three images from the underwater video taken by divers taken as the *R/V Athena* passed by.

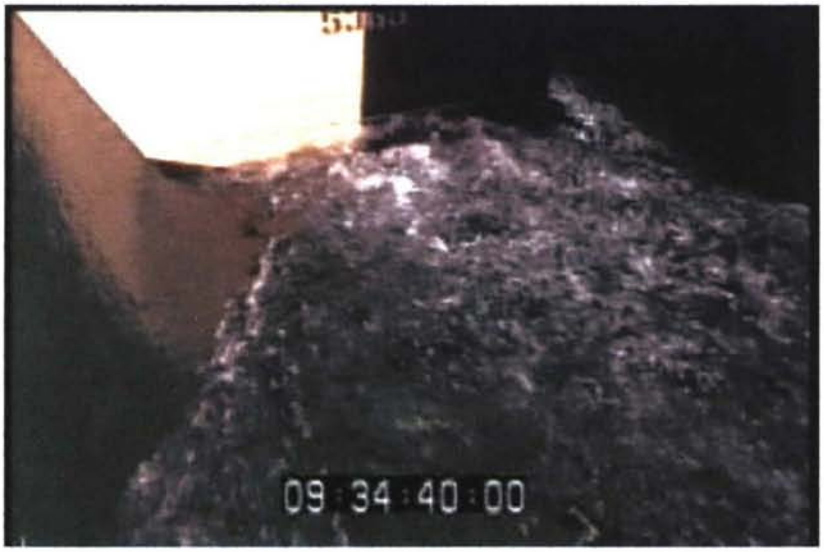

Figure 15. Stern image of Model 5365 during testing at 1.88 m/s (6.17 ft/s), corresponding to 5.4 m/s (17.7 ft/s), or 10.5 knots, full-scale.

Figure 16. Stern image of full-scale R/V Athena during testing at 5.4 m/s (17.7 ft/s), or 10.5 knots.

Figure 17. Stern image of Model 5365 during testing at 3.22 m/s (10.48 ft/s), corresponding to 9.3 m/s (30.4 ft/s), or 18.0 knots, full-scale.

Figure 18. Stern image of full-scale R/V Athena during testing at 9.3 m/s (30.4 ft/s), or 18.0 knots.

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