Near Bottom Measurement of Wave Environment in a Tidal Current

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***Abstract* - Passenger ferries running from Woods Hole to Martha's Vineyard in Massachusetts enter Vineyard Sound at the Woods Hole Harbor entrance and turn from south to east where summer southwesterly winds often set up a short chop. Occasional stronger blows create a swell running across or opposed to the strong tidal current. Northeasters are common from October to May and set up a chop and swell at the Martha's Vineyard end of the passage as well as at the turning point off Woods Hole. Directional wave measurements were made for the Woods Hole and Martha's Vineyard Steamship Authority in June and July 2004 to characterize the wave climate for design of a new fast ferry that will serve this route.**

Heavy boat traffic makes surface buoys at the critical turning region impractical but shallow depths permit a directional wave spectrum to be computed from near bottom measurements of vector velocity and pressure. However the strong tidal currents add a new element to the computational task of projecting near bottom wave velocities back to the surface. In extreme cases, the wave period observed at the bottom may be very long when the waves propagate into the current yet the attenuation relation for waves near the bottom must use the wave period relative to the near surface moving water. This back tracking of current presents a problem that has not been well addressed by existing wave models. In the Vineyard Sound case, shallow depths and unstratified conditions permit a computation of the surface current from the near bottom measurements for this reconstruction.

I. INTRODUCTION

Ferry service between Woods Hole and Vineyard Haven, Massachusetts crosses Vineyard Sound, a four mile wide body of water open to the southwest from which come the prevailing summer winds and in which tidal current is typically three knots. The region is also open to the east from which come northeaster storm winds typically from October to May but which can occur at any time of the year. A new ferry commissioned by the Steamship Authority, operators of the service, is to be constructed for the Woods Hole to Vineyard Haven route. This ferry is to be faster than the one it will replace so that a more regular connection can be made to the bus service between Woods Hole and Boston. However, critics of the new ferry claimed that the design was not suitable for the chop that often develops where the ferry turns to the southeast after leaving Woods Hole Harbor for the run across Vineyard Sound. The naval architects sought actual wave measurements to model the behavior of the designed vessel in response to this criticism but were only able to obtain wave data from Buzzards Bay Coast Guard Light Tower, 15 miles away and exposed to the open Atlantic Ocean to the southeast. To provide a wave data base more appropriate to the situation that will be experienced by the ferry, we deployed a wave and current measuring tripod in 11 meters depth where the ferry will turn from south to east and be exposed broadside to a chop from the southwest wind or swell from the Atlantic propagating down Vineyard Sound or to northeasterly waves generated from a northeaster wind event. During the 51 day deployment from May 25, 2004 to July 15, 2004, four moderately high wave events were observed, two from the southwest and two from the northeast.

II. INSTRUMENTATION

A. Tripod

The wave tripod from which the directional wave measurements were made is 1.66 meters tall and 2.13 meters between the feet with 6.4 cm struts to the apex where a MAVS (Modular Acoustic Velocity Sensor) current meter [1] was mounted in a mooring cage with the sensor rings defining the measurement volume positioned 2.50 meters above the base. Fig. 1 shows the tripod with one of two Pop-Up recovery lines still mounted and two acoustic command releases so that no surface floats were needed in the high ferry traffic area of its deployment.

Fig. 2 shows a chart of the deployment site, at the north edge of the deep channel of Vineyard Sound just seaward of the Woods Hole entry channel buoys. While Pop-Up floats [2] permit tripod recovery without divers or ground lines and grappling, they do present some hazard to upward extending sensors and a mooring frame was mounted to the tripod apex into which the MAVS was mounted to protect against fouling by the Pop-Up release line.

Two Pop-Up releases were mounted for redundancy as a guard against acoustic command release malfunction or a cut line during ship recovery of the tripod. These releases were mounted on two of the bottom struts of the tripod to keep flow disturbance low. Room was provided on a footpad opposite the MAVS for an RDI ADCP (Acoustic Doppler Current Profiler) to profile the current velocity to the surface but this was removed before deployment and the footpad was only weighted with the 20 kg lead weights provided for each of the legs. Both the desire for this measurement and the consequences of providing for the instrument and then not mounting it will be touched upon later. Normally the MAVS is mounted at the apex of the tripod with the sensor pointed down so that the sensor occupies a volume as far removed from the struts as possible and this location provides protection from lines and drifting detritus. However, on a previous deployment at this location, there were clear indications of wake effects from the Pop-Up releases for one tidal current direction

Fig. 1. Wave tripod with MAVS current meter, one of two Pop-Up recovery floats, and two acoustic command releases, after recovery from Vineyard Sound. Seaweed on the protective mooring cage seldom affected the measurement of waves and current during the 51 day deployment.

and the hope had been that an elevated sensor location would eliminate this artifact.

B. Directional Wave Measurements

Surface waves are traditionally measured from either a surface array of wires [3] or from a buoy that responds to the waves in heave [4] or by following the surface slope [5]. Where a ferry passes every two hours is a poor location for a surface array of wires or a wave buoy of either type. In the last two decades there has been increased interest in making wave measurements from submerged sensors. Pressure fluctuations can be used for wave spectra measurements where the water is relatively shallow (as it is at the ferry turning point) and horizontal velocity fluctuations can be combined with pressure fluctuations to determine directional wave spectra. If a vector velocity measurement can be made at a distance above the bottom sufficiently great to obtain a vertical wave velocity signal, no pressure observation is required for a directional wave spectrum calculation. Since MAVS measures velocity in three dimensions with a very low noise floor (0.05 cm/s), the three velocity component method was intended for this deployment.

The influence of surface waves attenuates with depth with a hyperbolic cosine dependence on wave number. This affects horizontal velocity and pressure. The vertical component of velocity has an additional attenuation by the ratio of height above bottom to the water depth. This was the motivation for elevating the sensor from the normal deployment depth of 0.75 m to 2.5 m above bottom. In fact, since MAVS also has a pressure sensor, the directional wave spectrum could be obtained two ways with Nobska Development's program, MWAVES [6] and, in retrospect, this was a good thing.

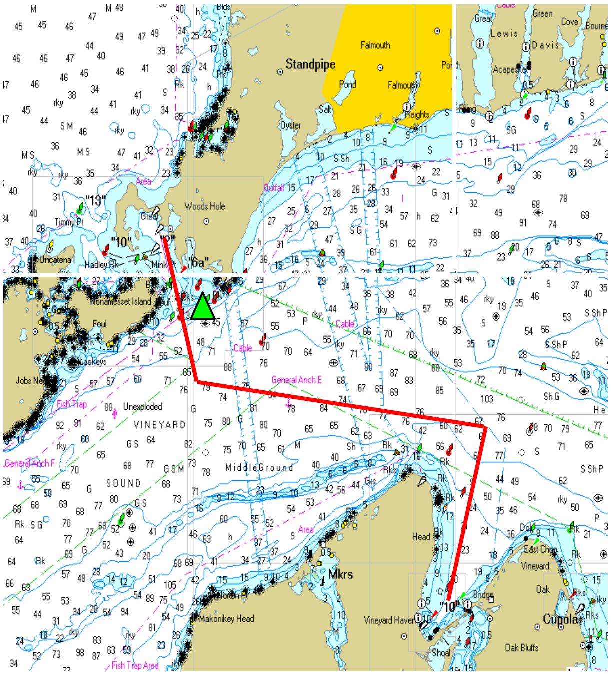

Fig. 2. Chart of Vineyard Sound where the tripod of Fig. 1 was deployed (green). Woods Hole and Great Harbor is at the upper left and Vineyard Haven on Martha's Vineyard is to the lower right. The ferry track is shown approximately by the red line. The deployment site is on the side of the deep channel made by Vineyard Sound trending northeast. It is shallow enough to measure waves but deep enough to refract them only slightly.

C. Waves and Current

Waves of interest to the naval architects and ferry passengers are surface waves as experienced in the moving frame of the Vineyard Sound tidal current. Measurement of pressure and velocity on the bottom reflects the Doppler shifted surface wave characteristics and as such requires correction from the observations back to the moving surface. Mean velocities measured near the bottom can be projected to the surface for an estimate of the surface current but it was judged useful to obtain a direct measurement of the surface current if possible with an ACDP. The acoustic beams from the ADCP required an unobstructed view past the MAVS and its mooring cage. This required an asymmetric arrangement of the MAVS to one side with space for the ADCP on the other side, an element in the misadventure that ensued. Events conspired to prevent the ADCP from being readied in time for the deployment and it was removed as the boat was loaded for launching the tripod to avoid risking it needlessly. This unbalanced the tripod as the record of tilt revealed upon recovery two months later.

The effect of current on estimates of surface wave elevation and period made from near bottom measurements has two parts. The surface waves are Doppler shifted so that the period measured on the bottom is not the correct period to be used in the back estimation for depth attenuation. This factor is built into the directional wave program MWAVES. An incorrect wave period causes the inverse calculation to misrepresent the surface wave elevation. The second part is that the reported period of the wave is not that experienced by an observer drifting with the current on the surface. The second part is in fact the simpler correction to make because it is a Doppler correction involving only the vector component of the current at the surface in the direction of the wave propagation and the period measured on the bottom. The more difficult part is the correction for attenuation of the wave characteristics with depth because this depends on the surface wave period, which is not known from the bottom wave measurement. An appropriate process for incorporating current in a directional wave algorithm in these situations will first estimate the surface current from bottom current and a simple unstratified current profile model. Uncorrected directional wave estimates will be made but the directional wave field will be Doppler shifted by the estimate of surface current to produce a revised directional wave spectrum. Individual components of the revised spectrum will then be recomputed through the inverse attenuation relation to obtain new surface elevations. These calculations have so far not been automated in the MWAVES program.

D. *Attitude Measurements in MAVS*

In early 2004 a new attitude sensor was incorporated in MAVS [7]. Based upon a three-axis magneto-inductive sensor coupled with a two-axis solid state accelerometer, the solid state compass and tilt sensor was deployed for the first time on the MAVS used in the deployment in Vineyard Sound. The essential characteristics of this sensor for purposes of this report are that tilt is measured as pitch and roll offsets from level in a horizontal plane and these are used to correct the three axes of magnetic field measured by the orthogonal array of magneto-inductive sensors for projection of the earth's magnetic field direction onto the horizontal plane. This magnetic field direction is used as a magnetic compass would be used to rotate velocities measured in the MAVS instrument frame into an earth frame of east, north, and up. In addition to the direction cosines of the magnetic field direction projected onto the horizontal plane, Mx and My, the pitch and roll angles in degrees from horizontal are recorded. The two-axis accelerometer senses the component of the earth's gravitational field that is parallel to the XY plane of the instrument frame in the X direction and the Y direction and interprets this as the sine of the roll and the pitch respectively. This sensor is linear in sine of angle out to 50° within 1° and out to 70° within 3°. As 90° is approached slight offsets in the reading or the calibration factor can cause the sensed component of acceleration of gravity to exceed 1 g by a small amount. This is a problem when applying the arcsine conversion since the arcsine of a quantity greater than 1 does not exist. The arcsine conversion returns the angle 0° in this case. When the tripod was recovered and the data were offloaded, the pitch was initially found to be 0.0°. Because this was a constant with no measurement noise even at the 0.1° level, we realized the pitch accelerometer was sensing a value very close to 1 g meaning that the tripod was on its side with the Y axis close to vertical. We were able to duplicate the alignment of MAVS to obtain these same readings and constrain its attitude within about 2° so all of the data were recoverable.

The fall of the tripod upon launch is almost certainly a result of the imbalance due to removal of the ADCP from the foot and the displacement of the MAVS and mooring cage from the center to provide clear water for the ADCP beams. The result of the fall was that determining directional wave spectra from three axes of velocity was no longer viable and two horizontal velocities and pressure were used instead. One last benefit of the solid state attitude sensor was experienced when about half-way through the deployment the tripod rolled over onto another side. Here the pitch and roll values were on scale and the transformation of instrument frame coordinates into earth frame coordinates was done correctly, even though roll was 58°.

III. RESULTS

A. *Directional Wave Data*

The MAVS-3 acoustic current sensor used in the study was deployed at approximately noon on May 25, 2004 and recovered at approximately noon on July 15, 2004. The instrument was programmed to collect data bursts upon which a directional wave spectral analysis could be performed using MWAVES. MAVS-3 and MWAVES are products of Nobska Development, Inc.

The instrument was deployed in Vineyard Sound at a depth of approximately 11 meters. The site is south of Juniper Point at approximately 41° 30' 30" north latitude and 70° 39' 55" west longitude (Fig. 2). The instrument recorded date and time, velocity in the instrument and earth frames, temperature, pressure, compass, and tilt measurements at 2 Hz with 4096 records in each burst. The duration of each burst is approximately 34 minutes. Bursts were scheduled to begin every 2 hours for the duration of the study. Ultimately, 612 bursts were collected for analysis.

Of these 612 bursts, 68 were automatically rejected by MWAVES because they contained regions of flagged velocity measurements. MAVS-3 automatically flags failed velocity measurements. Manual analysis of the rejected data files indicated with high probability that these particular measurement bursts had been contaminated by bio-fouling. The fouling was probably the air-filled swim bladder of a small fish temporarily blocking an acoustic pathway in the sensor.

Additionally, 9 files were manually rejected during the analysis. Manual inspection of the spectra of these bursts suggested that seaweed or fish had fouled the sensor during the burst without actually blocking the acoustic measurement paths.

It should be noted that the tripod supporting the sensor did not deploy cleanly, landing on its side and placing the sensor within 20 cm of the bottom. On June 3, between two bursts, the tripod rolled onto a second side, again leaving the sensor close to the bottom. Other than the one clean roll, the tripod was stable for the duration of the deployment. An altitude of 20 cm is not optimal for measurements of vertical velocity. However, we conducted the analysis using the horizontal velocity and pressure measurements, which were not compromised.

The tipping of the tripod oriented the sensor outside the range within which it can automatically reference the velocity measurements to the earth frame. Directional wave spectra could still be calculated, however, because we had also recorded instrument frame velocities as well as compass and tilt measurements. From this information we were able to accurately reconstruct the earth frame velocities during initial post-processing. The reconstructed measurements were clean and of high quality, greatly facilitating the spectral analysis.

In sum, 535 clean, high quality bursts of time-stamped velocity and pressure measurements were collected over a 51-day period. These bursts were analyzed using MWAVES software. Those results were examined and verified by the authors. Additional post-processing of the results was conducted to produce and verify the accuracy of the calculations.

B. Summary of Calculated Wave Statistics

Fig. 3 presents a summary of the statistical quantities that characterize the wave field. The horizontal axis is elapsed time in days since the beginning of the experiment at noon on May 25, 2004. Table I relates elapsed time to particular calendar days. Each triplet of plotted points in the time-series of Fig. 3 is calculated from the measurements in an individual burst using MWAVES.

The first panel of Fig. 3 charts the evolution of significant wave height, $H_{1/3}$, in meters. There were four relatively energetic events over the course of the study. Significant wave height remained above 0.5 meters for several hours to a day and peaked at over 1.0 meter in each case. These events are correlated with increases in local wind forcing and shorter wave periods. Wave propagation was towards the southwest during the Day 12 and Day 48 events and towards the northeast during the Day 21 and Day 27 events. The direction of wave propagation during these four events was consistent with observations of wind direction recorded in the log of the M/V Martha's Vineyard.

Times that were dominated by relatively long period swell, 7 to 9 second waves, were typically associated with low significant wave height. We interpret this to mean that longer period waves can only weakly propagate into Vineyard Sound from the open Atlantic. Such swell can only dominate the wave field in the Sound when locally forced short period waves are very weak or entirely absent. The energetic events in

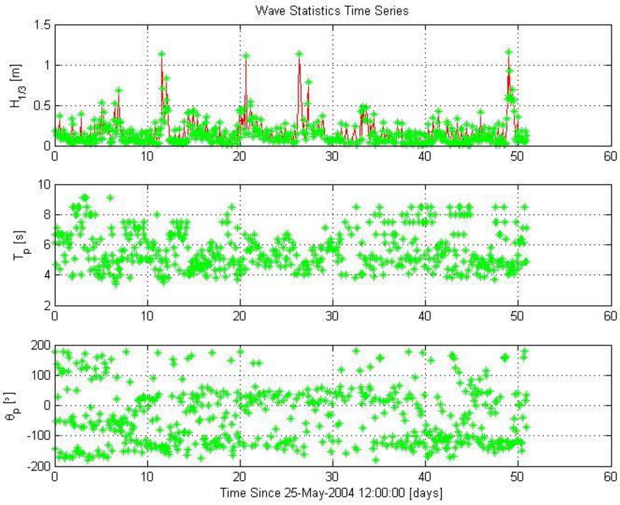

Fig. 3. Directional wave spectra from Vineyard Sound. Panel 1 shows significant wave height. Panel 2 shows the period of the most energetic wave. Panel 3 shows the direction of propagation of that wave. The elapsed days since May 25, 2004 are plotted but the dates are shown in Table I.

Vineyard Sound tend to be locally forced and dominated by short period, 4 to 6 second waves, and chop.

The second panel of Fig. 3 shows changes in the period of the dominant (most energetic) waves. The wave field was strongly dominated by 4 to 6 second waves throughout the study. Observed periods were never shorter than 3 seconds or longer than 10 seconds.

It should be noted that long period waves may be able to propagate into the Sound with greater strength during, and in the aftermath of, a more powerful storm. No such event occurred during the period of the study. Energetic short period waves would also be present during such an event.

TABLE I
ELAPSED DAYS TO CALENDAR DAYS

Elapsed Day	Calendar Day
0	May 25, 2004
10	June 4, 2004
20	June 14, 2004
30	June 24, 2004
40	July 4, 2004
50	July 14, 2004

The third panel of Fig. 3 depicts the principal direction of wave propagation over time. The direction is given in "mathematical compass coordinates". In this system, east is 0°, north is +90°, south is -90°, and west is ±180°. Not unexpectedly, as these are the directions of greatest fetch, waves tend to propagate along the axis of the Sound, either to the southwest or to the northeast. However, cross-Sound propagation does occur with reasonable frequency. Fig. 4 shows a polar plot of this spectrum including a velocity vector as well in red.

C. M/V Martha's Vineyard Ship's Log Entries

Observations of wind speed and direction are recorded regularly in the ship's log of the M/V *Martha's*

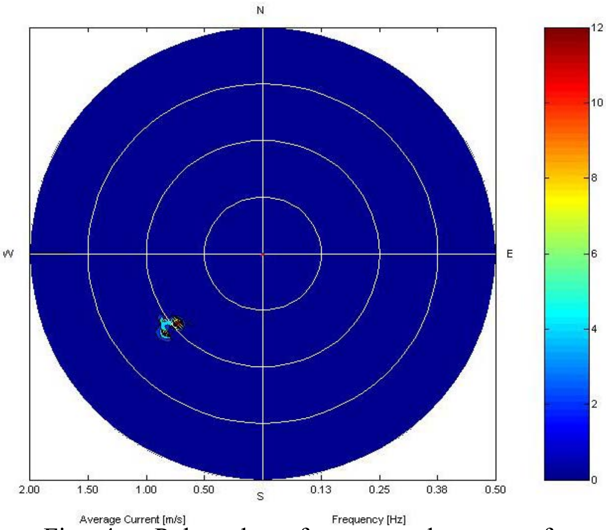

Fig. 4. Polar plot of wave and current for July 13, 2004. The waves are propagating southwest with a frequency of 0.25 Hz (4 s). The current was nil as shown by the very short red line slightly to the southwest.

Vineyard, the existing ferry. Selected entries were provided to us by SSA for comparison with the calculated wave characteristics described in this report. Table II summarizes the comparison.

The four most energetic wave events, those with significant wave heights greater than 1 meter, occurred on June 6, June 14, June 20, and July 13. Observed winds reached Force 5-6 on the Beaufort scale on each of those days. Those were the only days during the study with wind strength above Force 3-4. Wave periods were short on those days, indicative of generation by local winds. Wind direction and the direction of wave propagation were aligned during each of these events.

D. Distribution of Significant Wave Heights

Fig. 5 shows the distribution of significant wave heights during the wave study. This period was generally calm. Fully 480 of 535 bursts (~90%) have significant wave heights at or below 33 cm. The significant wave height exceeded 60 cm only 11 times and exceeded 1 m only 4 times during the 51-day study period.

TABLE II
M/V MARTHA'S VINEYARD LOG ENTRIES

Event Number	Elapsed Day	Date In 2004	Wind From	Waves Towards	Wind Strength [Beaufort]	Wave Height [m]	Wave Period [s]
1	12	June 6	ENE	SW	5-6	1.13	4.0
2	21	June 14	SSW	NE	5	1.11	4.5
3	27	June 20	WSW	NE	5-6	1.13	4.5
4	48	July 13	SE	SW	5	1.16	4.5

E. Distribution of Dominant Wave Periods

The histogram of Fig. 6 shows the distribution of wave periods during the wave study. This period was dominated by short, locally generated waves, with periods between 4 and 6 s. These were also the most energetic waves observed during the study. Longer period waves were not uncommon, but these waves, ocean swell propagating into Vineyard Sound, were always weak, with typical significant wave heights of only 10 cm.

F. Distribution of Directions of Wave Propagation

The histogram of Figure 7 shows the distribution of wave propagation directions during the wave study. The direction is given in "mathematical compass coordinates". In this system east is 0°, north is +90°, south is -90°, and west is ±180°. The study period was dominated by waves propagating to the southwest, down the axis of the Sound. Most common after that were waves propagating up the Sound to the northeast. Cross-Sound waves propagating southeast (from Woods Hole towards Martha's Vineyard) are next. Only occasionally did waves propagate to the northwest.

G. Observed Correlations

Correlations between significant wave height and direction of propagation and between wave period and direction of propagation were weak. The only reliable correlation between the triplets of data points in the time-series of wave statistics is the observation that long period waves had very small significant wave heights. Energetic events with relatively large significant wave heights were invariably locally generated, short period wave fields.

Notably, all four of the energetic events observed during the study period are well correlated with the record in the log of the M/V *Martha's Vineyard*. Significant wave heights, wave periods, and directions of propagation calculated from the MAVS-3 sensor measurements are completely consistent with the observations of wind speed and direction in the ship's log.

H. General Comments

The wave study was conducted during a relatively calm period. As such, the results are representative of normal spring and summer operating conditions for the Steamship Authority. Unfortunately, no major storms passed through the area while the MAVS-3 instrument was deployed and recording. The difficult wave

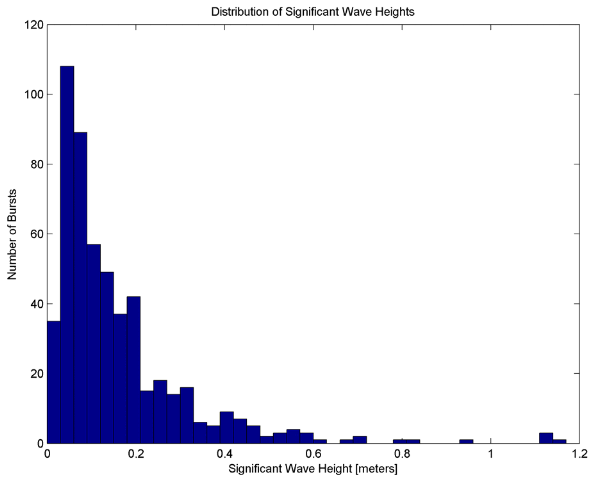

Fig. 5. Histogram of significant wave heights in the Vineyard Sound deployment.

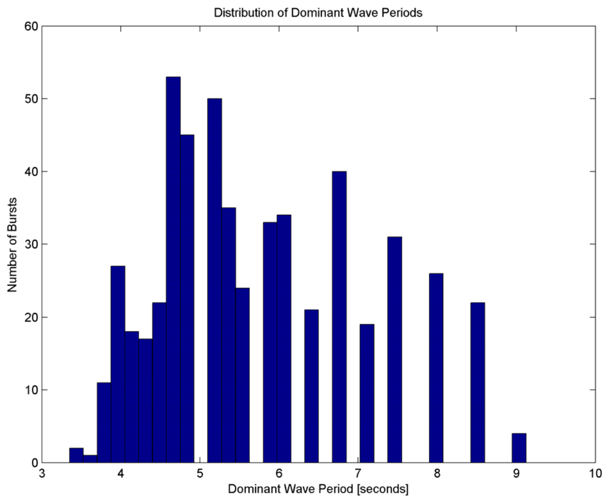

Fig. 6. Histogram of dominant periods in the Vineyard Sound deployment.

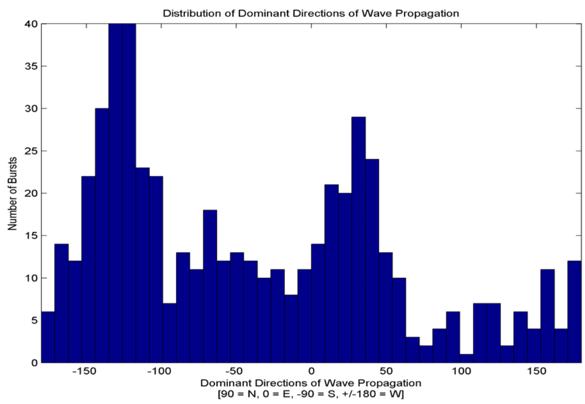

Fig. 7. Histogram of dominant wave propagation directions during the deployment.

conditions that occasionally occur at the study site, and which cause a change in the normal track followed by SSA vessels, were not observed.

IV. CONCLUSION

Waves were measured from a tripod deployed in 11-meters depth under a position where ferry boats turn from south to east and are exposed to southwest or northeast waves. Despite falling on its side, the MAVS current meter recovered horizontal velocities and pressure fluctuations that permitted directional wave spectra to be computed and presented to the client, the Woods Hole and Martha's Vineyard Steamship Authority, for examination by their naval architects in the design of a new fast ferry. Concerns arose concerning the effect of strong tidal current on the ability of the MWAVES program to predict wave period and wave amplitude on the surface from measurements made near the bottom but agreement with observations from the logbook of ferries transiting the area confirmed the measurements were reasonable, particularly during the four significant wave events that occurred during the 51-day deployment.

ACKNOWLEDGMENT

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