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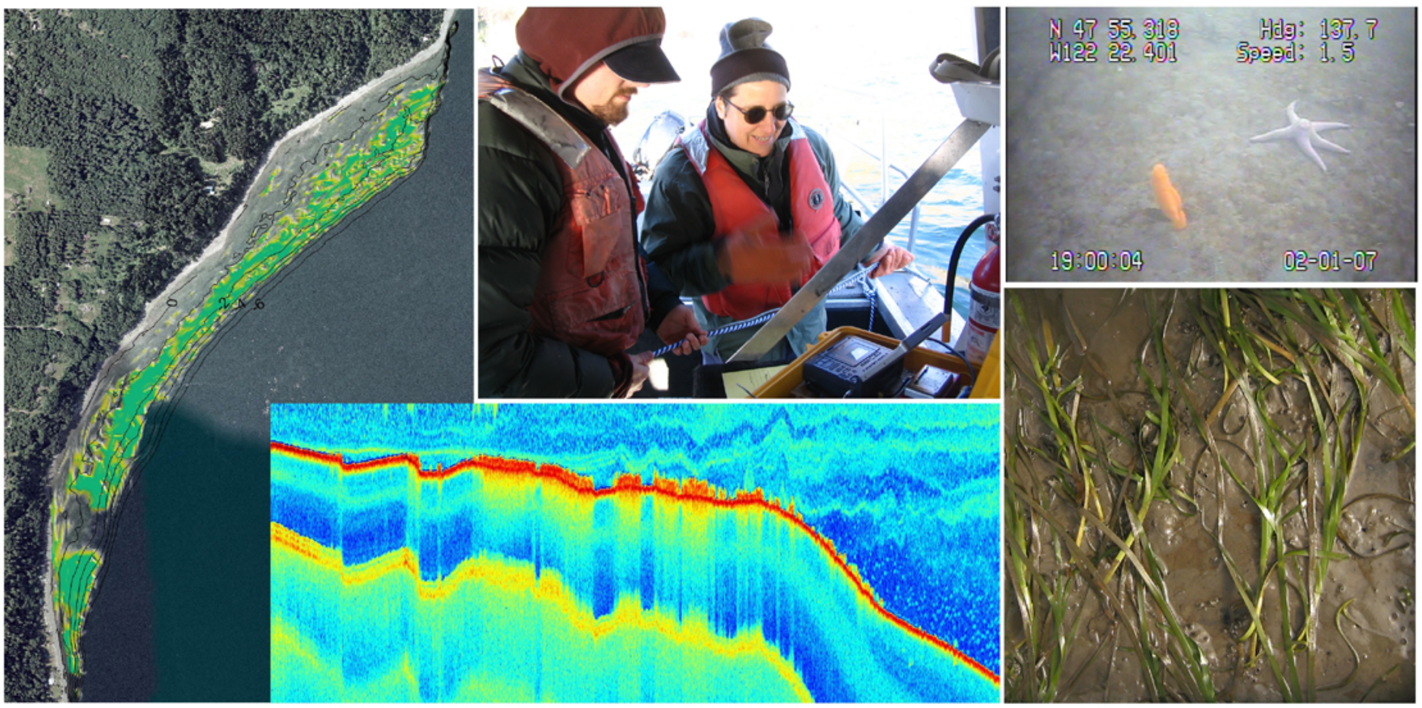
# Evaluation of a Single-Beam Sonar System to Map Seagrass at Two Sites in Northern Puget Sound, Washington




Scientific Investigations Report 2008–5009

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By Andrew W. Stevens, Jessica R. Lacy, David P. Finlayson, and Guy Gelfenbaum

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# Evaluation of a Single-Beam Sonar System to Map Seagrass at Two Sites in Northern Puget Sound, Washington

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## Abstract

Seagrass at two sites in northern Puget Sound, Possession Point and nearby Browns Bay, was mapped using both a single-beam sonar and underwater video camera. The acoustic and underwater video data were compared to evaluate the accuracy of acoustic estimates of seagrass cover. The accuracy of the acoustic method was calculated for three classifications of seagrass observed in underwater video: bare (no seagrass), patchy seagrass, and continuous seagrass. Acoustic and underwater video methods agreed in 92 percent and 74 percent of observations made in bare and continuous areas, respectively. However, in patchy seagrass, the agreement between acoustic and underwater video was poor (43 percent). The poor agreement between the two methods in areas with patchy seagrass is likely because the two instruments were not precisely colocated.

The distribution of seagrass at the two sites differed both in overall percent vegetated and in the distribution of percent cover versus depth. On the basis of acoustic data, seagrass inhabited 0.29 $km^2$ (19 percent of total area) at Possession Point and 0.043 $km^2$ (5 percent of total area) at the Browns Bay study site. The depth distribution at the two sites was markedly different. Whereas the majority of seagrass at Possession Point occurred between -0.5 and -1.5 m MLLW, most seagrass at Browns Bay occurred at a greater depth, between -2.25 and -3.5 m MLLW. Further investigation of the anthropogenic and natural factors causing these differences in distribution is needed.

## Introduction

Seagrass is an important component of nearshore ecosystems that support many estuarine species, including a number of commercially important fisheries (Deegan, 2002). In Puget Sound, the most abundant, as well as the most ecologically important, seagrass is the eelgrass *Zostera marina*. The distribution of seagrass is controlled by light availability (Duarte, 1991), as well as by several physical, geological, and geochemical factors in the nearshore environment (Koch, 2001). Many of the habitat requirements of seagrass can be disrupted by human activities, and loss of seagrass habitat can often be attributed to anthropogenic causes (Short and Wyllie-Echeverria, 1996). Recent worldwide losses in seagrass habitat have caused many government agencies and environmental groups to develop monitoring programs for this important coastal resource.

The need to monitor seagrass has led to the use of numerous methods for assessing its distribution and attributes, including land-based surveys, diving-based surveys, aerial photography, and underwater video (Duarte and Kirkman, 2001). Recently, there has been extensive research into using acoustic devices, such as single-beam sonar (Sabol and others, 2002), side-scan sonar (Pasqualini and others, 2000), multibeam sonar (Komatsu and others, 2003), and acoustic Doppler current profilers (Warren and Peterson, 2007) to quantify seagrass habitat. Underwater video data have been used extensively in monitoring programs to estimate areal coverage of subtidal aquatic vegetation in Puget Sound (Norris and others, 1997; Gaeckle and others, 2007). Underwater video data provide an unambiguous assessment of seagrass presence, but quantitative information other than presence or absence is very difficult to extract. Many acoustic devices, on the other hand, have the potential to determine relevant descriptors of seagrass habitat, including plant cover, plant height, and biovolume (area × percent cover × plant height) (for example, Thomas and others, 1990; Sabol and others, 2002; Warren and Peterson, 2007). Acoustic methods can be used in conditions that are challenging for collecting underwater video, such as in turbid estuaries where visibility is minimal. However, the accuracy of acoustically derived vegetation maps can be lower than those created with underwater video because of errors associated with interpreting and classifying acoustic data. With a few exceptions (for example, Winfield and others, 2007), the accuracy of acoustically derived plant attributes is either not determined or not reported.

In this report, we describe data-collection and analysis methods for characterizing seagrass distribution using a Biosonics single-beam sonar and their application to two sites in northern Puget Sound. Underwater video was collected synchronously with the acoustic data in a subset of the survey lines. We compare results from the two techniques to better understand the accuracy, benefits, and limitations of acoustic mapping of seagrass. Metadata for this report are available at http://walrus.wr.usgs.gov/infobank/b/b207ps/html/b-2-07-ps.meta.html.

# Methods

## Study Sites and Survey Design

Two study sites in northern Puget Sound, Washington (fig. 1) were selected to conduct bathymetric and seagrass surveys using a single-beam sonar system and underwater video camera on U.S. Geological Survey Cruise B-2-07-PS. The two sites are separated by Possession Sound, a deep channel that connects the main body of Puget Sound to the south with Saratoga Pass and Skagit Bay to the north. The first study site, Possession Point, is located on Whidbey Island on the west side of Possession Sound (fig. 2). The Possession Point site is characterized by a wide range of conditions in both vegetation and bottom type. During a low-tide site visit, we observed regions populated with seagrass, regions populated with kelp, and unvegetated regions, as well as both continuous and patchy seagrass. Bottom substrates included grain sizes from boulders to sand, large bed forms, and ripples. Results of the acoustic mapping at Possession Point were used to site instruments in a study of the influence of seagrass on hydrodynamics and sediment transport during the spring of 2007.

A total of 163 sonar lines were planned to cover the Possession Point study site. The majority of planned lines, 148, were oriented in the cross-shore direction, and 15 lines were along-shore (see appendix A, fig. A1). The cross-shore survey lines were followed from as close to shore as possible to a depth of roughly 20 m. In the southern and middle sections of the study site (lines 1-72), survey lines were spaced at 50-m intervals. In the northern section, lines 73-148 were spaced at 25-m intervals. The higher density of lines in the northern part of the study site was intended to better resolve bed forms that had been observed during previous site visits (J. Lacy, oral communication, 2007).

The second study site, Browns Bay, is located on the east side of Possession Sound, roughly 5 km to the south of the Possession Point study site. At Browns Bay, the inshore edge of the beach is bounded by a railroad grade and tracks, which extend below the high water line along much of the shoreline. The extent of seagrass coverage in the nearshore adjacent to the railroad grade is known to be very low. Browns Bay was selected as a site on the east shore of Puget Sound with some seagrass present. Because both tidal currents and exposure to southerly winds and waves are thought to be fairly similar for the northern part of the Possession Point and Browns Bay sites, we anticipated that the two sites might contribute to understanding the influence of factors other than hydrodynamics on seagrass distribution and health. In particular, the potential impact of shoreline armoring on nearshore habitat is a significant concern for environmental managers in Puget Sound.

For the Browns Bay study site, 126 lines were planned. The majority of lines, 123, were oriented cross-shore at roughly 15-m intervals, and another 3 lines were oriented in along-shore (see appendix B, fig. B1).

## Equipment and Data Collection

The primary components of the acoustic survey equipment were a deck unit, a laptop computer, transducers, and a real-time kinematic global positioning system (GPS) (fig. 3). The transducers used in this survey were 199 kHz and 420 kHz Biosonics DT-X series digital transducers with beam width of 6 degrees. The ping rate for both transducers was set to 5 Hz (200-ms intervals), and the duration of each pulse was 0.4 ms and 0.1 ms for the 199 kHz and 420 kHz transducer, respectively. The operating range of both transducers was set to 20 m.

Control of the transducers and a real-time display of the output from the system was achieved through Biosonics acquisition software installed on a laptop personal computer (PC). The laptop PC was connected through an Ethernet cable to a deck unit that sends and receives signals from the transducers and integrates data from the echo sounder with available external sensors (in this case, the GPS). Return echoes from the transducers were digitized by a dedicated processor in the deck unit at 41.67 kHz, leading to an approximate vertical resolution of 1.8 cm.

The horizontal and vertical positions of the transducers were determined using a real-time kinematic global positioning system (RTK GPS). The RTK GPS system consisted of a base station and a roving receiver. The base station was equipped with a Trimble 4400 receiver with a Trimble L1/L2 antenna and a Pacific Crest 35-Watt radio transmitter. The rover unit consisted of a Trimble 4700 receiver, a Trimble Zepher Antenna and a Pacific Crest radio receiver.

The base station was placed on a survey benchmark. Using the known location, the base station transmitted real-time corrections to the roving receiver (that is, the Trimble 4700 receiver on the ship) using a radio transmitter. The manufacturer of the GPS equipment reports root mean square (RMS) accuracies of ± 3 cm plus 2 mm per km baseline length (distance from the base station) for horizontal positions and ± 5 cm plus 2 mm per km baseline length for vertical positions (Trimble Navigation Unlimited, 1998). RTK-corrected GPS data were sent to the sonar deck unit at 1 Hz and incorporated directly into the acoustic data files.

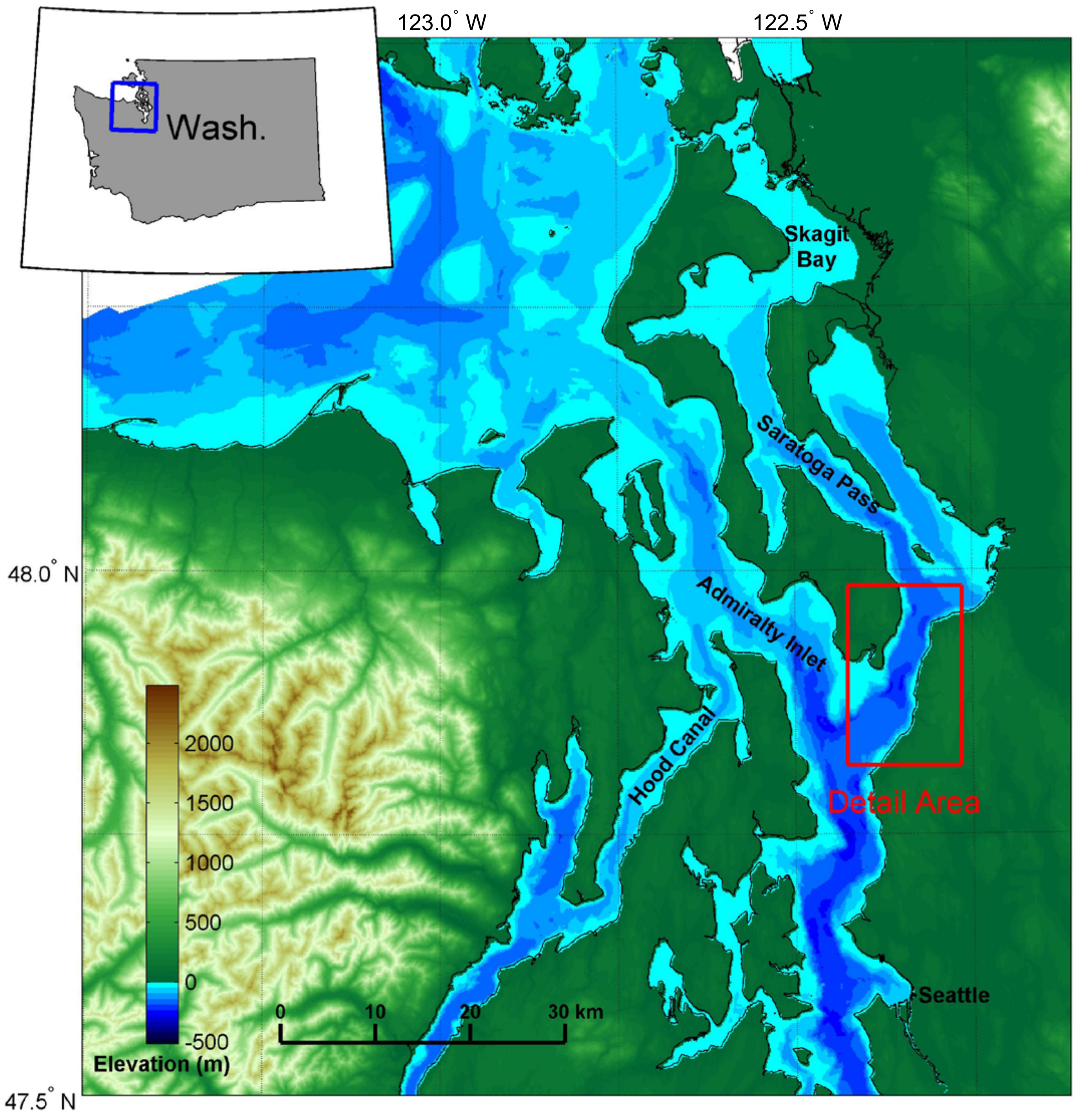


**Figure 1.** Map of northern Puget Sound, Washington State. The detail area (red box) shows the location of the surveys conducted in this study (see fig. 2). DEM source was Finlayson and others, 2000.

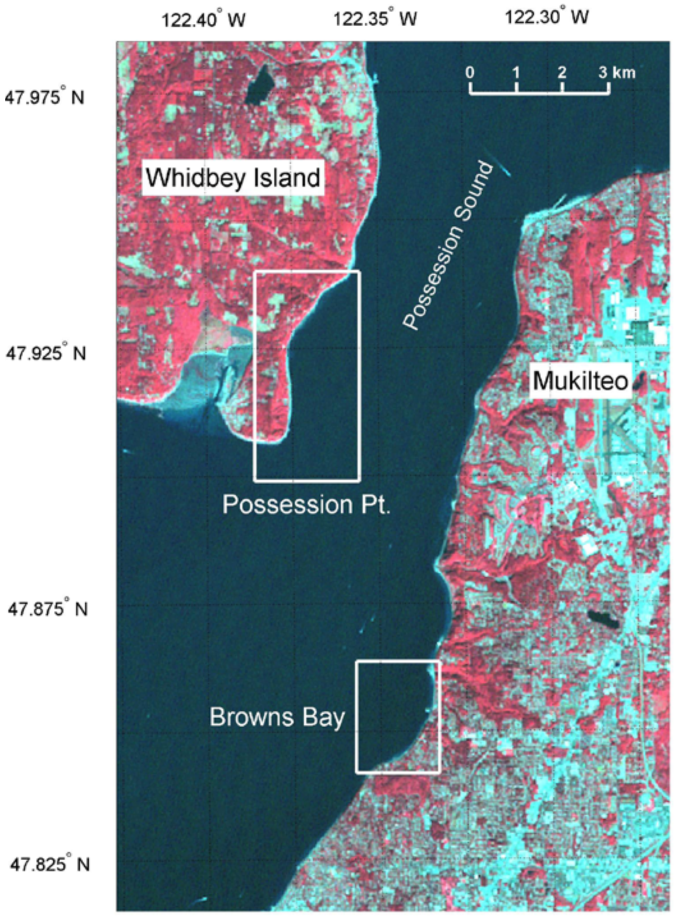


**Figure 2.** Detailed map showing the two study sites, Possession Point and Browns Bay. The two sites are approximately 5 km apart, separated by Possession Sound. The base map is a mosaic of images taken by the Landsat satellite between 2000 and 2001.

Additionally, the RTK-corrected GPS signals were sent to a laptop computer mounted near the boat operator. During data collection, this computer was used in conjunction with the computer program Hypack Max to navigate along planned survey lines (fig. A1 and fig. B1). Once the boat (the R/V *Jet2*) was positioned at the start of a planned line, the recorder was turned on and acoustic backscatter data were collected while the boat navigated along the line. The typical operating speed during data collection was 4-5 knots.

Sediment samples were collected at Possession Point with a grab sampler from the R/V *Jet2* or from the R/V *Karluk* during a later site visit (U.S. Geological Survey Cruise, K-2-07-PS). Several additional surface samples were collected during low-tide surveys. The grain-size distributions were determined using standard techniques. Wet samples were sieved to separate coarser particles from the silt and clay. The coarse fraction was dried, gravel (> 2 mm) was separated, and gravel fractions were determined with sieves. The sand fractions (2 mm – 63 µm) were quantified using a 2-m settling tube and fine fractions (<63 µm) with a Beckman Coulter Model LS230 laser diffraction particle analyzer.

An underwater video camera was used on selected survey lines to evaluate the accuracy of the acoustically derived seagrass maps. The underwater camera system consisted of a SeaViewer Camera and LED lights housed in a small metal frame (fig. 4). The live video signal could be viewed on a standard CRT monitor and was recorded directly to digital-8 tape. Time, date, location, and ship speed were determined using a Garmin GPSMAP 60Csx handheld GPS. The manufacturer-supplied horizontal accuracy of the Garmin GPS is within 3 m when receiving wide area augmentation system (WAAS) corrections.

The positional information from the GPS was outputted at 0.5 Hz and overlaid on the video using the Sea-Trak GPS overlay system developed by SeaViewer Cameras. The GPS data were also directly integrated with the digital video recording using Red Hen Systems (RHS) VMS200 hardware. The VMS200 receives NMEA message strings from the GPS and encodes the information on the audio channel of the video tape. These data can later be read by RHS MediaMapper software to determine the ship's position at the time the video was recorded.

Underwater video data were collected in cross-shore transects in a similar manner as the acoustic data except that, in order to collect the best possible imagery of the sea floor, the ship's speed was kept at a minimum (1-2 knots). This made navigation along the planned transects difficult because of winds and currents. Acoustic data were recorded at the same time as underwater video for a side-by-side comparison (see section on "Underwater Video and Acoustic Data Comparison," below, for details).

## Underwater Video Classification

The first step in the classification of underwater video was to create and export a file containing the positional information encoded on the audio track of the video recording using MediaMapper software. The exported spreadsheet contained latitude, longitude, and time at 2-s intervals. Next, the underwater video recording was reviewed and the presence of seagrass was determined for each 2-s segment of video tape. Each segment was classified into one of three categories: bare (no seagrass), patchy seagrass, or continuous seagrass. The categories were defined as follows with respect to each 2-s segment of video: bare—no seagrass observed; patchy—both seagrass and bare areas observed; continuous—fully vegetated with seagrass. As the video tape was reviewed, the seagrass habitat classification was added to the spreadsheet containing the positional information. A single person reviewed all of the underwater video and used consistent standards for classification in order to minimize differences due to personal judgment.


**Figure 3.** Photographs showing the main components of the acoustic survey equipment.

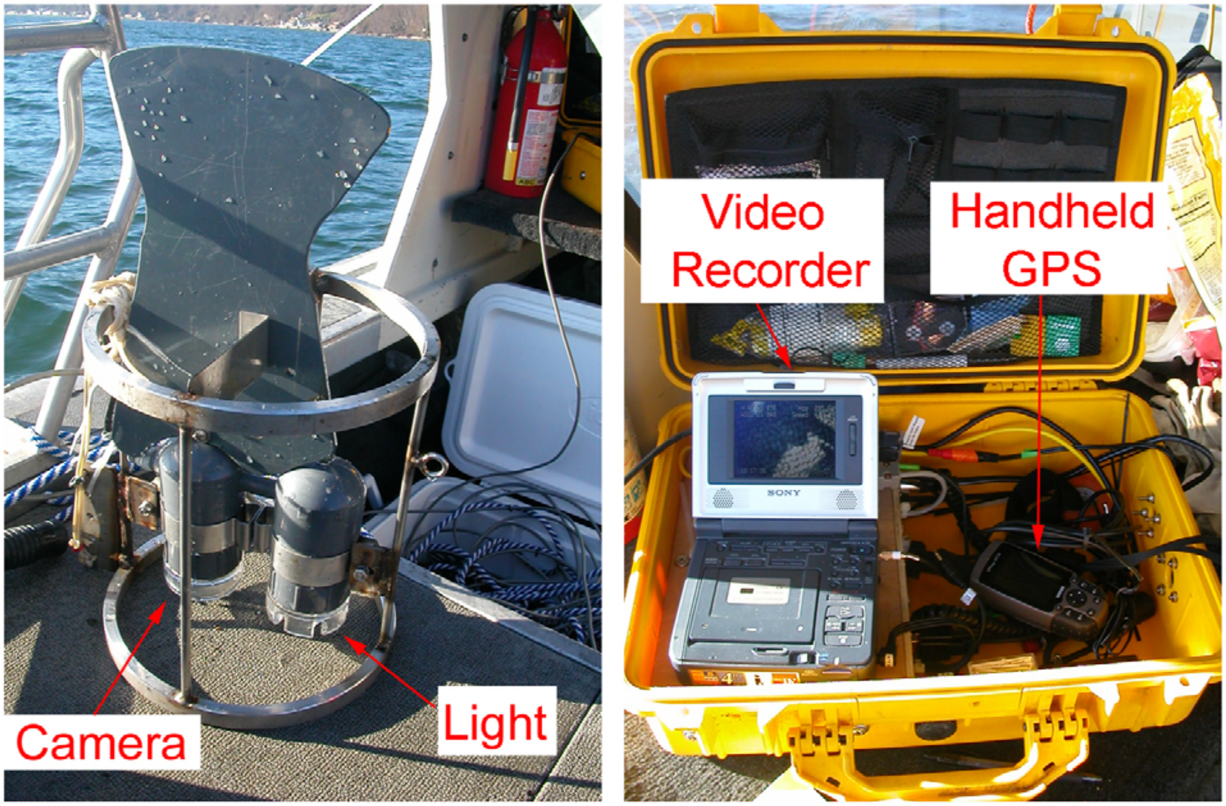


**Figure 4.** Photographs showing the main components of the underwater video system.

## Acoustic Data Analysis

### Bottom Detection and Plant Recognition in Single-Beam Data

A single-beam echo sounder works by emitting a short burst of sound (ping) towards the sea floor and recording reflected sound (echoes). The strength of reflected sound (backscatter or echo intensity) is recorded at a series of time intervals, resulting in a profile of acoustic backscatter versus time. The distance between the transducer and objects in the water (range) is calculated based on the speed of sound in sea water. As the ship navigates along survey lines, data from multiple pings are recorded, resulting in a two-dimensional picture of backscatter intensity.

Acoustic data from a Biosonics DT-X series echo sounder were analyzed to determine the sea-floor bathymetry and the presence or absence of vegetation. The analysis is performed on each ping, and relies on distinct differences in the acoustic backscatter signal from vegetated and unvegetated surfaces. The signal-processing technique described here is based on an algorithm described in Biosonics (2004a) and Sabol and others (2002).

Before classification of the acoustic data, raw backscatter data were converted to target strength in decibels (dB) or volume scattering strength (in dB) using equations 4a and 4b in Biosonics (2004b). Both of these common acoustic quantities remove the effect of sound attenuation in seawater by applying a time-varied gain to the raw acoustic backscatter amplitude. The absorption, or attenuation coefficient (dB/m), was calculated using the equations given in Francios and Garrison (1982) and surface the temperature and salinity values measured during the survey.

A simple example illustrates the signal-processing technique in an area without seagrass (fig. 5). A profile of acoustic backscatter for one ping is shown on the right. The backscatter at that ping (450) is low (~-95 dB) and relatively uniform from 1 to 6.5 m from the transducer. At ~6.5-m range, a single sharp, narrow peak in acoustic backscatter occurs. This sharp, narrow peak is typical of a bare, unvegetated bottom. The bottom depth (z) is identified as the point of greatest positive slope associated with the largest peak in backscatter.

The profile of backscatter intensity is quite different at an earlier ping on the same transect (fig. 6). At ping 330, an area of low backscatter exists from 1 to ~4.5 m below the transducer. Below that, the backscatter increases, although more gradually than at ping 450, and stays high until 5.5-m range. Multiple local maxima within the broad region of

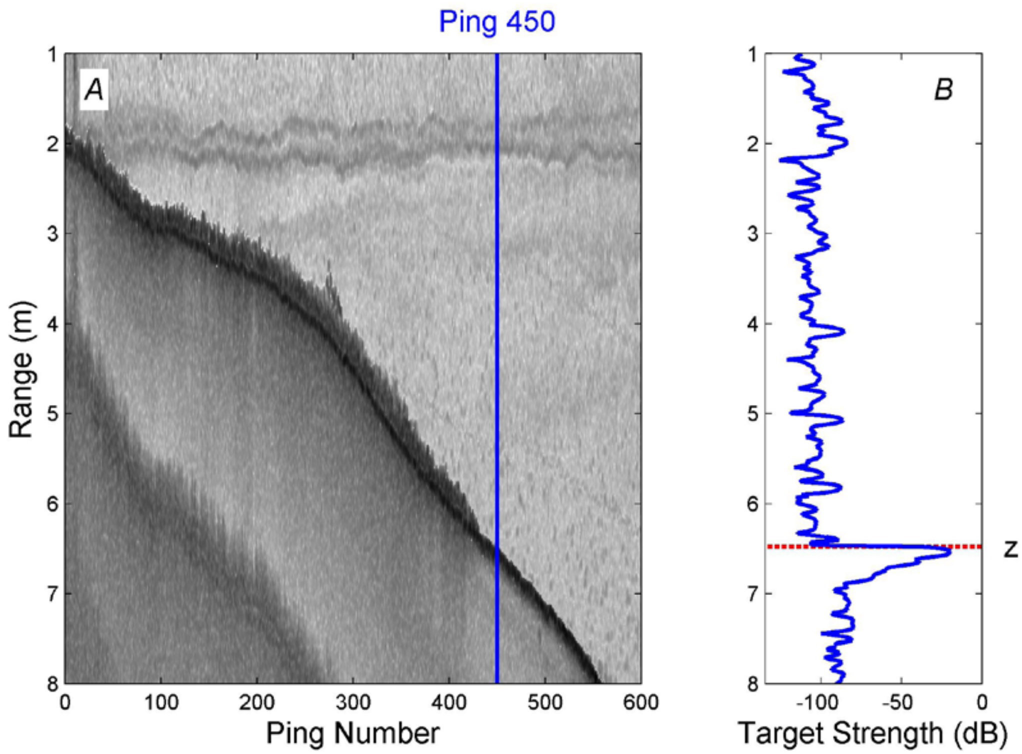


**Figure 5.** Acoustic results for a portion of line 59. *A*, Backscatter versus range. Blue line shows the location of ping 450. *B*, Backscatter versus range for ping 450 in a region without seagrass. The classified bottom depth (z) is shown by dotted red line.

elevated backscatter are evident. These features are characteristic of a vegetated bottom. The top of the vegetation canopy (gz, green line) is defined as the first (that is, closest to the transducer ) value in backscatter intensity that exceeds a threshold value. The threshold value was typically between 1 and 2.5 standard deviations above the mean backscatter intensity for each ping. As for ping 450, bottom depth (z) is the point of greatest positive slope associated with the largest peak in backscatter.

The first step of the classification algorithm is to determine the first point below the transducer where backscatter intensity exceeds a threshold value. Once the region of strong backscatter is identified, the location of the bottom is determined (the greatest rise in backscatter intensity). The region between the first elevated value and the greatest rise in backscatter intensity is considered the acoustic bottom envelope. If the height of the bottom envelope is greater than a predetermined value, the ping is classified as vegetated and vegetation height is calculated by subtracting the top of the vegetation canopy from the bottom depth. Otherwise, the ping is classified as unvegetated. The algorithm completes this assessment for each ping in an echogram, or backscatter record (fig. 7). Threshold values for determining the bottom location and the minimum bottom envelope height in the algorithm are determined for each survey line based on visual inspection of the acoustic data.

## Analyzing Real-World Data

Although the basics of plant detection are quite simple in theory, there are several factors that make automated classification of vegetation challenging (see Sabol and others, 2002, for a list of challenges). For instance, a rapidly changing bottom depth in a localized area causes the bottom to appear thicker acoustically and may result in the site being classified as vegetated in a fully automated, unsupervised algorithm.

Another major challenge for acoustic seagrass detection is that there can be objects on the sea floor (for example, other plant species, woody debris, or other organisms) that acoustically resemble seagrass. Oftentimes, a trained analyst will be able to distinguish these objects from seagrass, but an automated system will not (though complex techniques involving adaptive computer algorithms may be used in the future). For this study, underwater video was used to determine whether any such objects were present. Underwater video showed, in addition to seagrass (fig. 8), two habitat types that would have been classified incorrectly by an automated algorithm. The first was red algae growing mostly in rocky areas (fig. 9). The second was clusters of orange sea pens, *Ptilosarcus gurneyi* (T. D'Andrea, written comm., 2007), a common megafauna found in the Puget Sound (Birkland, 1974)(fig. 10). Fortuitously, these potential targets did not overlap spatially with seagrass. Specifically, the red

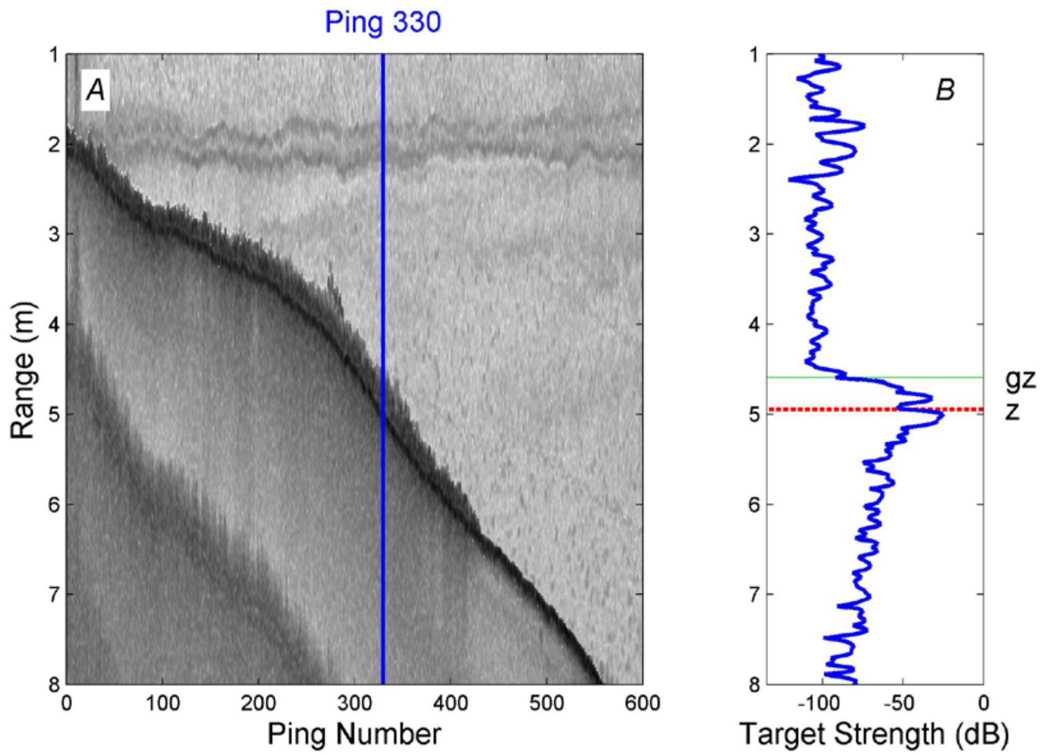


**Figure 6.** Acoustic results for a portion of line 59. *A*, Backscatter versus range. Blue line shows the location of ping 330. *B*, Backscatter versus range for ping 330 in a region with vegetation. The classified bottom depth (z) is shown as dotted red line and the top of the vegetation canopy (gz) is shown in green.

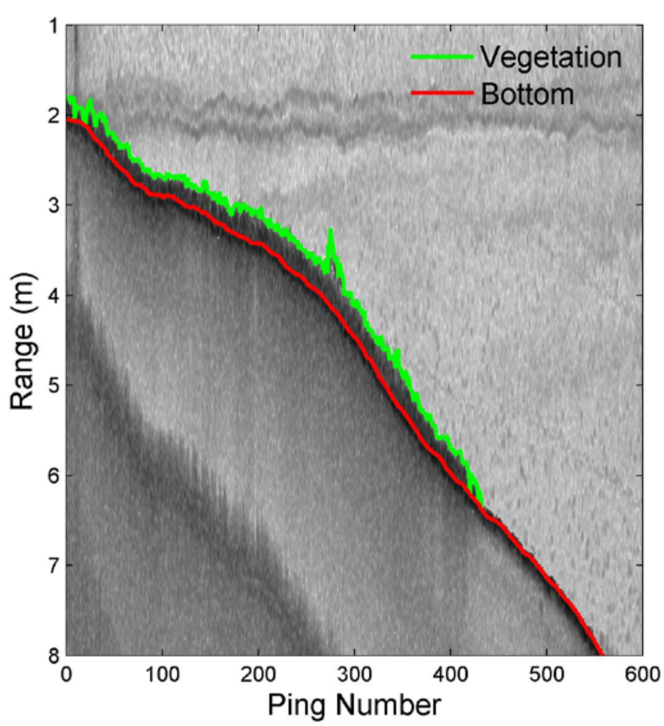


**Figure 7.** Classified acoustic data for a portion of line 59 showing the bottom depth (red line) and top of vegetation canopy (green).

algae were observed in rocky areas to the south of the seagrass meadows, and sea pens were found in deeper water (> 8 m) than the seagrass. Once the acoustic characteristics and spatial distribution of these habitat types were established, a trained analyst was able to differentiate them from seagrass in the backscatter data without referring back to the video data (that is, the video data were not consulted during acoustic data processing).

In order to overcome some of the challenges of detecting vegetation acoustically, an algorithm with adjustable parameters was created that allowed for some subjective decision making by the data analyst. A graphical user interface (GUI) was developed using the computer program MATLAB to rapidly adjust several key parameters in conjunction with visual inspection of the echo-sounder data and resulting classification (fig. 11). Adjustable parameters included the maximum depth at which classification as vegetated was allowed and the minimum bottom-envelope width classified as vegetated. Changes in the classification parameters were applied to all pings from an acoustic data file (typically a survey line). This allowed the analyst to tune the parameters to correctly distinguish seagrass from other habitat types as well as to remove acoustic noise at the surface. Once the analyst was satisfied with the classification, it was exported as both a text file and a MATLAB data structure.

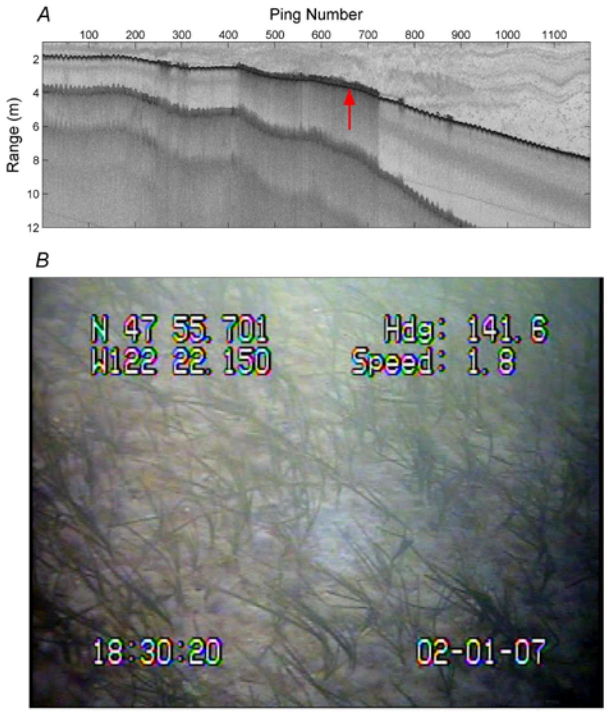


**Figure 8.** Comparison between acoustic data and a still frame taken from the underwater video camera. *A*, Acoustic data from line 93 in the northern portion of Possession Point showing the typical acoustic signature of seagrass. The red arrow denotes the location of a still frame, *B*, taken from underwater video data showing seagrass.

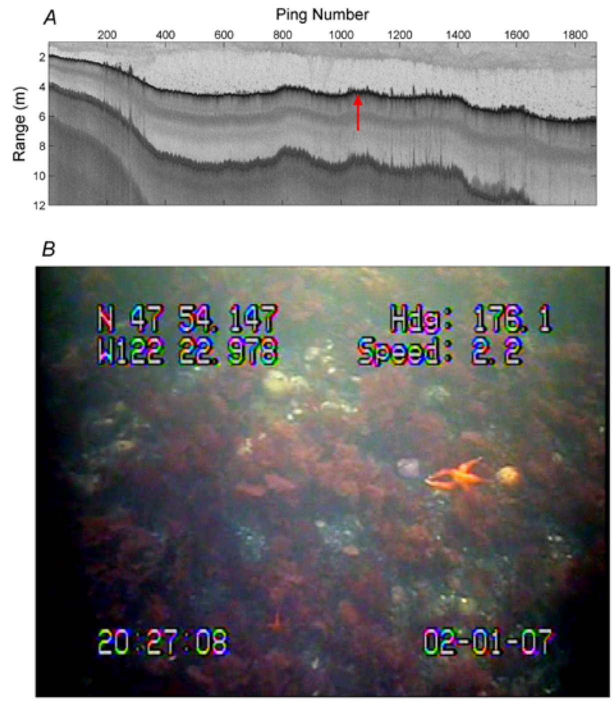


**Figure 9.** Comparison between acoustic data and a still frame taken from the underwater video camera. *A*, Acoustic data from line 5 in the southern portion of Possession Point showing the typical acoustic signature of red algae. The red arrow denotes the location of a still frame, *B*, taken from underwater video data showing red algae.

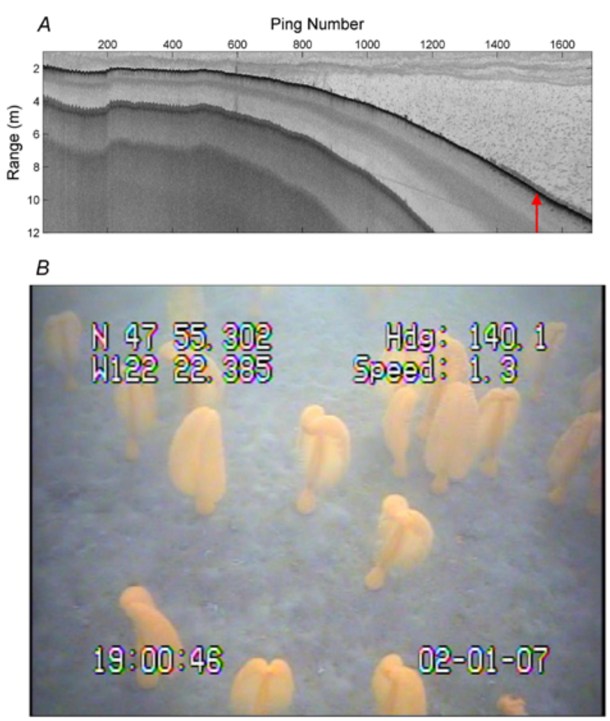


**Figure 10.** Comparison between acoustic data and a still frame taken from the underwater video camera. *A*, Acoustic data from line 63 in the central portion of Possession Point showing the typical acoustic signature of sea pens. Note the elevated near-bottom backscatter at ranges greater than 8 m. The red arrow denotes the location of a still frame, *B*, taken from underwater video data showing sea pens.

## Data Output

After the classification was completed, the raw data output included x and y coordinates interpolated for each ping, raw bottom depth (range), vegetation presence or absence, and vegetation height. The raw bottom depths were corrected to the vertical datum NAVD88 by adding the GPS height to raw depths and subtracting the distance between the GPS antenna and transducer. The computer program VDatum (Spargo and others, 2006) was used to compute the difference between NAVD88 elevations and mean lower low water (MLLW). In this study, the survey area was small and a static offset of

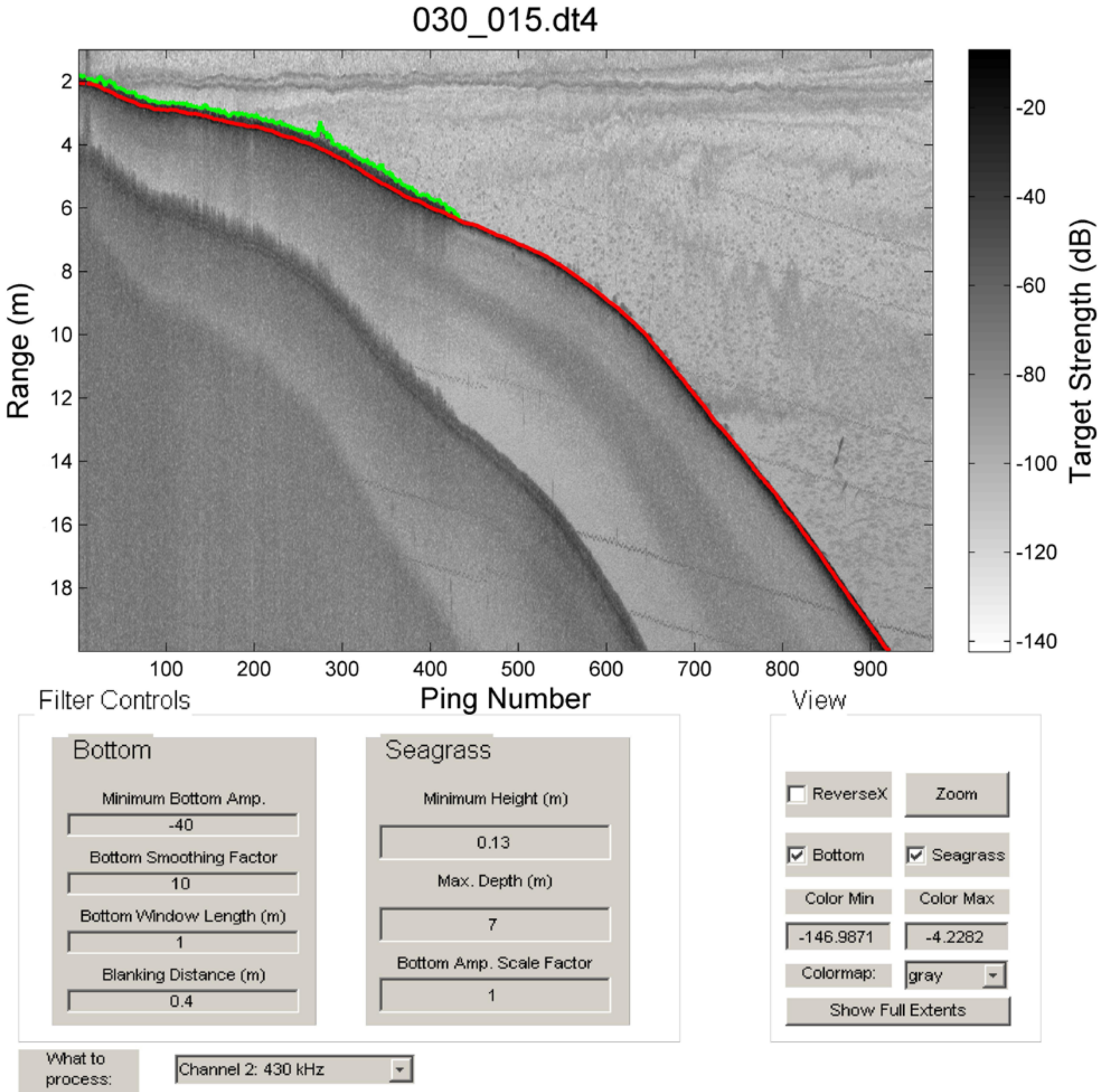


**Figure 11.** Screen shot of the graphical user interface (GUI) created for seagrass and depth classification. Adjustable parameters (edit boxes above) allow the signal-processing algorithm to be rapidly adjusted.

+0.605 cm was added to all NAVD88 elevations to convert to MLLW. Using the same system, Grossman and others (2007) calculated the root-mean-squared (RMS) error of vertical elevations (including error from the RTK-GPS, the sonar, and errors introduced during data processing) to be between 2.6 and 9.8 cm.

Rather than outputting each ping individually, pings were grouped into packets of 10. For each group of 10 pings, mean x and y positions were calculated, as well as mean depth and seagrass height. The fraction of pings in each group classified as vegetated was reported as an estimate of percent cover. The final result of the processing was a data point reported every 2 s corresponding to a between-point horizontal distance of approximately 4-5 m, assuming a boat speed of 4-5 knots.

Smooth surfaces of bottom depth were generated using linear, Delaunay interpolation. However, using linear interpolation for seagrass, a feature that is inherently patchy in nature, can lead to errors (Guan and others, 1999; Valley and others, 2005) and a misleading representation of small-scale patchiness (Fonseca and others, 2002). Both Guan and others

(1999) and Valley and others (2005) suggest kriging as the best interpolation method for seagrass attributes (that is, height and percent cover). Kriging is a procedure that uses a model of the observed spatial variability of a data set, or semivariogram, to interpolate between sample locations (Davis, 2002). For this study, interpolations of seagrass percent cover were performed with Surfer using kriging with a spherical model of the semivariogram.

# Results and Discussion

## Underwater Video and Acoustic Data Comparison

In this section we compare results from acoustic data and simultaneous underwater video transects in order to better understand the accuracy, benefits, and limitations of using acoustics to describe seagrass habitat.

In many cases, underwater video and acoustic data show remarkable agreement. For example, consider the qualitative differences in acoustic backscatter associated with changes in seagrass abundance observed in underwater video from survey line 123 in the Possession Point study site (fig. 12). Bare and vegetated areas can be clearly distinguished in the acoustic data, and differences in seagrass percent cover appear to be evident as well (compare B and C). The acoustic data also appear to be sensitive to changes in plant height caused by the orientation of the plants in the water column (compare B and D). This indicates that estimates of plant height and biovolume from acoustic data should be used with extreme caution in areas subject to strong currents, as has been noted by Sabol and others (2002).

A quantitative comparison between acoustic data (fig. 13*A*) and classified underwater video (fig. 13*B*) along line 123 also shows broad agreement. The bare areas observed in the underwater video (white areas, in *B*) coincide with areas classified acoustically as unvegetated (0 percent cover, red line). On the other hand, continuous seagrass identified in the underwater video (black areas, in *B*) coincide with areas of high percent cover from the acoustic data (red line). In seagrass classified as patchy in the video (gray areas, in *B*), acoustically derived seagrass cover is highly variable, but mostly greater than zero. The classified underwater video data overlaid on a map of interpolated seagrass percent cover from acoustic data (fig. 13*C*) reveals a complex spatial distribution in this area that may account for some of the differences between the two techniques.

Comparison of acoustic seagrass percent cover versus underwater video for the entire Possession Point data set is summarized in figure 14. For each underwater video data point, the nearest acoustic data point was determined. Only points with GPS locations less than 3 m apart were used in the analysis (NOTE: This distance does not include the layback or the offset between underwater video camera and GPS). The acoustically derived percent cover estimates were binned according to the three video classes (B= bare, P = patchy, and C = continuous). Overall, mean acoustically derived percent cover in areas classified with the underwater video as bare, patchy, and continuous are 4, 65 and 93 percent, respectively (fig. 14*A*). Histograms for the three categories (fig. 14*B*-*D*) show that the acoustic technique is highly efficient at determining whether an area is bare or has continuous seagrass. However, within areas classified with the video as patchy seagrass, a wide variety of acoustic percent cover estimates were observed.

A confusion matrix (see, for example, Fielding and Bell, 1997) showing the number of correct and incorrect acoustic-based percent cover estimates and their associated accuracies is given in table 1. Out of 808 underwater video observations that were classified as bare, 740 (91.6 percent) were correctly classified with acoustics. Within areas classified as patchy seagrass in underwater video, the sonar classification was considered correct if it fell between 10 and 90 percent cover. The acoustic cover estimates of patchy seagrass were correct in 186 out of 428 observations (43.5 percent). Finally, in areas observed to be continuous seagrass with underwater video, the acoustic data were correct in 155 out of 203 observations (76.4 percent).

One reason for the wide range of acoustic percent cover estimates in the patchy underwater video class (fig. 14*B*) is the definition used for classification of the underwater video data. For example, in a 2-s segment of underwater video, 1.8 s was vegetated and 0.2 s was bare. This 2-s segment would

**Table 1.** Confusion matrix of acoustic versus underwater-video characterization of seagrass cover in the Possession Point study site.

| | | Underwater Video | | |
|---|---|---|---|---|
| | | **Bare** | **Patchy** | **Continuous** |
| **Acoustic** | Bare | 740 | 75 | 4 |
| | Patchy | 51 | 186 | 44 |
| | Continuous | 17 | 167 | 155 |
| | Total | 808 | 428 | 203 |
| | Accuracy (percent) | 91.6 | 43.5 | 76.4 |

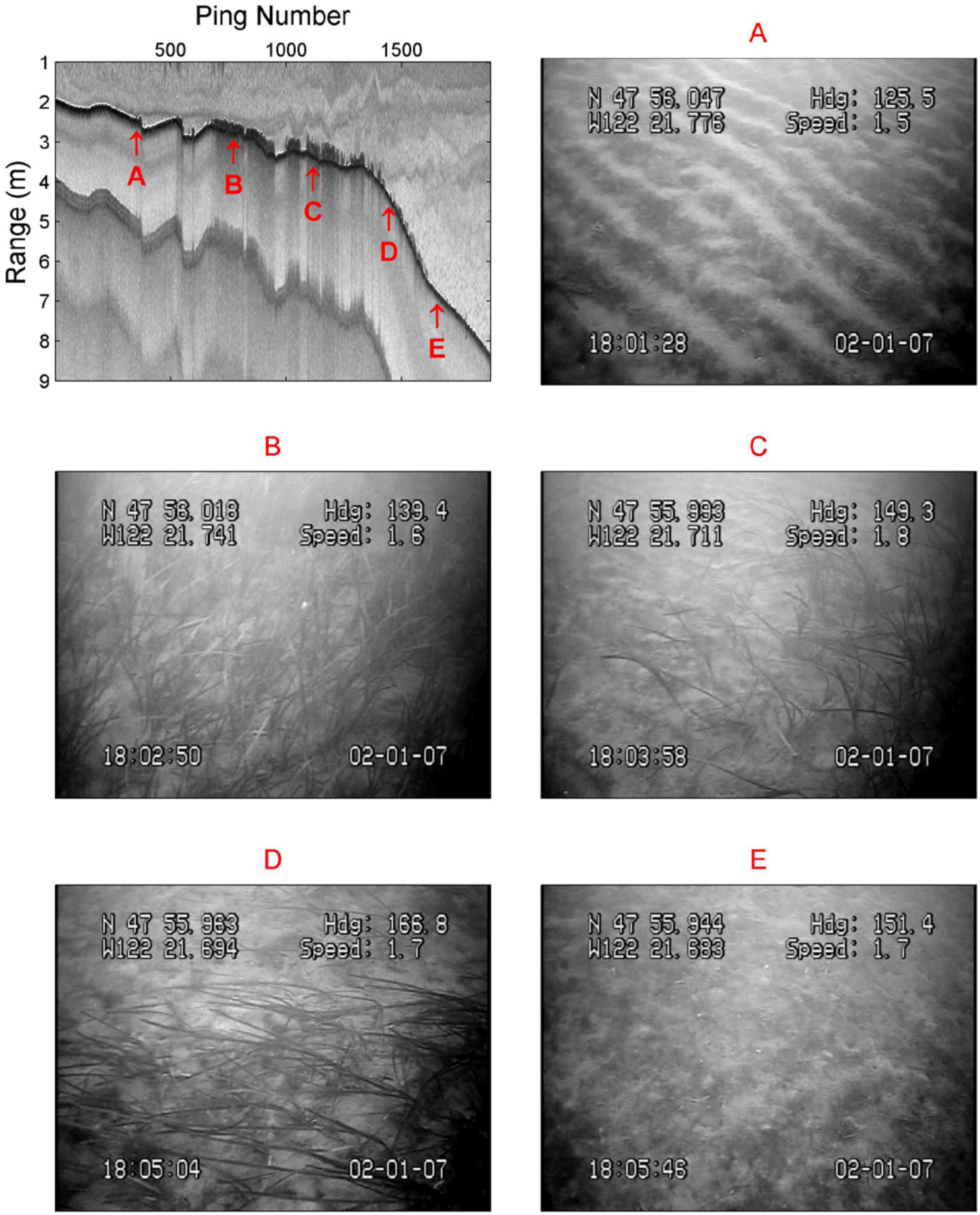


**Figure 12.** Acoustic backscatter data from line 123 (top left) with black and white video stills containing no seagrass (*A, E*), dense seagrass (*B*) and patchy seagrass (*C,D*). The same letters mark the location of the stills in the acoustic data.

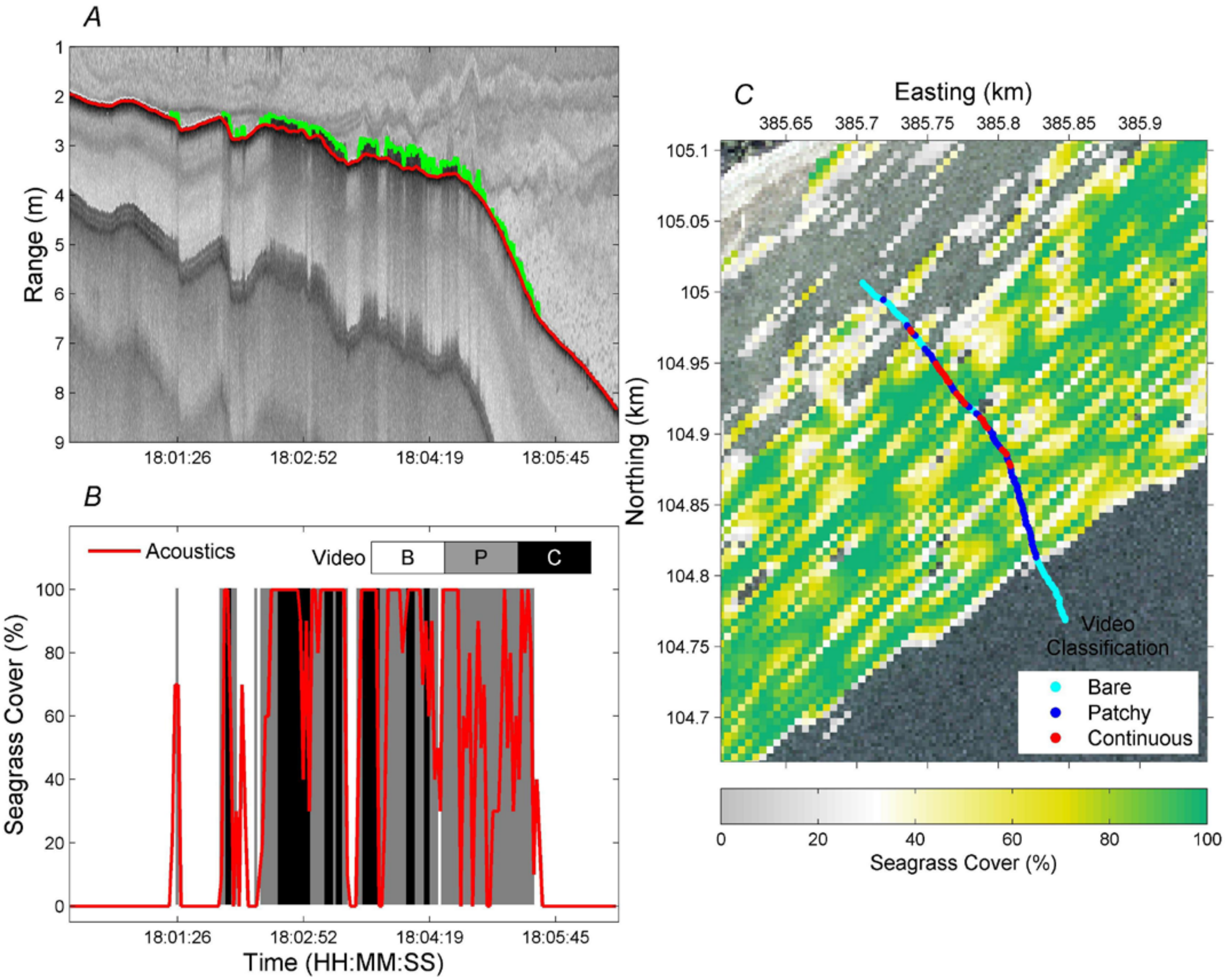


**Figure 13.** Comparison of acoustic and video classification along line 123 at the Possession Point study site. *A*, Classified acoustic backscatter data. *B*, Numerical comparison of acoustic percent cover with underwater video data. Red line is the acoustic seagrass percent cover. The video classification is represented with white (bare), gray (patchy), and black (continuous) areas. *C*, Map view of classified underwater video overlaid on grid of acoustic seagrass cover.

be classified as patchy using the definitions of the classification scheme in this study. Meanwhile, the acoustic estimate of percent cover would be 90 percent. Now suppose that 0.2 s of video was sparsely vegetated and 1.8 s was bare. This too would be considered patchy seagrass, but the acoustic percent cover would only be as much as 10 percent. Possible solutions to this problem include adding more classification categories to the underwater video analysis or breaking the video into smaller units of 0.5 or 1 s. However, this example does not explain why so many points classified as patchy seagrass in the underwater video were observed to be either 0 or 100 percent cover with the acoustic technique.

Additional sources of error arising from the techniques used to collect and process the data contribute to the differences between underwater video and acoustic estimates of seagrass habitat, especially in areas with patchy seagrass. First, although acoustic and underwater video data were collected simultaneously, they were not precisely colocated. The echo sounder was operated from the starboard side of the ship, whereas the underwater video was deployed from the port side. Furthermore, layback between the underwater video camera tow-fish and the shipboard GPS recording the video camera position was occasionally observed during data collection. The layback increases with the depth of the video

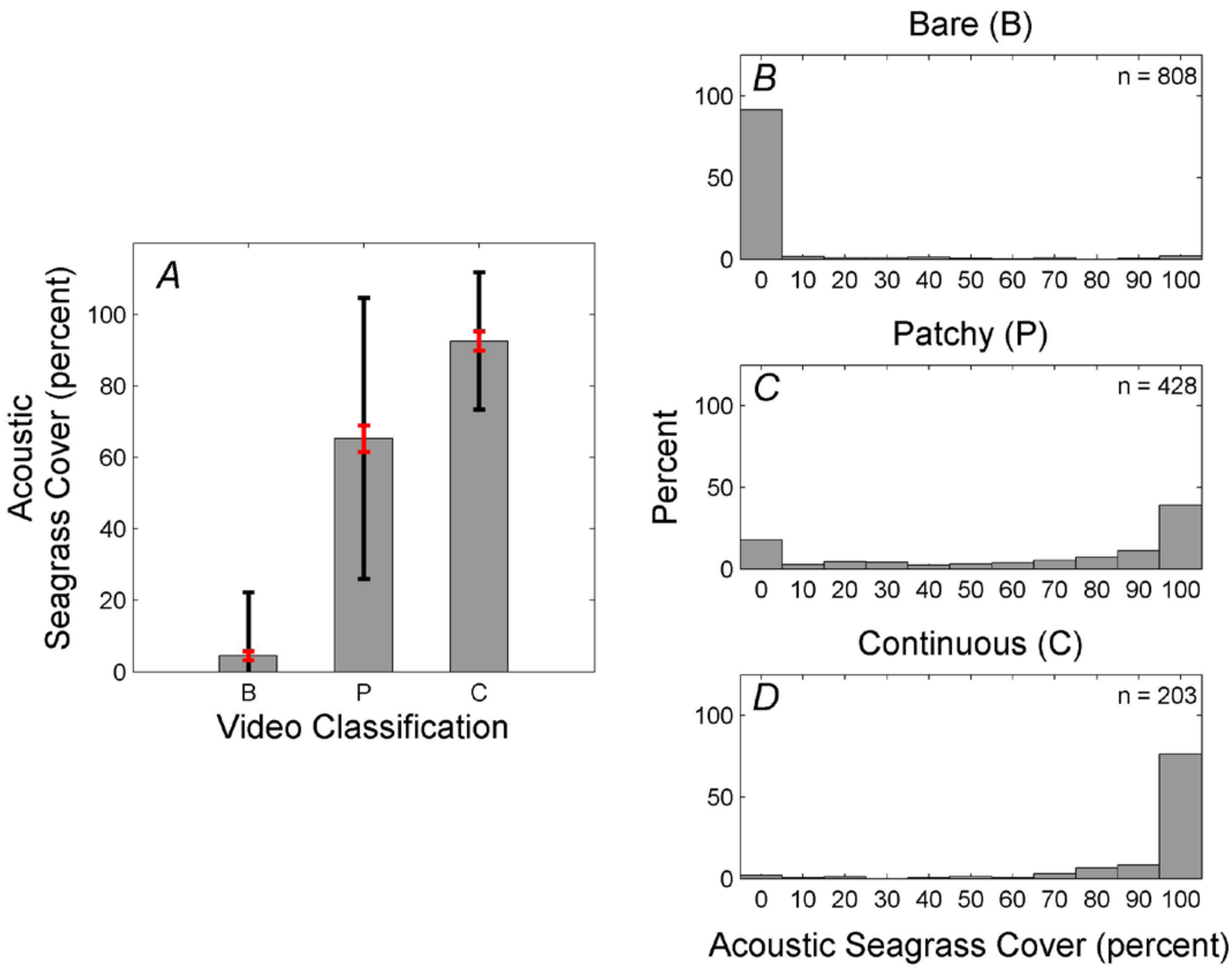


**Figure 14.** Comparison of acoustic and video classification for different densities of seagrass. *A*, Mean acoustic seagrass percent cover (± 1 standard deviation, black lines, ± 95 percent confidence interval, red lines) compared with classified underwater video (B = bare, P = patchy and C = continuous) collected at Possession Point. *B-D*, Normalized histograms of acoustic percent cover of seagrass for each video classification group.

camera and the speed of the ship. Using calculations given in Gibbs and others, 2005, the layback of the camera could be as great as 15 m in water depths greater than 10 m. This problem is minimized because most of the seagrass habitat occurred in shallow areas where the video camera was just below the surface and very near the GPS. Nevertheless, uncertainties in the relative position between the underwater video and acoustic survey equipment likely contribute to the poor agreement between the two methods in patchy seagrass.

Another limitation of the direct comparison is that the area of the sea floor sampled (the instrument footprint) may be different. Ideally for a direct comparison, the two techniques would be sampling a similar area of the sea floor. In this case, the unit area for both methods is based on a 2-s interval of continuous data (10 pings at 5 Hz are averaged for the acoustic data, 2 s of underwater video in between GPS fixes). However, the field of view changes for the video camera with the distance between the camera and the sea floor, and the area that is sampled by the sonar equipment changes with the distance between the transducer and the seabed (6 degree beam-angle). These differences may be significant when trying to quantitatively compare measurements of plant cover from the two techniques.

## Possession Point

Acoustic data were collected along 163 survey lines in the Possession Point study site between January 30 and February 1, 2007 (fig. 15). A total of 60 km of acoustic data was collected, with individual line lengths ranging from 33 m to 3.7 km. A list of survey line number, filename, time of collection, as well as elapsed time and distance for each line collected at Possession Point is given in appendix A. Additionally, 4.6 km of underwater video data was collected along 19 cross-shore survey lines throughout the study site (fig. 15).

The bathymetric grid produced by the acoustic survey data (fig. 16) reveals a complex morphology with prominent changes from north to south. At the very northern end of the study site (north of 105.25 km northing), the low-tide terrace is narrow, with steep slopes very near the shoreline (fig. 17). From 105.25 to 103 km northing, the low-tide terrace is broad, reaching as much as ~300 m wide. North of 104.5 km northing, large shore-parallel bed forms (~30 m wavelength) are evident in the shaded bathymetry. The bed-form morphology is further elucidated by local changes in the direction of slope of the seabed (fig. 18). Whereas most of the bathymetry is sloped away from shore at roughly 45-60 degrees, the inshore sides of the bed forms are directed in the opposite direction. Farther south, between 103 and 102 km northing, the low-tide terrace is narrow and steep, with slope angles typically greater than 10 degrees. At the southern tip of Possession Point, the low-tide terrace again widens and flattens, stretching towards the south, where Possession Sound and Admiralty Inlet intersect.

The distribution of seagrass at the Possession Point study site derived from acoustic data is shown in figures 19-21. The majority of seagrass at Possession Point is limited to the broad, shallow low-tide terrace region between 103 and 105.25 km northing, though some seagrass extends as far south as 102.3 km northing. The cross-shore extent of seagrass appears to largely be controlled by local water depth, with seagrass mostly observed between 0.5 and -4.5 m MLLW. One stark contrast in this pattern is a gap in the seagrass between 103.5 and 103.75 km northing. The sediment in this bare region is distinctly coarser (fig. 22), with a mean grain size as large as -2 phi. The coarser sediment may be the reason for the lack of seagrass (Koch, 2001). Grain size in phi units can be converted to grain size in millimeters using equation 1:

$$\text{millimeter} = 2^{-\text{phi}} \quad (1)$$

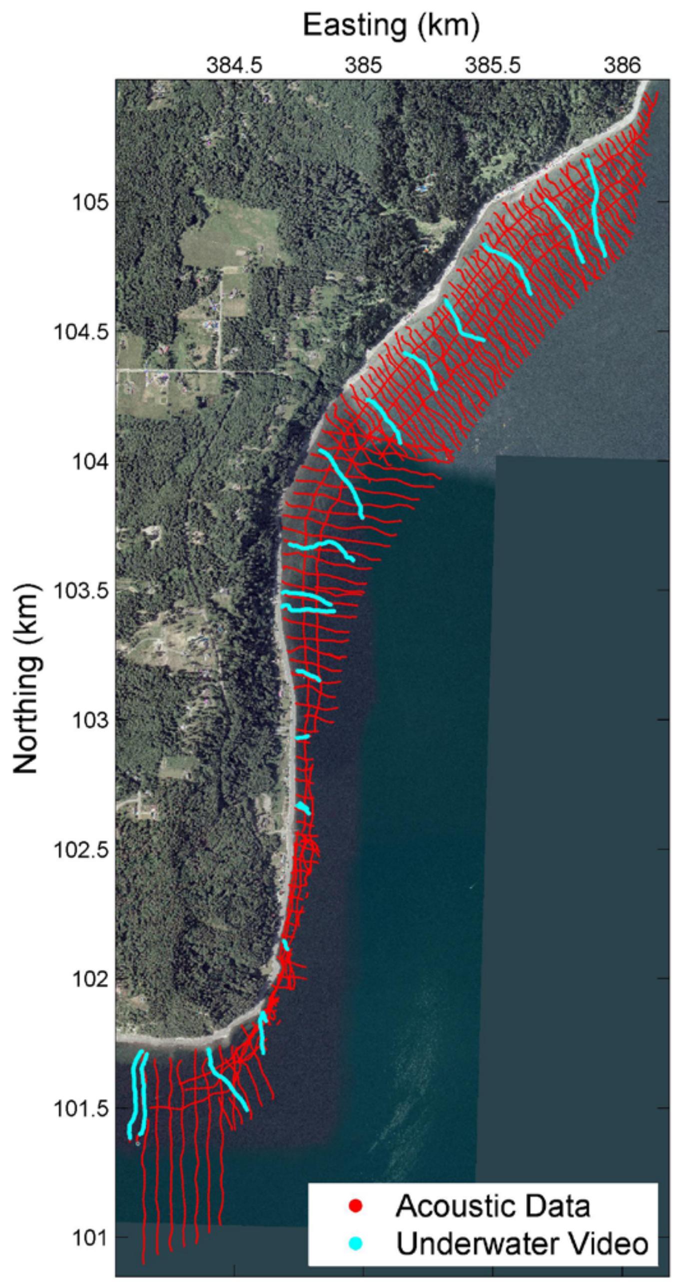


**Figure 15.** Acoustic (red lines) and underwater-video (cyan lines) data coverage for the Possession Point study site. Map projection is Washington State Plane North.

The apparent spatial complexity of seagrass shown in figure 20 increases from south to north, coinciding with the increased presence of bed forms in the far northern portion of the study site. This patchiness could be indicative of increased wave and current energy in that area (Fonseca and Bell, 1998). However, the true complexity of the seagrass distribution is not fully resolved because of a transect spacing of 25 m.

Using the interpolated grid of percent seagrass cover, the total aerial coverage of seagrass was estimated by summing the fractional percent cover estimates in each grid cell multiplied by the grid cell area. At the Possession Point study area, seagrass covered roughly 0.29 $km^2$ (19 percent) of the total 1.51 $km^2$ area surveyed.

Both the total area of seagrass and percent seagrass cover are strongly affected by water depth (fig. 21). The observed seagrass habitat was limited to depths between 0.5 and -4.5 m, though a very small amount was found in both shallower and deeper water. The most abundant and highest

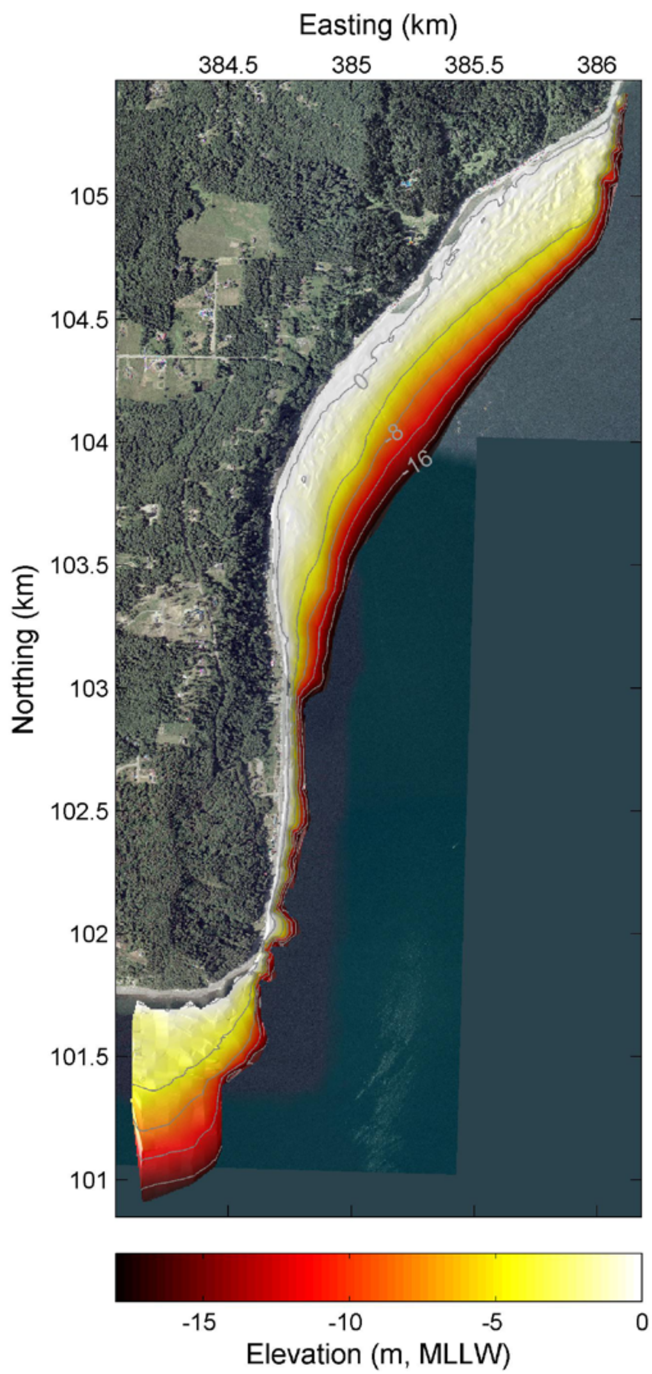


**Figure 16.** Interpolated bathymetry from acoustic survey data at Possession Point. The grid resolution is 5 m and contour interval is 4 m. Vertical datum is MLLW.

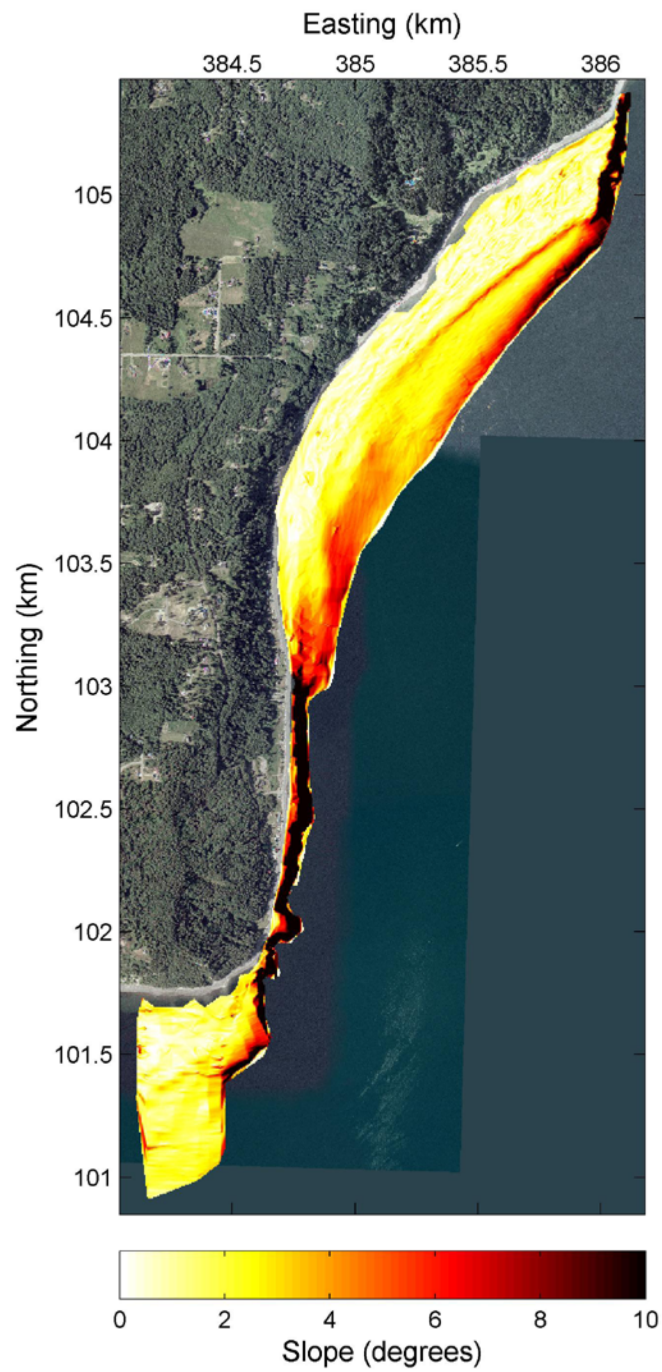


**Figure 17.** Interpolated seabed slope at Possession Point. The grid resolution is 5 m.

percent cover of seagrass were found at water depths between -0.5 and -2.5 m, where as much as 50 percent of the total area was 90-100 percent seagrass cover. Below -2.5 m water depth, both the amount of total seagrass habitat and percent cover decrease exponentially. By -5 m water depth, seagrass habitat was found in only 2 percent of the area surveyed. The pronounced decline in seagrass habitat with depth is typically associated with light limitation (Duarte, 1991). In shallow water, between 0.5 and -1 m water depth, the meadow is characterized by a higher proportion of low percent seagrass cover. The seagrass in shallow water is not light limited, but growth is most likely limited by physical factors such as desiccation or increased wave energy reaching the bottom (Koch, 2001).

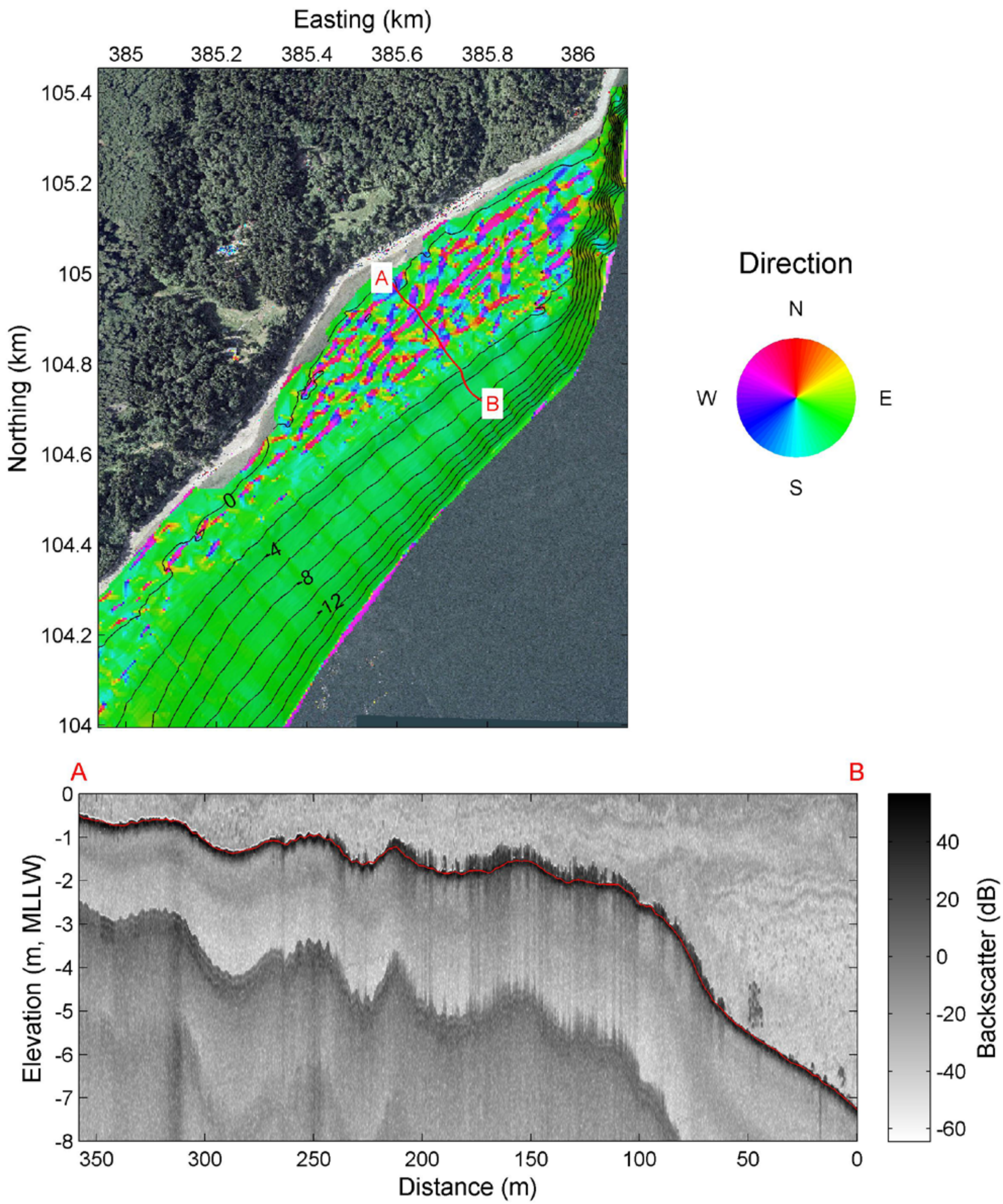


**Figure 18.** Interpolated bathymetric slope angle for the northern portion of the Possession Point study site (top). Generally, the slope of the seabed is to the southeast (green colors), but shore-parallel bed forms with landward sides facing northwest (pink) are also evident. The grid resolution is 5 m. The red line (A-B) shows the location of acoustic data in the bottom panel. The bathymetric cross-section (thin red line, bottom panel) shows large-scale bed forms with wavelengths of 30-60 m.

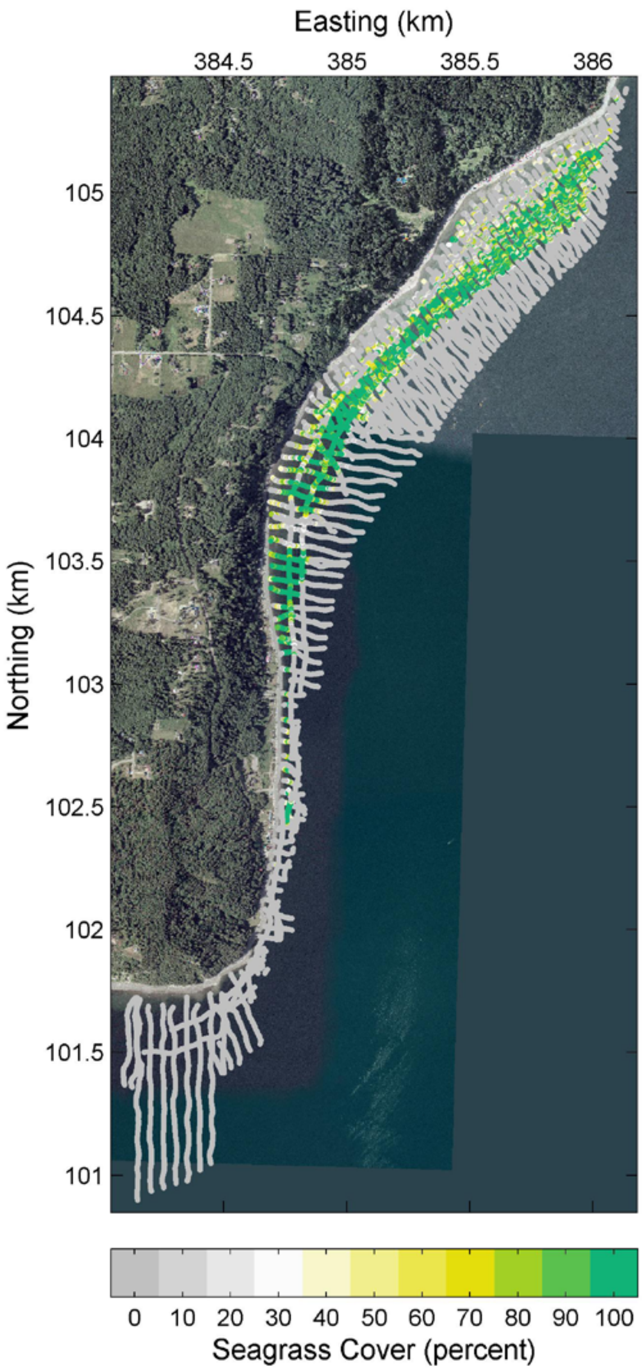


**Figure 19.** Classified acoustic data for percent cover of seagrass.

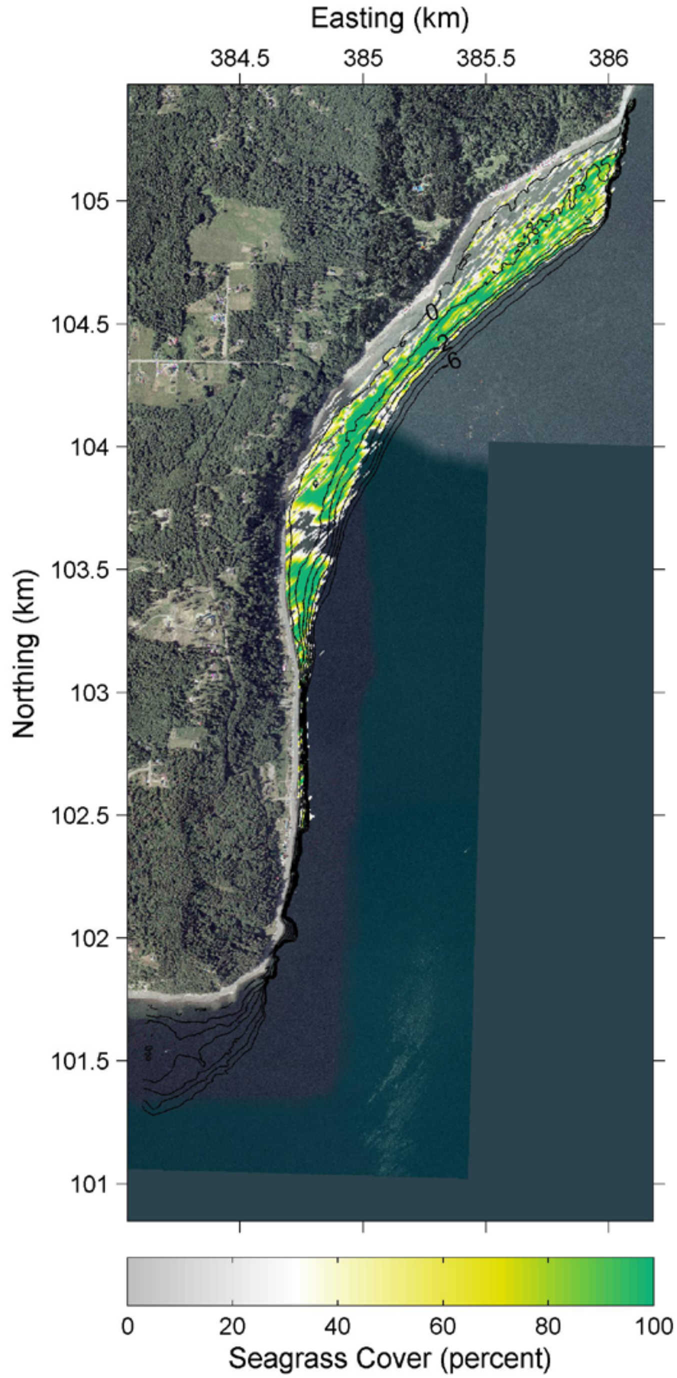


**Figure 20.** Percent cover of seagrass at Possession Point interpolated from raw fractional ping data shown in figure 19. Grid resolution is 5 m. Bathymetric contour interval is 1 m.

The classified underwater video data showed a similar pattern as the acoustic data, with most of the seagrass habitat concentrated in the northern portion of the study site (fig. 23). Of the 2,317 individual video segments, 1,456 (63 percent) were classified as being bare, 515 (22 percent) were classified as patchy seagrass, and the remaining 346 (15 percent) were continuous seagrass.

## Browns Bay

Acoustic data were collected along 65 lines in the Browns Bay study site on February 2, 2007 (fig. 24). A total of 18 km of acoustic data was collected, with individual line lengths ranging from 73 m to 3.1 km. A list of line number, filename, time of collection, as well as elapsed time and dis-

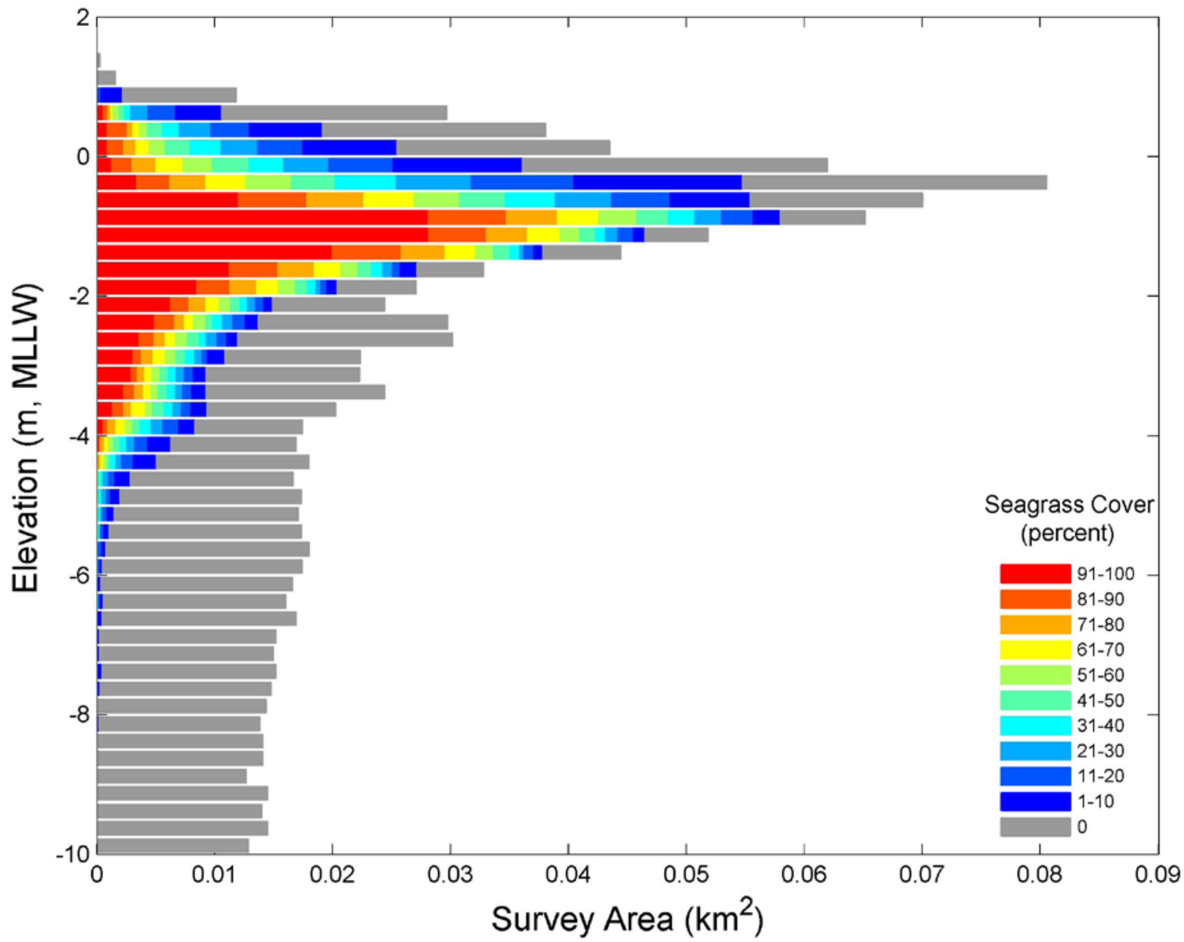


**Figure 21.** Depth distribution of seagrass at Possession Point calculated from the interpolated grid of seagrass percent cover. The total length of the bar represents the total area surveyed in each 0.25-m depth interval. Colors indicate the distribution of seagrass percent cover in each depth interval.

tance for each line collected at Browns Bay is given in appendix B. Additionally, 2.4 km of underwater video data were collected in 12 cross-shore transects throughout Browns Bay.

The bathymetric grid of Browns Bay generated from the acoustic survey data (fig. 25) shows a relatively simple morphology compared to that at Possession Point, although the width of the shallow low-tide terrace does vary somewhat from north to south. No large-scale bed forms were evident in the bathymetric data.

The seagrass in Browns Bay is mainly distributed in four distinct beds (figs. 26 and 27). Very little seagrass was observed at the extreme north and south ends of the Browns Bay study site. The total areal coverage of seagrass was estimated by summing the fractional percent cover estimates at each location multiplied by the area in each grid cell. At the Browns Bay study area, seagrass covered roughly 0.043 $km^2$ (5 percent) of the total 0.84 $km^2$ area surveyed.

The presence and percent cover of seagrass are strongly affected by water depth (fig. 28). Seagrass was mainly limited to depths ranging from -1.75 to -6 m, though a very small amount was found in both shallower and deeper water. No seagrass occurs in depths shallower than -0.25 m. The most abundant seagrass habitat in terms of areal coverage occurred at a depth of -1.25 m MLLW. However, a large percentage of seagrass habitat at that depth was sparse (between 1 and 10 percent). Higher percent cover seagrass occupied a larger portion of the area at greater depths (-2.5 to -3.5 m). The depth distribution is shifted into deeper water than at Possession Point.

The underwater video data show very little continuous seagrass in the Browns Bay study site (fig. 29). Of the 1078 individual data points, 881 (82 percent) were classified as bare, 177 (16 percent) were classified as patchy seagrass habitat, and the remaining 20 (2 percent) were continuous seagrass.

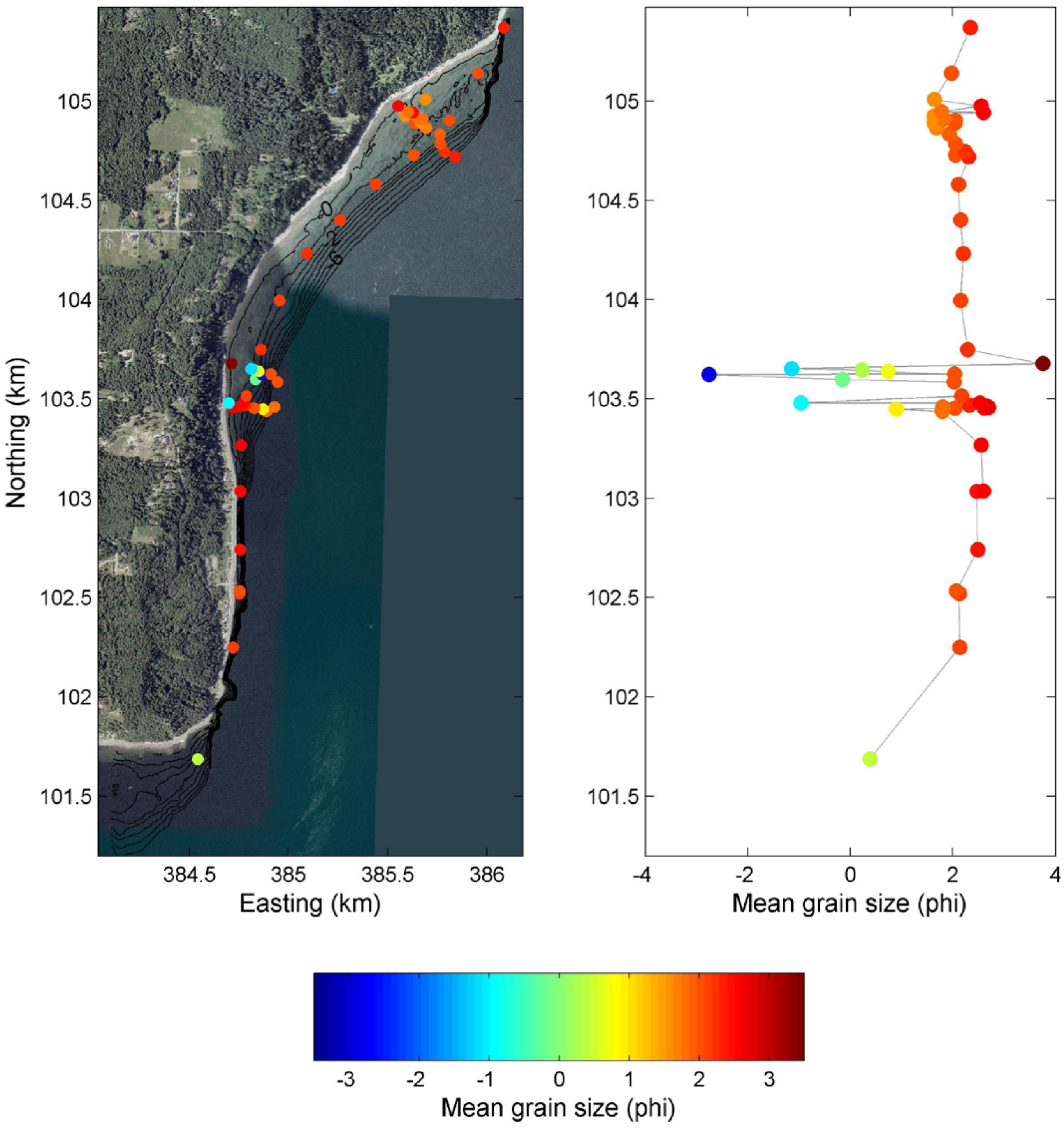


**Figure 22.** Locations of surface-sediment samples (left panel) and their mean grain sizes in phi units (right panel) along the Possession Point study site. The colors of the markers corresponds to mean grain size in both plots. Phi units can be converted to millimeters using equation 1.

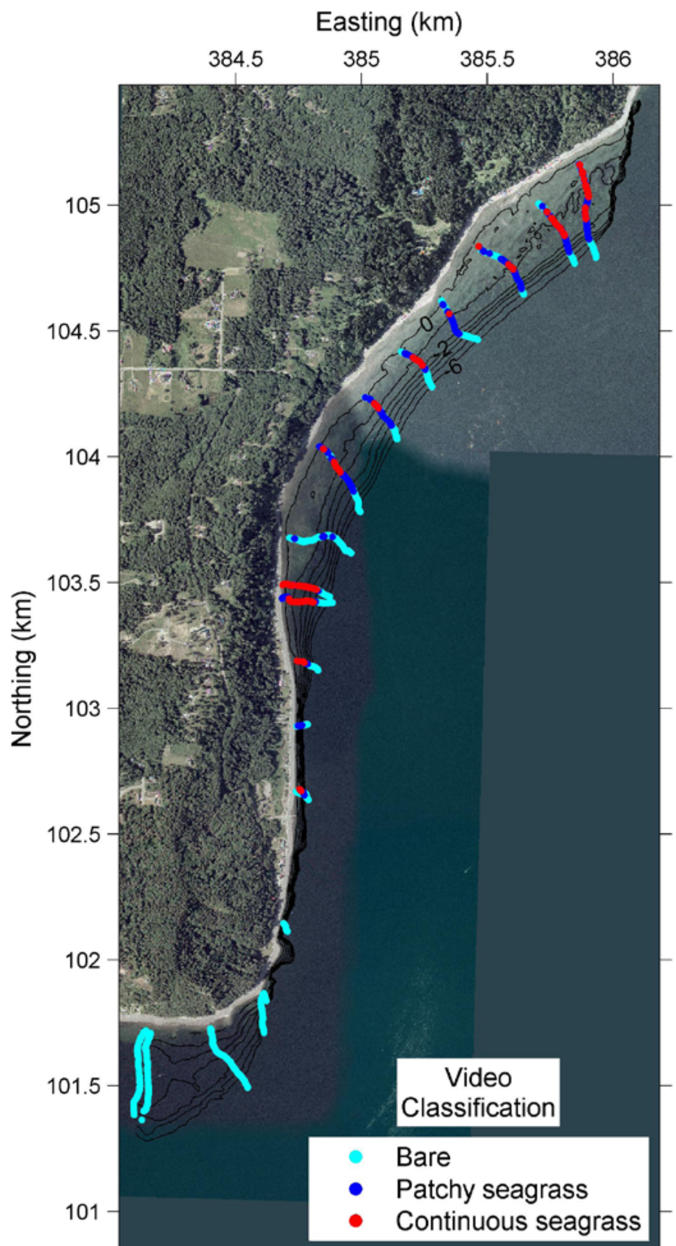


**Figure 23.** Classified underwater video data from the Possession Point study site. Bathymetric contour interval is 1 m.

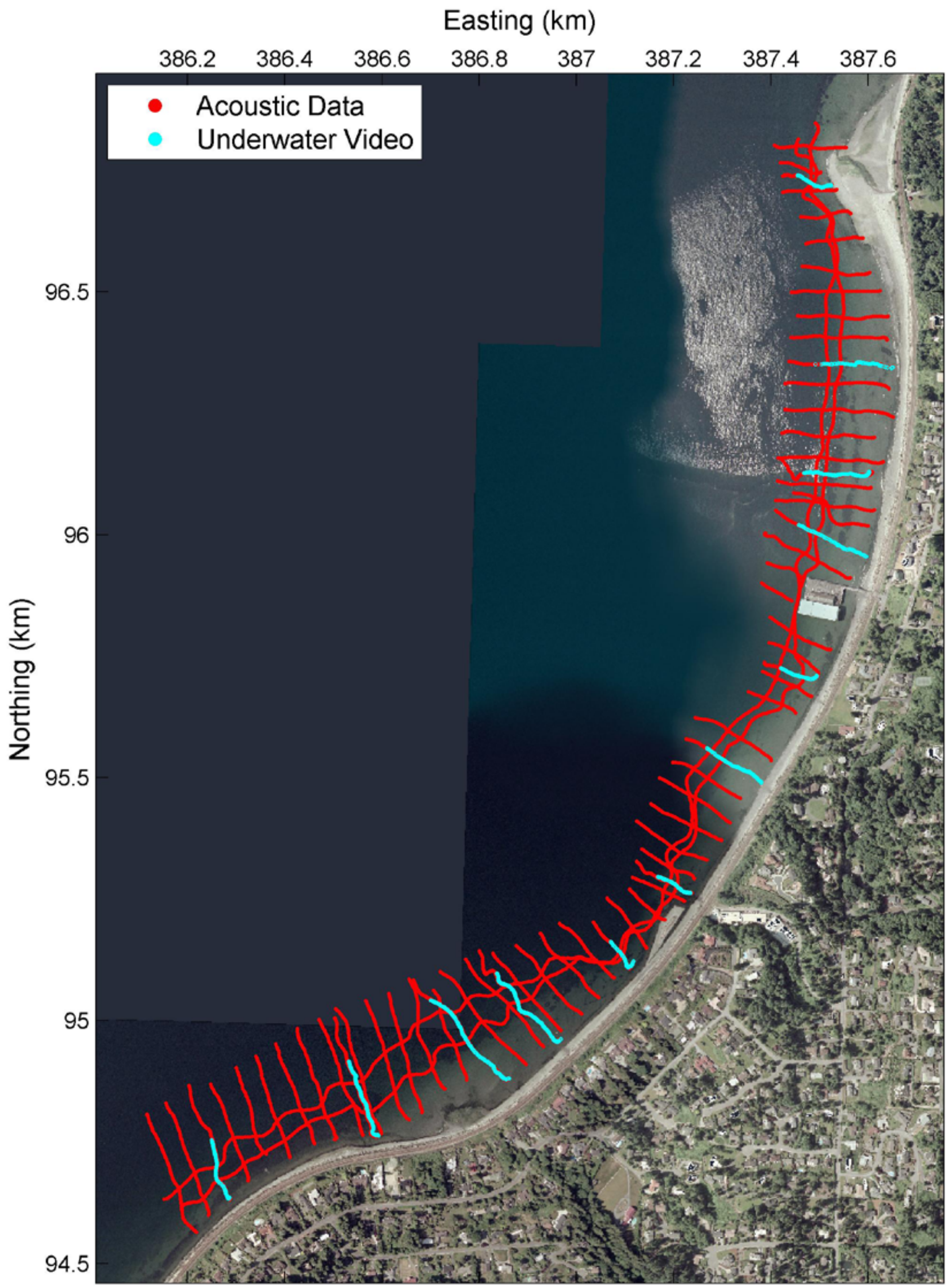


**Figure 24.** Acoustic (red lines) and underwater video (cyan lines) data coverage for the Browns Bay study site. Map Projection is Washington State Plane North.

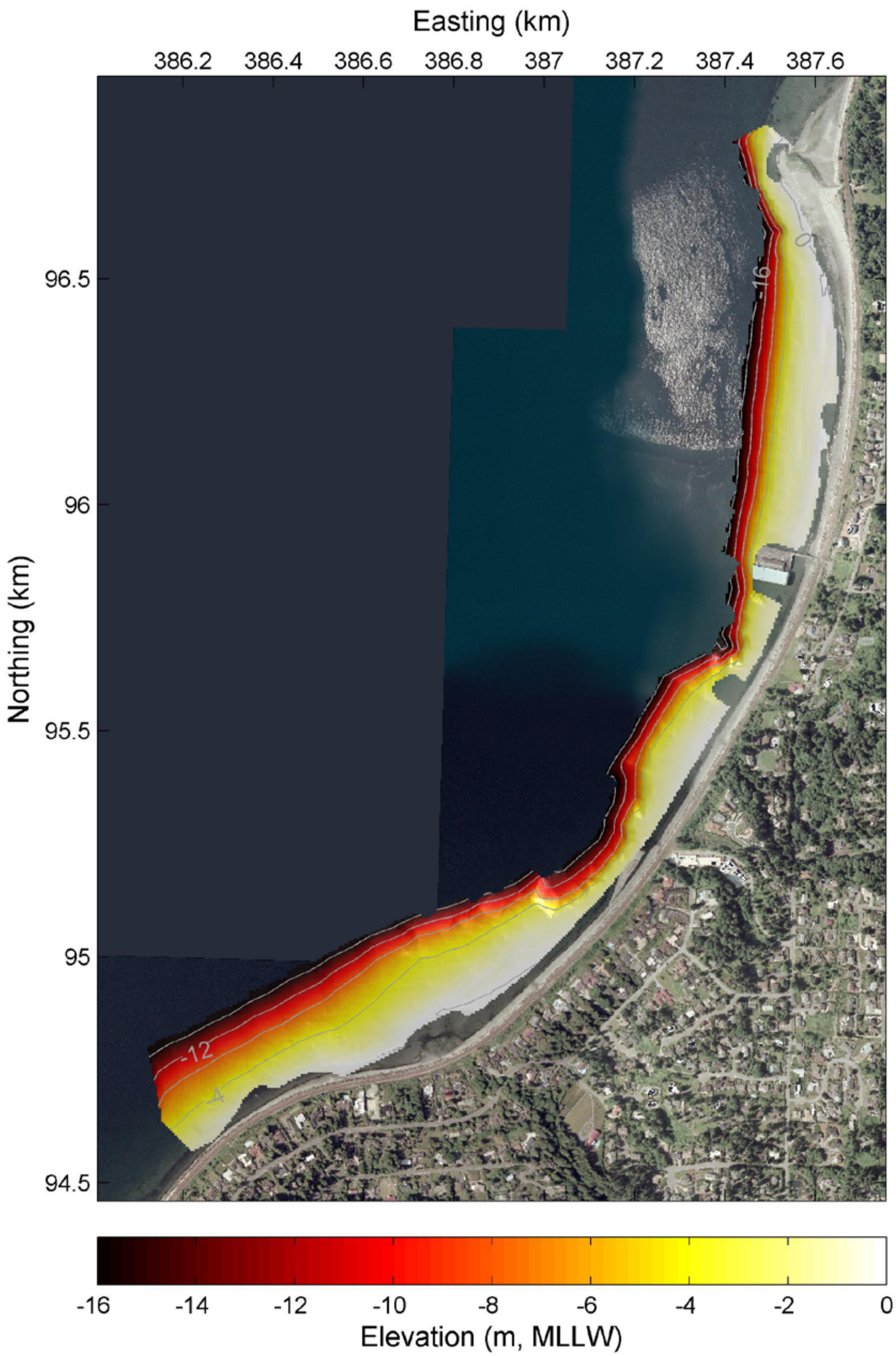


**Figure 25.** Interpolated bathymetry from acoustic data at Browns Bay. The grid resolution is 3 m and bathymetric contour interval is 4 m. Vertical datum is MLLW.

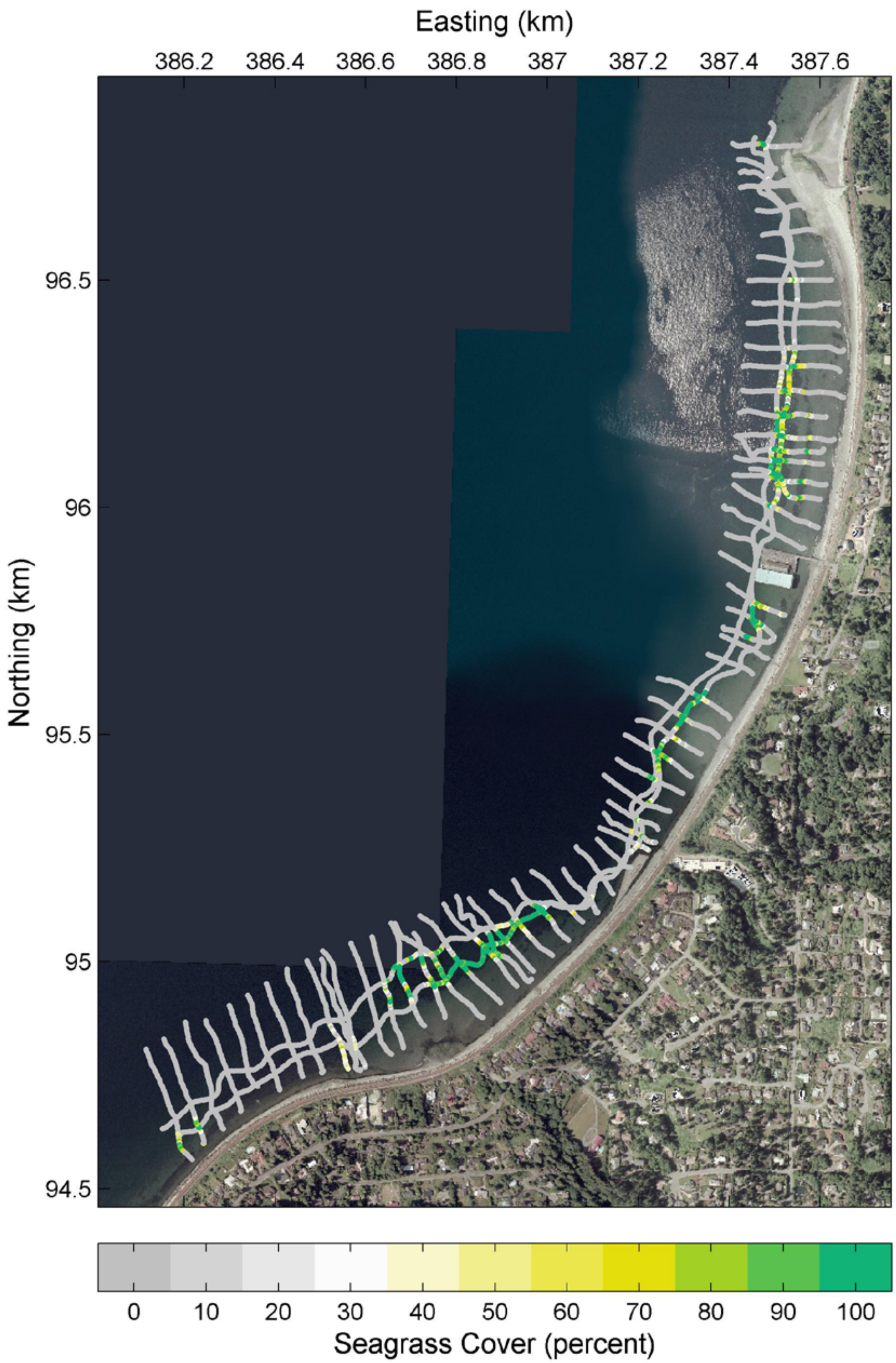


**Figure 26.** Classified acoustic data for percent cover of seagrass.

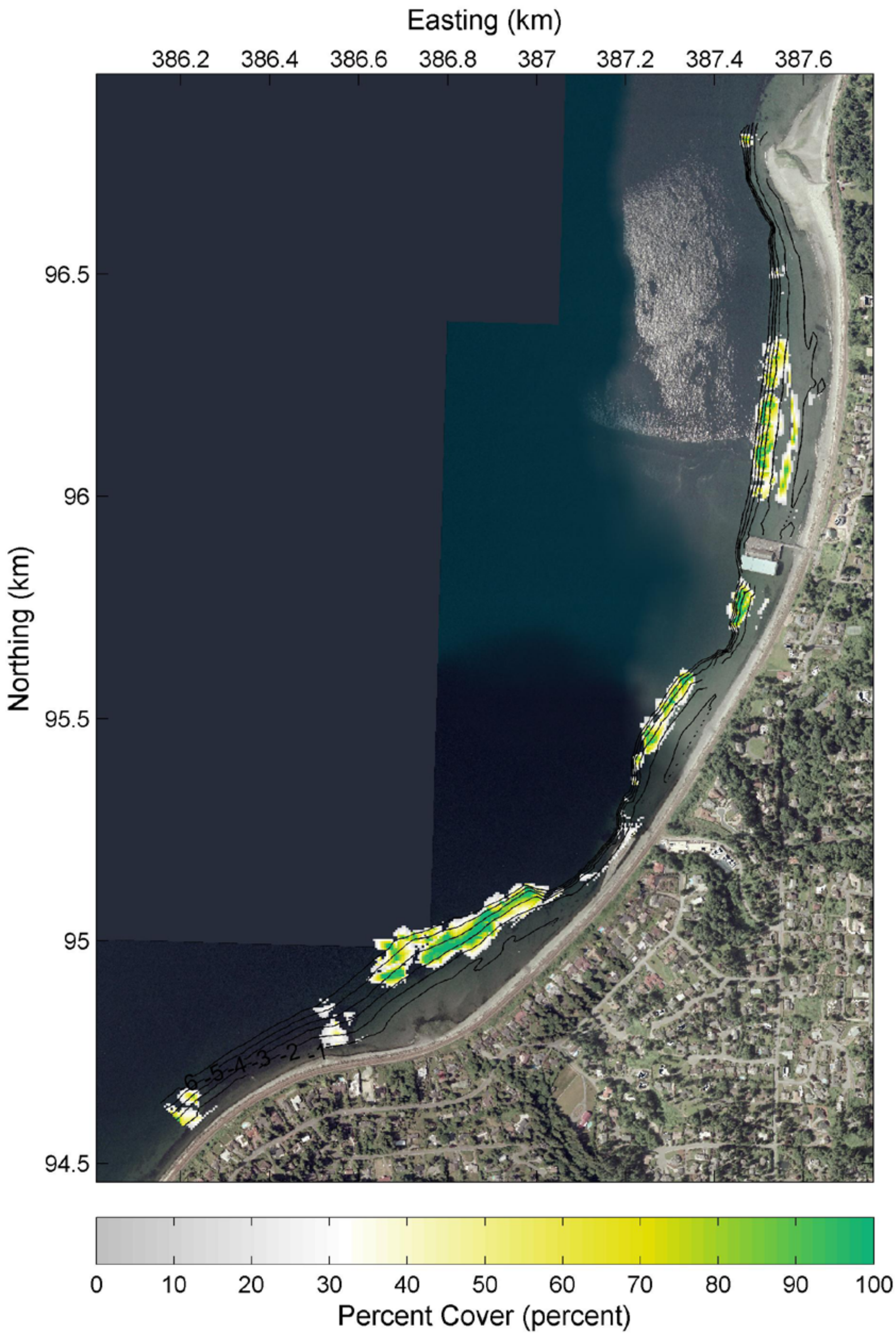


**Figure 27.** Percent cover of seagrass at Browns Bay interpolated from raw fractional ping data shown in figure 26. Grid resolution is 3 m. Bathymetric contour interval is 1 m.

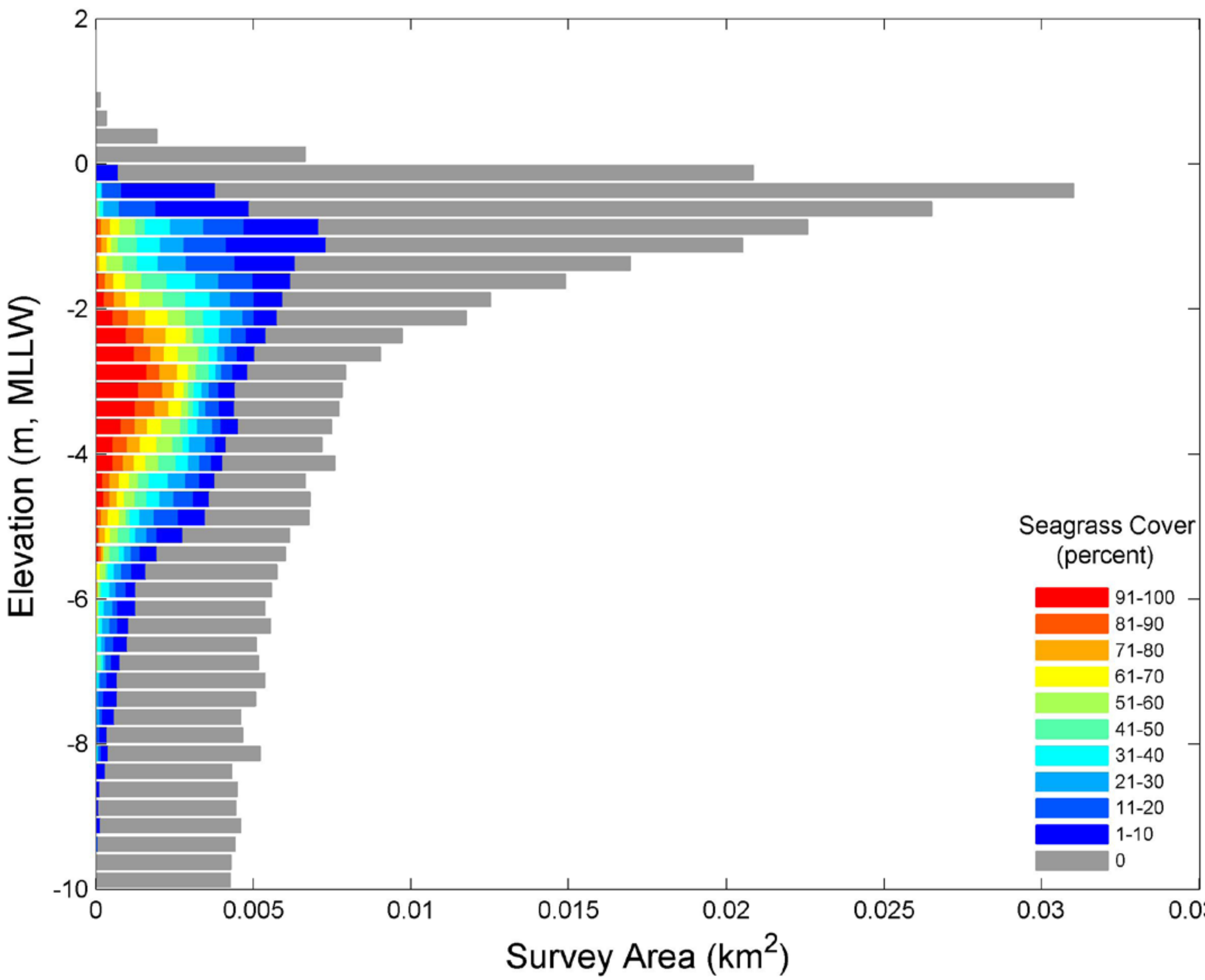


**Figure 28.** Depth distribution of seagrass at Browns Bay calculated from the interpolated grid of seagrass percent cover. The total length of the bar represents the total area surveyed in each 0.25-m depth interval. Colors scale indicate the distribution of seagrass percent cover in each depth interval.

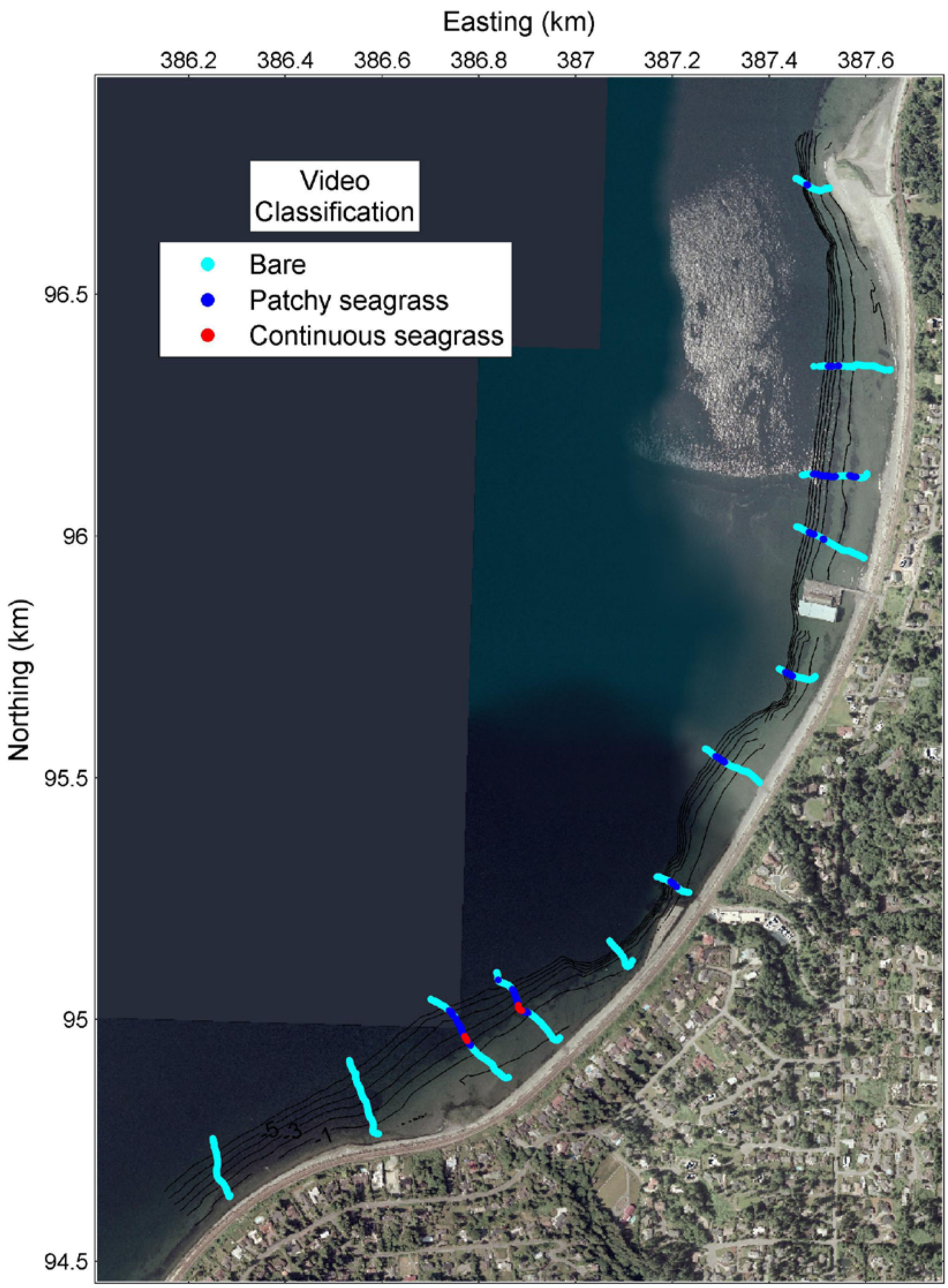


**Figure 29.** Seagrass habitat from classified underwater video transects collected from the Browns Bay study site. Bathymetric contour interval is 1 m.

## Summary and Conclusions

This study has shown that a single-beam acoustic system can accurately map seagrass and has demonstrated some of the strengths and weaknesses of the method. Classification of single-beam acoustic data for seagrass was simple, fast, and intuitive relative to other mapping techniques. However, in areas where more than one type of vegetation was present, underwater video or some other form of ground-truth data was needed in order to accurately interpret the acoustic data. We conclude that classification algorithms should not be fully automated, but rather should be supervised in order to properly adjust relevant parameters according to site-specific needs and to separate other vegetation types from seagrass during data processing.

Comparison of underwater video and acoustic data collected synchronously at Possession Point showed that classification of the acoustic data was highly accurate for determining the presence or absence of seagrass. For video segments classified as bare, patchy seagrass, and continuous seagrass, the accuracy of the acoustic classification was 92, 42, and 76 percent, respectively. We believe that the low accuracy measured in patchy areas is due in part to the fact that the video and acoustic equipment were not precisely co-located. Specifically, the underwater video camera and sonar were operated from different sides of the survey vessel during data collection. Acoustic methods have a much greater potential for measuring percent cover than video, because the high spatial resolution of the sampling lends itself to quantitative analysis. Another benefit of acoustic methods is the ability to survey in turbid areas, where visibility is minimal.

Seagrass distributions at two sites in northern Puget Sound, Possession Point and Browns Bay, were quantified using both acoustics and underwater video. Acoustic mapping revealed extensive seagrass meadows in the northern two-thirds of the Possession Point site. Seagrass occupied a depth range of 1 to -5.5 m MLLW, with the greatest area of > 70 percent cover occurring between -0.5 and -1.5 m MLLW. Patchiness of the meadow increased in the northern part of the area, where there were large sand dunes. A bare patch in the middle of the densely vegetated area was observed, coinciding with a region of substrate with much larger particle size. Seagrass coverage in Browns Bay was relatively sparse. The depth range was 0 to -7 m MLLW, with greatest area of > 70 percent cover occurring between -2.25 and -3.5 m MLLW. Tidal currents and exposure to southerly winds and waves are thought to be fairly similar at Possession Point and Browns Bay. A major difference between the two sites is the railroad grade and tracks that extend below the high water line along much of the shoreline at Browns Bay. Human alteration of nearshore processes is one of many possible factors influencing the seagrass distributions at Possession Point and Browns Bay. Further investigation into why the distribution of seagrass at these two seemingly similar sites is so different may shed light on the effects of human alteration of nearshore processes on seagrass throughout Puget Sound.

## Acknowledgments

The authors acknowledge several groups and individuals without whom this study would not have been possible. First and foremost, we would like to thank several people at the USGS Columbia River Research Lab in Cook, Washington. Marty Liedtke was instrumental in facilitating the loan of both the Biosonics system and a boat for the work presented in this report. In addition, we borrowed one of her technicians, Collin Smith, who ably navigated the boat during the surveys. Tom Batt shared his knowledge of the Biosonics system during the testing phase of this work. The cooperation between the Biological Resource Division facility in Cook and our group was tremendous.

Andrew Schwartz of the Washington State Department of Ecology helped install the benchmark and operated the GPS equipment for the surveys. Art Pratt at the Possession Point Waterfront Park went out of his way to help keep the boat ramp clear of sand so that we could launch and retrieve our boat each day. He also provided storage for the boat and trailer during the surveys. Mike Burger at Biosonics provided last minute help troubleshooting the acoustic gear. Gerry Hatcher of the USGS in Santa Cruz, California, was a tremendous help in setting up the video and sonar systems during tests conducted at the Columbia River Research Lab. Tom Reiss, also of the USGS in Santa Cruz, installed and surveyed the benchmark that was used in this study.

This report was improved tremendously by excellent reviews from Ann Gibbs (USGS), Ted DeWitt (U.S. Environmental Protection Agency) and Jeff Gaeckle (Washington State Department of Natural Resources). We thank all our friends and colleagues for their support during this effort.

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# Appendix A. Data Collected at Possession Point

Appendix A provides a list of all acoustic and underwater video data collected at Possession Point between January 30 and February 1, 2007. The location of planned lines is given in figure A1. The line numbers, acoustic data filenames, collection dates and line lengths collected each day are provided in tables A1 through A3. The tide heights during data collection for each day are shown in figures A2 through A4.

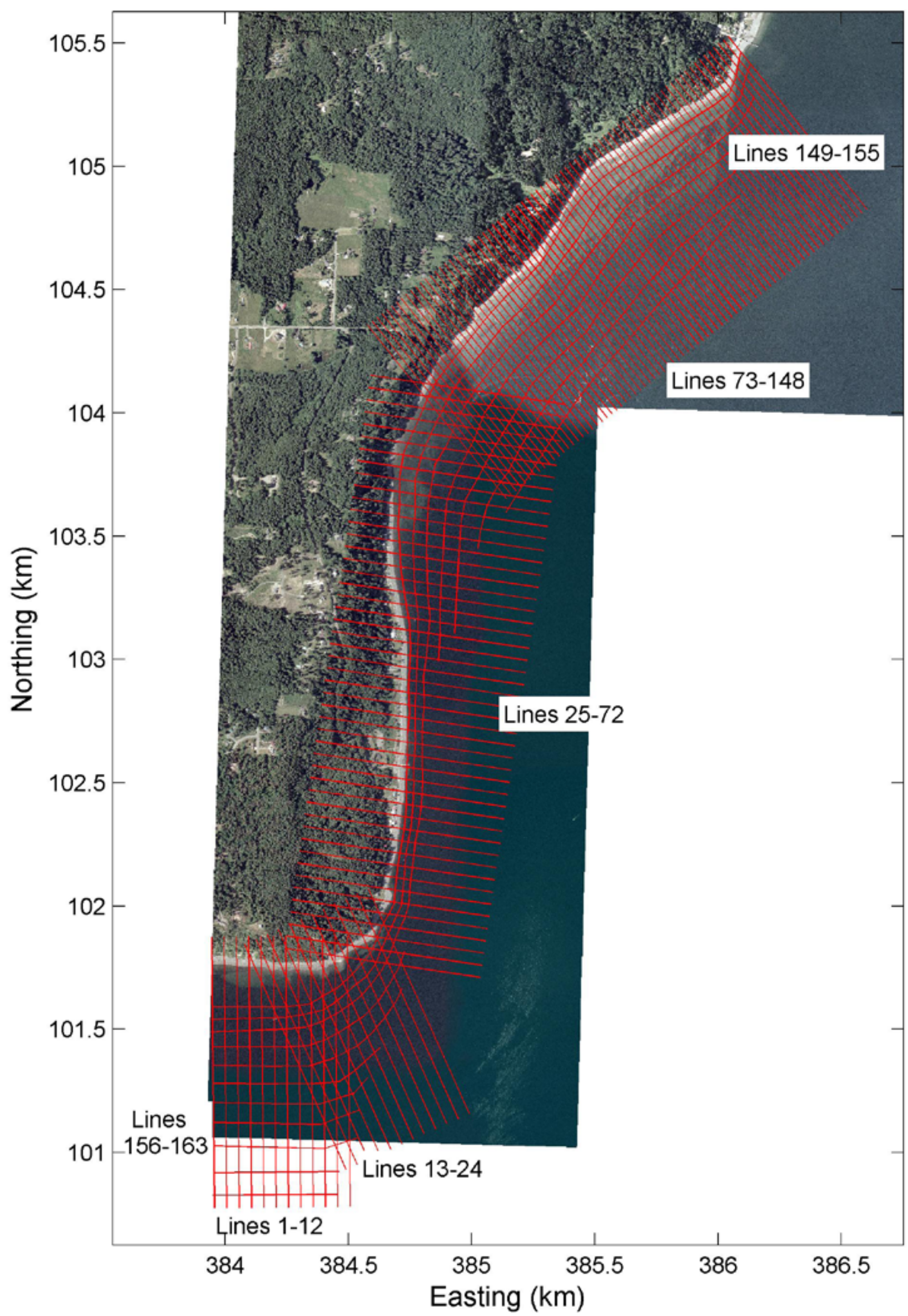


**Figure A1.** Planned lines for acoustic survey at Possession Point. Cross-shore lines 1-72 were spaced 50 m apart and lines 73-148 were spaced 25 m apart. Lines 149-163 were oriented alongshore.

**Table A1.** List of lines completed, elapsed time, and distance covered at the Possession Point study site, January 30, 2007.

| Line | Filename | Time Collected (GMT) | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 42 | 20070130_165012.dt4 | 1/30/2007 16:50 | 0.8 | 68.2 |
| 43 | 20070130_165314.dt4 | 1/30/2007 16:53 | 0.9 | 77.1 |
| 44 | 20070130_165510.dt4 | 1/30/2007 16:55 | 0.8 | 67.5 |
| 45 | 20070130_165712.dt4 | 1/30/2007 16:57 | 0.7 | 69.0 |
| 46 | 030_001.dt4 | 1/30/2007 17:12 | 0.9 | 60.2 |
| 47 | 030_002.dt4 | 1/30/2007 17:14 | 1.0 | 64.1 |
| 48 | 030_003.dt4 | 1/30/2007 17:15 | 0.9 | 48.2 |
| 49 | 030_004.dt4 | 1/30/2007 17:18 | 1.3 | 84.6 |
| 50 | 030_005.dt4 | 1/30/2007 17:20 | 1.6 | 117.1 |
| 51 | 030_006.dt4 | 1/30/2007 17:23 | 2.1 | 164.9 |
| 52 | 030_007.dt4 | 1/30/2007 17:25 | 2.2 | 171.2 |
| 53 | 030_008.dt4 | 1/30/2007 17:29 | 2.5 | 196.5 |
| 54 | 030_009.dt4 | 1/30/2007 17:32 | 2.4 | 202.4 |
| 55 | 030_010.dt4 | 1/30/2007 17:36 | 0.8 | 70.2 |
| 55a | 030_011.dt4 | 1/30/2007 17:40 | 2.6 | 217.0 |
| 56 | 030_012.dt4 | 1/30/2007 17:44 | 2.4 | 238.6 |
| 57 | 030_013.dt4 | 1/30/2007 17:47 | 3.1 | 258.8 |
| 58 | 030_014.dt4 | 1/30/2007 17:51 | 2.9 | 288.2 |
| 59 | 030_015.dt4 | 1/30/2007 17:55 | 3.2 | 285.1 |
| 60 | 030_016.dt4 | 1/30/2007 17:59 | 1.9 | 190.8 |
| 60a | 20070130_100803.dt4 | 1/30/2007 18:08 | 2.8 | 316.1 |
| 61 | 20070130_101123.dt4 | 1/30/2007 18:11 | 3.4 | 336.5 |
| 62 | 20070130_101533.dt4 | 1/30/2007 18:15 | 3.5 | 354.1 |
| 63 | 20070130_101939.dt4 | 1/30/2007 18:19 | 3.7 | 382.5 |
| 64 | 20070130_102422.dt4 | 1/30/2007 18:24 | 4.0 | 420.5 |
| 65 | 20070130_102914.dt4 | 1/30/2007 18:29 | 4.4 | 450.0 |
| 66 | 20070130_103422.dt4 | 1/30/2007 18:34 | 4.3 | 459.6 |
| 67 | 20070130_104002.dt4 | 1/30/2007 18:40 | 4.8 | 476.6 |
| 68 | 20070130_104600.dt4 | 1/30/2007 18:46 | 4.7 | 482.1 |
| 69 | 20070130_105128.dt4 | 1/30/2007 18:51 | 5.3 | 523.8 |
| 70 | 20070130_105745.dt4 | 1/30/2007 18:57 | 5.8 | 522.4 |
| 71 | 20070130_110428.dt4 | 1/30/2007 19:04 | 5.2 | 526.5 |
| 72 | 20070130_111040.dt4 | 1/30/2007 19:10 | 6.1 | 519.1 |
| 77 | 20070130_115648.dt4 | 1/30/2007 19:56 | 1.6 | 157.9 |
| 79 | 20070130_120014.dt4 | 1/30/2007 20:00 | 2.3 | 210.1 |
| 81 | 20070130_120516.dt4 | 1/30/2007 20:05 | 2.6 | 256.2 |
| 83 | 20070130_120837.dt4 | 1/30/2007 20:08 | 3.6 | 355.9 |
| 85 | 20070130_121304.dt4 | 1/30/2007 20:13 | 3.7 | 382.4 |
| 87 | 20070130_121727.dt4 | 1/30/2007 20:17 | 4.0 | 416.9 |
| 89 | 20070130_122255.dt4 | 1/30/2007 20:23 | 5.1 | 506.6 |
| 91 | 20070130_122838.dt4 | 1/30/2007 20:28 | 5.0 | 504.8 |
| 93 | 20070130_123540.dt4 | 1/30/2007 20:35 | 5.5 | 487.8 |
| 95 | 20070130_124141.dt4 | 1/30/2007 20:41 | 5.3 | 472.8 |
| 97 | 20070130_124914.dt4 | 1/30/2007 20:49 | 5.1 | 354.3 |
| 99 | 20070130_125626.dt4 | 1/30/2007 20:56 | 6.0 | 415.8 |
| 101 | 20070130_131004.dt4 | 1/30/2007 21:10 | 6.3 | 409.8 |
| 103 | 20070130_131712.dt4 | 1/30/2007 21:17 | 6.0 | 420.2 |
| 105 | 20070130_132537.dt4 | 1/30/2007 21:25 | 6.0 | 431.1 |
| 107 | 20070130_133231.dt4 | 1/30/2007 21:32 | 6.5 | 447.6 |
| 109 | 20070130_134113.dt4 | 1/30/2007 21:41 | 6.4 | 450.0 |

**Table A1.** List of lines completed, elapsed time, and distance covered at the Possession Point study site, January 30, 2007—Continued.

| Line | Filename | Time Collected (GMT) | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 111 | 20070130_135120.dt4 | 1/30/2007 21:51 | 6.6 | 439.7 |
| 113 | 20070130_135934.dt4 | 1/30/2007 21:59 | 6.6 | 454.7 |
| 115 | 20070130_140646.dt4 | 1/30/2007 22:06 | 7.1 | 473.8 |
| 117 | 20070130_141522.dt4 | 1/30/2007 22:15 | 7.5 | 473.1 |
| 119 | 20070130_142345.dt4 | 1/30/2007 22:23 | 7.7 | 476.1 |
| 121 | 20070130_143339.dt4 | 1/30/2007 22:33 | 7.2 | 438.0 |
| 123 | 20070130_144159.dt4 | 1/30/2007 22:41 | 6.6 | 433.9 |
| 125 | 20070130_145054.dt4 | 1/30/2007 22:51 | 8.3 | 449.4 |
| 127 | 20070130_150019.dt4 | 1/30/2007 23:00 | 6.7 | 440.3 |
| 129 | 20070130_150928.dt4 | 1/30/2007 23:09 | 6.8 | 409.4 |
| 131 | 20070130_151727.dt4 | 1/30/2007 23:17 | 5.4 | 384.9 |
| 133 | 20070130_152510.dt4 | 1/30/2007 23:25 | 5.7 | 338.9 |

**Table A2.** List of lines completed, elapsed time, and distance covered at the Possession Point study site January 31, 2007.

| Line | Filename | Time Collected (GMT) | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 135 | 20070131_090923.dt4 | 1/31/2007 17:11 | 4.6 | 278.7 |
| 137 | 20070131_091441.dt4 | 1/31/2007 17:14 | 2.0 | 232.0 |
| 139 | 20070131_091954.dt4 | 1/31/2007 17:20 | 2.1 | 193.5 |
| 141 | 20070131_092250.dt4 | 1/31/2007 17:22 | 1.1 | 119.7 |
| 143 | 20070131_092644.dt4 | 1/31/2007 17:26 | 0.7 | 69.4 |
| 145 | 20070131_092821.dt4 | 1/31/2007 17:28 | 0.4 | 32.7 |
| 147 | 20070131_093039.dt4 | 1/31/2007 17:30 | 0.8 | 55.2 |
| 152 | 20070131_093505.dt4 | 1/31/2007 17:35 | 12.9 | 1,537.3 |
| 76 | 20070131_095105.dt4 | 1/31/2007 17:51 | 2.2 | 256.2 |
| 78 | 20070131_095409.dt4 | 1/31/2007 17:54 | 2.4 | 234.1 |
| 80 | 20070131_095745.dt4 | 1/31/2007 17:57 | 2.2 | 284.4 |
| 82 | 20070131_100029.dt4 | 1/31/2007 18:00 | 2.6 | 320.9 |
| 84 | 20070131_100351.dt4 | 1/31/2007 18:03 | 2.7 | 344.3 |
| 86 | 20070131_100710.dt4 | 1/31/2007 18:07 | 3.5 | 439.8 |
| 88 | 20070131_101127.dt4 | 1/31/2007 18:11 | 3.8 | 468.0 |
| 90 | 20070131_101551.dt4 | 1/31/2007 18:15 | 3.8 | 468.3 |
| 92 | 20070131_102106.dt4 | 1/31/2007 18:21 | 4.0 | 453.7 |
| 94 | 20070131_102541.dt4 | 1/31/2007 18:25 | 3.8 | 458.6 |
| 96 | 20070131_103045.dt4 | 1/31/2007 18:30 | 3.7 | 426.5 |
| 98 | 20070131_103513.dt4 | 1/31/2007 18:35 | 3.4 | 408.3 |
| 100 | 20070131_103957.dt4 | 1/31/2007 18:39 | 3.4 | 402.7 |
| 102 | 20070131_104402.dt4 | 1/31/2007 18:44 | 3.2 | 392.3 |
| 104 | 20070131_104827.dt4 | 1/31/2007 18:48 | 3.1 | 388.4 |
| 106 | 20070131_105217.dt4 | 1/31/2007 18:52 | 3.3 | 396.6 |
| 108 | 20070131_105628.dt4 | 1/31/2007 18:56 | 3.3 | 414.1 |
| 110 | 20070131_110022.dt4 | 1/31/2007 19:00 | 3.6 | 432.9 |
| 112 | 20070131_110653.dt4 | 1/31/2007 19:06 | 3.3 | 414.5 |
| 114 | 20070131_111054.dt4 | 1/31/2007 19:10 | 3.9 | 461.2 |
| 116 | 20070131_111557.dt4 | 1/31/2007 19:15 | 3.7 | 442.0 |
| 118 | 20070131_112017.dt4 | 1/31/2007 19:20 | 3.9 | 458.5 |
| 120 | 20070131_113305.dt4 | 1/31/2007 19:33 | 3.9 | 455.7 |

**Table A2.** List of lines completed, elapsed time, and distance covered at the Possession Point study site January 31, 2007—Continued.

| Line | Filename | Time Collected (GMT) | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 122 | 20070131_113808.dt4 | 1/31/2007 19:38 | 4.1 | 460.5 |
| 124 | 20070131_114307.dt4 | 1/31/2007 19:43 | 4.0 | 434.1 |
| 126 | 20070131_114751.dt4 | 1/31/2007 19:47 | 3.9 | 410.4 |
| 128 | 20070131_115323.dt4 | 1/31/2007 19:53 | 4.1 | 409.9 |
| 130 | 20070131_115814.dt4 | 1/31/2007 19:58 | 3.6 | 395.2 |
| 132 | 20070131_120419.dt4 | 1/31/2007 20:04 | 3.8 | 357.6 |
| 134 | 20070131_120942.dt4 | 1/31/2007 20:09 | 2.6 | 309.1 |
| 136 | 20070131_121536.dt4 | 1/31/2007 20:15 | 2.3 | 243.4 |
| 138 | 20070131_121822.dt4 | 1/31/2007 20:18 | 2.1 | 234.1 |
| 140 | 20070131_122238.dt4 | 1/31/2007 20:22 | 1.3 | 127.6 |
| 142 | 20070131_122430.dt4 | 1/31/2007 20:24 | 1.0 | 115.4 |
| 142a | 20070131_122738.dt4 | 1/31/2007 20:27 | 0.9 | 95.4 |
| 144 | 20070131_122945.dt4 | 1/31/2007 20:29 | 0.8 | 67.1 |
| 146 | 20070131_123115.dt4 | 1/31/2007 20:31 | 0.7 | 66.6 |
| 151 | 20070131_123402.dt4 | 1/31/2007 20:34 | 30.0 | 3,703.0 |
| 151a | 20070131_130402.dt4 | 1/31/2007 21:04 | 7.1 | 911.1 |
| 5 | 20070131_131645.dt4 | 1/31/2007 21:16 | 8.0 | 833.4 |
| 6 | 20070131_132536.dt4 | 1/31/2007 21:25 | 5.6 | 756.7 |
| 7 | 20070131_133205.dt4 | 1/31/2007 21:32 | 7.6 | 750.7 |
| 8 | 20070131_134030.dt4 | 1/31/2007 21:40 | 5.5 | 727.3 |
| 9 | 20070131_134701.dt4 | 1/31/2007 21:47 | 7.4 | 755.2 |
| 10 | 20070131_135514.dt4 | 1/31/2007 21:55 | 5.1 | 680.6 |
| 11 | 20070131_140137.dt4 | 1/31/2007 22:01 | 6.9 | 698.1 |
| 12 | 20070131_140916.dt4 | 1/31/2007 22:09 | 2.4 | 324.1 |
| 17 | 20070131_141920.dt4 | 1/31/2007 22:19 | 1.2 | 134.3 |
| 18 | 20070131_142122.dt4 | 1/31/2007 22:21 | 1.0 | 113.3 |
| 19 | 20070131_142326.dt4 | 1/31/2007 22:23 | 2.5 | 260.2 |
| 20 | 20070131_142713.dt4 | 1/31/2007 22:27 | 2.1 | 250.8 |
| 21 | 20070131_143038.dt4 | 1/31/2007 22:30 | 3.0 | 310.8 |
| 22 | 20070131_143421.dt4 | 1/31/2007 22:34 | 1.0 | 120.4 |
| 23 | 20070131_143702.dt4 | 1/31/2007 22:37 | 0.6 | 53.1 |
| 24 | 20070131_143830.dt4 | 1/31/2007 22:38 | 0.6 | 44.4 |
| 27 | 20070131_144056.dt4 | 1/31/2007 22:40 | 0.4 | 42.9 |
| 28 | 20070131_144152.dt4 | 1/31/2007 22:41 | 0.6 | 37.9 |
| 29 | 20070131_144322.dt4 | 1/31/2007 22:43 | 0.8 | 84.2 |
| 30 | 20070131_144458.dt4 | 1/31/2007 22:44 | 1.1 | 111.6 |
| 31 | 20070131_144650.dt4 | 1/31/2007 22:47 | 1.7 | 118.9 |
| 32 | 20070131_144907.dt4 | 1/31/2007 22:49 | 0.6 | 42.5 |
| 33 | 20070131_145056.dt4 | 1/31/2007 22:51 | 0.7 | 48.6 |
| 34 | 20070131_145217.dt4 | 1/31/2007 22:52 | 0.7 | 46.8 |
| 35 | 20070131_145346.dt4 | 1/31/2007 22:54 | 1.0 | 64.8 |
| 36 | 20070131_145531.dt4 | 1/31/2007 22:55 | 0.6 | 54.9 |
| 37 | 20070131_145655.dt4 | 1/31/2007 22:57 | 0.8 | 69.0 |
| 38 | 20070131_145824.dt4 | 1/31/2007 22:58 | 0.8 | 70.0 |
| 39 | 20070131_145955.dt4 | 1/31/2007 23:00 | 1.2 | 98.9 |
| 40 | 20070131_150150.dt4 | 1/31/2007 23:01 | 1.0 | 97.6 |
| 41 | 20070131_150350.dt4 | 1/31/2007 23:03 | 0.9 | 85.8 |
| 150 | 20070131_150612.dt4 | 1/31/2007 23:06 | 8.8 | 1,219.2 |
| 149 | 20070131_151534.dt4 | 1/31/2007 23:15 | 10.7 | 1,130.9 |

**Table A3.** List of lines completed, elapsed time, and distance covered at the Possession Point study site, February 1, 2007. Asterisks next to the line number indicate that underwater video was also collected.

| Line | Filename | Time Collected (GMT) | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 150a | 20070201_085716.dt4 | 2/1/2007 16:57 | 10.7 | 520.4 |
| 150b | 20070201_090805.dt4 | 2/1/2007 17:08 | 25.7 | 3,416.0 |
| 132v* | 20070201_094656.dt4 | 2/1/2007 17:46 | 7.3 | 395.6 |
| 123v* | 20070201_100013.dt4 | 2/1/2007 18:00 | 6.2 | 329.3 |
| 113v* | 20070201_101052.dt4 | 2/1/2007 18:10 | 4.1 | 284.9 |
| 103v* | 20070201_101936.dt4 | 2/1/2007 18:19 | 4.2 | 231.7 |
| 93v* | 20070201_102805.dt4 | 2/1/2007 18:28 | 3.9 | 207.0 |
| 83v* | 20070201_103610.dt4 | 2/1/2007 18:36 | 4.9 | 221.1 |
| 73v* | 20070201_104453.dt4 | 2/1/2007 18:44 | 6.9 | 327.0 |
| 63v* | 20070201_105539.dt4 | 2/1/2007 18:55 | 5.6 | 279.2 |
| 53v* | 20070201_110728.dt4 | 2/1/2007 19:07 | 2.4 | 98.1 |
| 43v* | 20070201_111426.dt4 | 2/1/2007 19:14 | 1.5 | 68.3 |
| 44v* | 20070201_111726.dt4 | 2/1/2007 19:17 | 1.1 | 45.1 |
| 33v* | 20070201_112319.dt4 | 2/1/2007 19:23 | 1.3 | 44.5 |
| 23va* | 20070201_112457.dt4 | 2/1/2007 19:24 | 6.7 | 728.7 |
| 23v* | 20070201_113734.dt4 | 2/1/2007 19:37 | 1.1 | 98.2 |
| 23v2* | 20070201_113844.dt4 | 2/1/2007 19:38 | 2.4 | 160.9 |
| 13v* | 20070201_114638.dt4 | 2/1/2007 19:46 | 6.3 | 378.8 |
| 5v* | 20070201_122337.dt4 | 2/1/2007 20:23 | 6.2 | 370.0 |
| 18v* | 20070201_123630.dt4 | 2/1/2007 20:36 | 5.5 | 281.6 |
| 149a | 20070201_124629.dt4 | 2/1/2007 20:46 | 10.4 | 1,083.0 |
| 48v* | 20070201_125945.dt4 | 2/1/2007 20:59 | 1.6 | 59.9 |

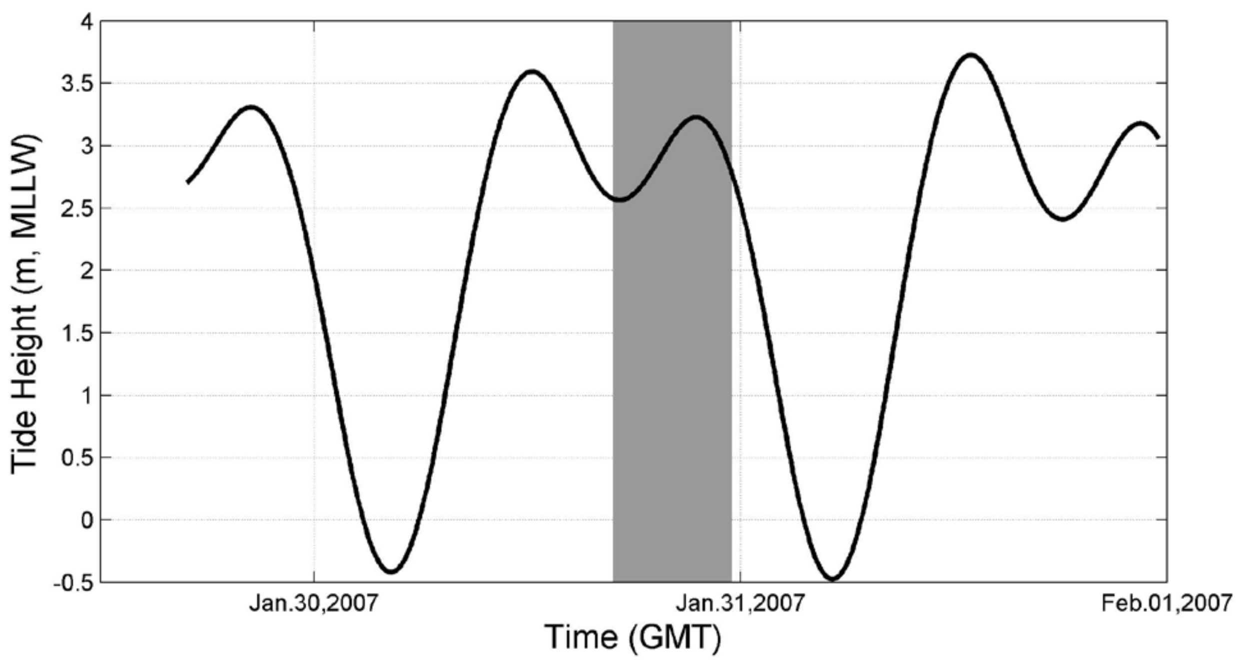


**Figure A2.** Predicted tidal elevations for Seattle (47.6 °N, 122.3 °W) for January 30, 2007. The gray bar shows the time span when data were collected at the Possession Point study site.

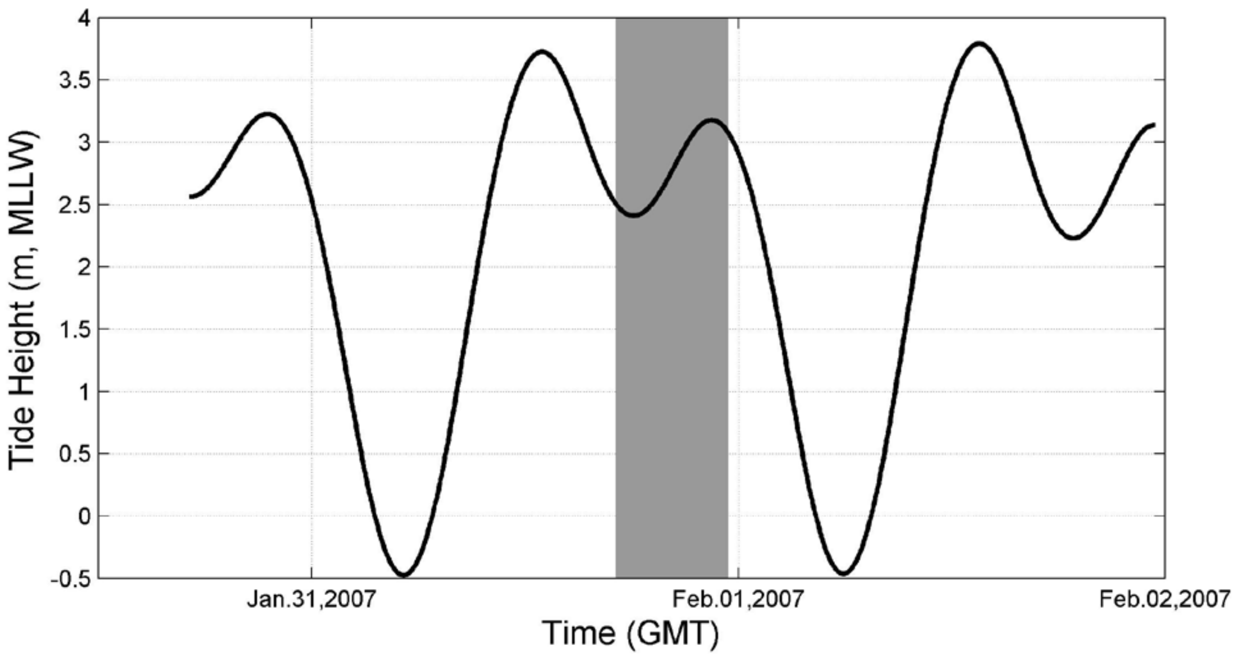


**Figure A3.** Predicted tidal elevations for Seattle (47.6 °N, 122.3 °W) for January 31, 2007. The gray bar shows the time span when data were collected at the Possession Point study site.

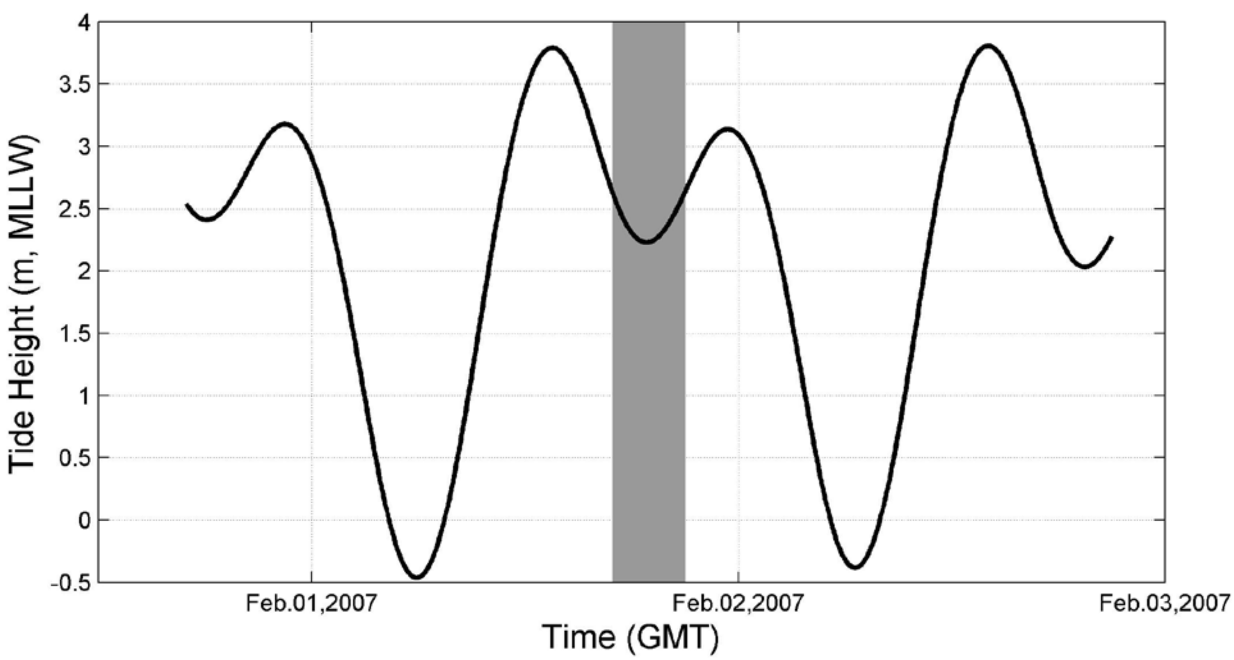


**Figure A4.** Predicted tidal elevations for Seattle (47.6 °N, 122.3 °W) for February 1, 2007. The gray bar shows the time span when data were collected at the Possession Point study site.

# Appendix B. Data Collected at Browns Bay

Appendix B provides a list of all acoustic data collected at Browns Bay on February 2, 2007. The locations of planned lines is shown in figure B1. The line numbers, acoustic data filenames, collection dates, and line lengths are provided in table B1. The tide height during data collection at Browns Bay is shown in figure B2.0

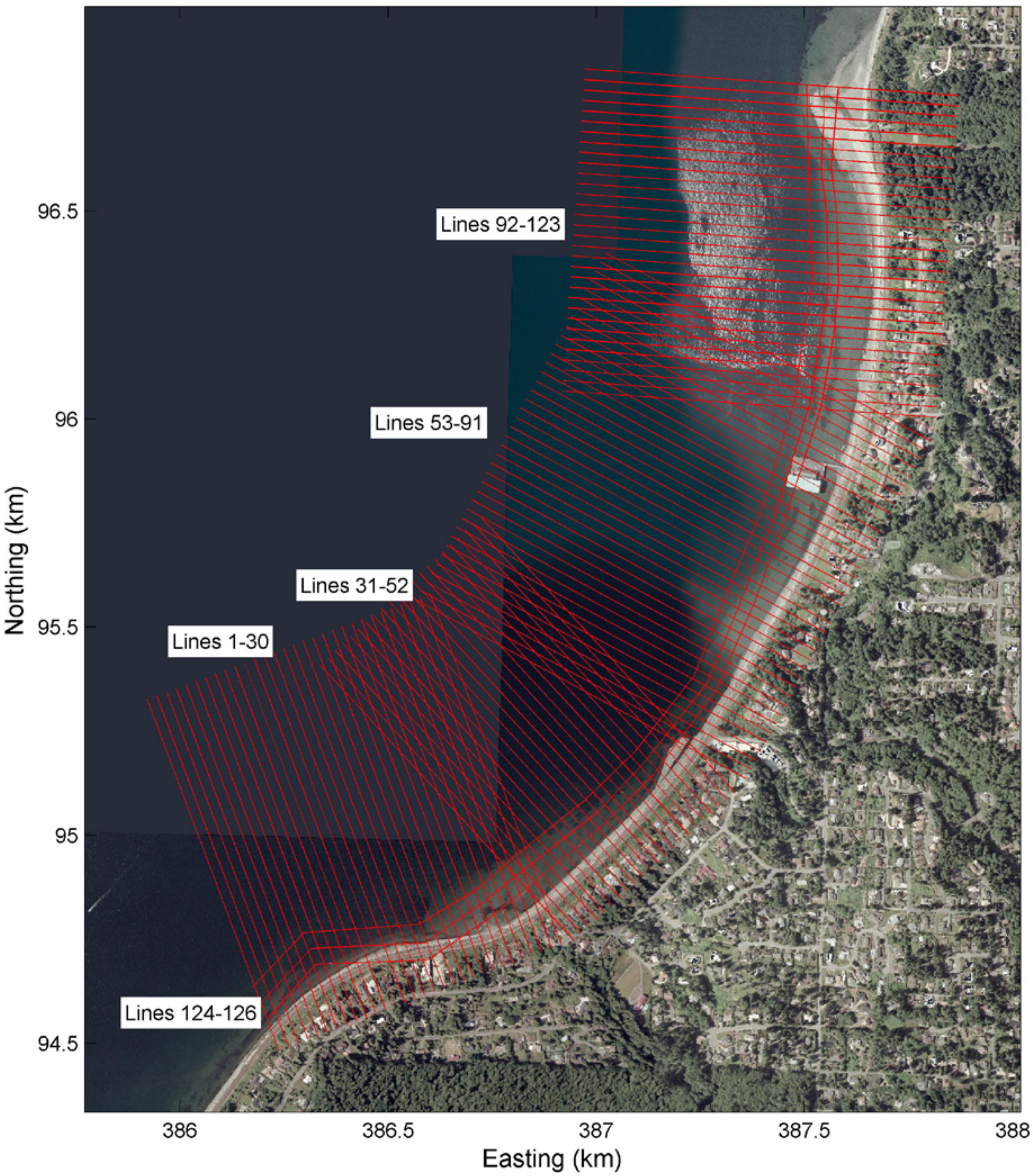


**Figure B1.** Planned lines for acoustic survey at Browns Bay. Cross-shore lines 1-123 were spaced roughly 15 m apart. Lines 124-126 were oriented alongshore.

**Table B1.** List of lines completed, elapsed time, and distance covered in Browns Bay study area, February 2, 2007. Asterisks next to the line number indicate that underwater video was also collected.

| Line | Filename | Date Collected | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 1 | 20070202_114339.dt4 | 2/2/2007 19:43 | 2.3 | 268.8 |
| 3 | 20070202_114103.dt4 | 2/2/2007 19:41 | 1.9 | 248.5 |
| 5* | 20070202_113617.dt4 | 2/2/2007 19:36 | 4.1 | 257.7 |
| 7 | 20070202_113356.dt4 | 2/2/2007 19:33 | 1.7 | 215.0 |
| 9 | 20070202_113130.dt4 | 2/2/2007 19:31 | 1.5 | 192.1 |
| 11 | 20070202_112909.dt4 | 2/2/2007 19:29 | 1.7 | 220.1 |
| 13 | 20070202_112631.dt4 | 2/2/2007 19:26 | 1.9 | 221.1 |
| 15 | 20070202_112340.dt4 | 2/2/2007 19:23 | 2.3 | 246.2 |
| 17 | 20070202_112032.dt4 | 2/2/2007 19:20 | 2.2 | 256.1 |
| 18* | 20070202_131751.dt4 | 2/2/2007 21:17 | 6.2 | 270.3 |
| 19 | 20070202_111735.dt4 | 2/2/2007 19:17 | 2.3 | 277.9 |
| 21 | 20070202_111427.dt4 | 2/2/2007 19:14 | 2.2 | 263.4 |
| 23 | 20070202_111159.dt4 | 2/2/2007 19:11 | 2.1 | 255.0 |
| 25 | 20070202_110914.dt4 | 2/2/2007 19:09 | 2.1 | 243.1 |
| 27 | 20070202_110656.dt4 | 2/2/2007 19:06 | 1.6 | 199.7 |
| 32* | 20070202_105844.dt4 | 2/2/2007 18:58 | 6.1 | 291.5 |
| 34 | 20070202_105544.dt4 | 2/2/2007 18:55 | 2.2 | 263.0 |
| 36 | 20070202_105234.dt4 | 2/2/2007 18:52 | 2.2 | 243.0 |
| 37* | 20070202_130617.dt4 | 2/2/2007 21:06 | 6.9 | 283.9 |
| 38 | 20070202_105009.dt4 | 2/2/2007 18:50 | 1.8 | 212.5 |
| 40 | 20070202_104731.dt4 | 2/2/2007 18:47 | 1.8 | 197.2 |
| 42 | 20070202_103903.dt4 | 2/2/2007 18:39 | 1.6 | 181.7 |
| 44 | 20070202_103657.dt4 | 2/2/2007 18:36 | 1.3 | 159.3 |
| 46* | 20070202_103327.dt4 | 2/2/2007 18:33 | 2.4 | 125.4 |
| 48 | 20070202_103114.dt4 | 2/2/2007 18:31 | 1.1 | 132.4 |
| 50 | 20070202_102928.dt4 | 2/2/2007 18:29 | 1.0 | 98.1 |
| 54 | 20070202_102611.dt4 | 2/2/2007 18:26 | 0.9 | 117.8 |
| 55* | 20070202_125917.dt4 | 2/2/2007 20:59 | 2.8 | 136.5 |
| 56 | 20070202_102415.dt4 | 2/2/2007 18:24 | 0.9 | 126.5 |
| 58 | 20070202_102007.dt4 | 2/2/2007 18:20 | 1.3 | 167.8 |
| 60 | 20070202_101818.dt4 | 2/2/2007 18:18 | 1.2 | 163.4 |
| 62 | 20070202_101607.dt4 | 2/2/2007 18:16 | 1.3 | 172.6 |
| 64 | 20070202_101420.dt4 | 2/2/2007 18:14 | 1.2 | 160.7 |
| 66* | 20070202_100952.dt4 | 2/2/2007 18:09 | 3.6 | 174.0 |
| 68 | 20070202_100732.dt4 | 2/2/2007 18:07 | 1.4 | 184.2 |
| 70 | 20070202_100408.dt4 | 2/2/2007 18:04 | 0.8 | 106.7 |
| 72 | 20070202_100408.dt4 | 2/2/2007 18:04 | 0.8 | 106.7 |
| 74 | 20070202_100230.dt4 | 2/2/2007 18:02 | 0.9 | 113.3 |
| 75* | 20070202_125136.dt4 | 2/2/2007 20:51 | 2.5 | 119.9 |
| 76 | 20070202_100100.dt4 | 2/2/2007 18:00 | 0.9 | 120.9 |
| 78 | 20070202_095855.dt4 | 2/2/2007 17:58 | 1.2 | 142.2 |
| 80 | 20070202_095626.dt4 | 2/2/2007 17:56 | 0.6 | 73.0 |
| 82 | 20070202_095506.dt4 | 2/2/2007 17:55 | 0.7 | 84.8 |
| 84 | 20070202_095226.dt4 | 2/2/2007 17:52 | 1.7 | 204.9 |
| 86* | 20070202_094743.dt4 | 2/2/2007 17:47 | 3.6 | 209.2 |
| 88 | 20070202_094458.dt4 | 2/2/2007 17:44 | 1.6 | 186.2 |
| 93 | 20070202_094145.dt4 | 2/2/2007 17:41 | 1.7 | 205.5 |
| 95 | 20070202_093935.dt4 | 2/2/2007 17:39 | 1.5 | 192.9 |
| 96* | 20070202_124135.dt4 | 2/2/2007 20:41 | 4.8 | 225.0 |

**Table B1.** List of lines completed, elapsed time, and distance covered in Browns Bay study area, February 2, 2007. Asterisks next to the line number indicate that underwater video was also collected—Continued.

| Line | Filename | Date Collected | Elapsed Time (min) | Total Length (m) |
|---|---|---|---|---|
| 97 | 20070202_093704.dt4 | 2/2/2007 17:37 | 1.8 | 218.0 |
| 99 | 20070202_093448.dt4 | 2/2/2007 17:34 | 1.5 | 193.2 |
| 101 | 20070202_093152.dt4 | 2/2/2007 17:31 | 1.9 | 226.0 |
| 103 | 20070202_092922.dt4 | 2/2/2007 17:29 | 1.8 | 216.6 |
| 105* | 20070202_092509.dt4 | 2/2/2007 17:25 | 3.4 | 217.4 |
| 107 | 20070202_092235.dt4 | 2/2/2007 17:22 | 1.8 | 200.5 |
| 109 | 20070202_092017.dt4 | 2/2/2007 17:20 | 1.7 | 188.4 |
| 111 | 20070202_091802.dt4 | 2/2/2007 17:18 | 1.6 | 182.4 |
| 113 | 20070202_091558.dt4 | 2/2/2007 17:15 | 1.3 | 142.1 |
| 115 | 20070202_091405.dt4 | 2/2/2007 17:14 | 1.0 | 118.3 |
| 117 | 20070202_091108.dt4 | 2/2/2007 17:11 | 0.9 | 106.4 |
| 119 | 20070202_090713.dt4 | 2/2/2007 17:07 | 1.1 | 110.5 |
| 120* | 20070202_123304.dt4 | 2/2/2007 20:33 | 2.4 | 111.7 |
| 121 | 20070202_090353.dt4 | 2/2/2007 17:03 | 0.8 | 87.9 |
| 123 | 20070202_090116.dt4 | 2/2/2007 17:01 | 1.6 | 148.9 |
| SP1 | 20070202_115451.dt4 | 2/2/2007 19:54 | 27.6 | 3103.7 |
| SP2 | 20070202_132847.dt4 | 2/2/2007 21:28 | 22.1 | 3,088.8 |

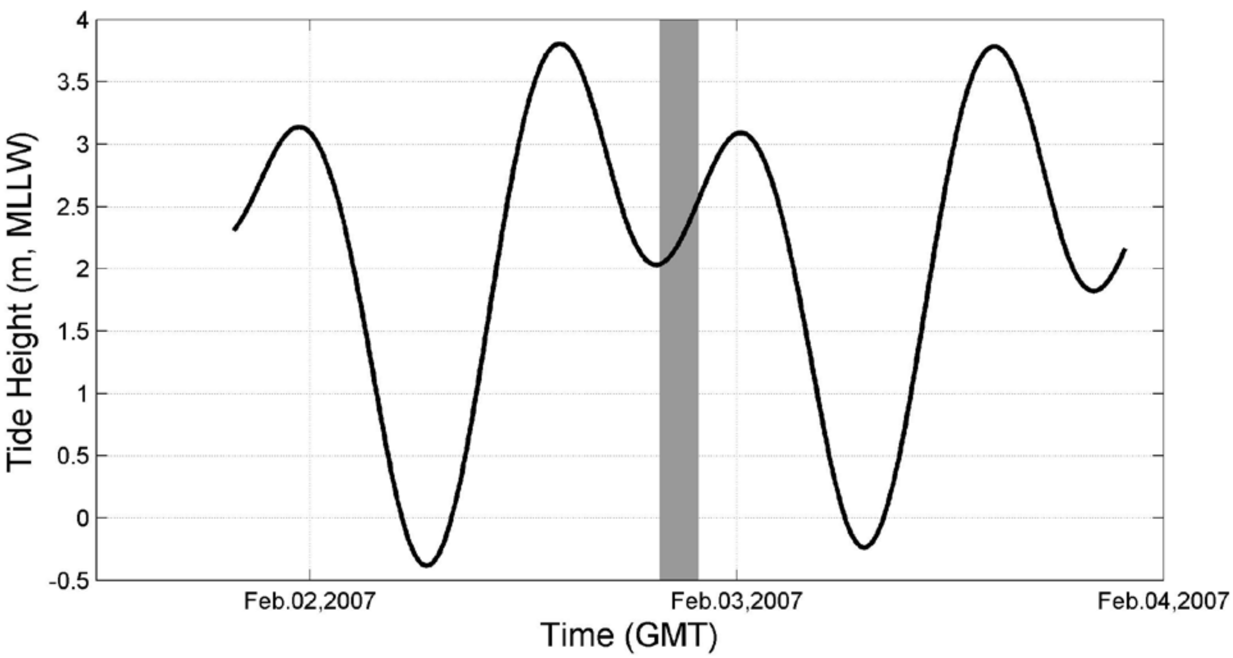


**Figure B2.** Predicted tidal elevations for Seattle (47.6 °N, 122.3 °W) for February 2, 2007. The gray bar shows the time span when data were collected at the Browns Bay study site.

# Appendix C. Grain-Size Data from Possession Point

Appendix C contains grain-size data collected at Possession Point between February 1 and April 20, 2007. Sample locations as well as summary statistics are provided in table C1. Sediment distributions for each sample are shown in figures C1 through C5. Statistical parameters including mean, variance, standard deviation, skewness and kurtosis were calculated using the graphical technique of Inman (1952).

**Table C1.** Locations and grain-size parameters for samples collected at Possession Point.

| Station ID | Collection Date | Latitude (deg N) | Longitude (deg W) | Gravel % | Sand % | Silt % | Clay % | Mean (phi) | Mean (mm) | Variance | Std. Dev. | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2/1/2007 22:19 | 47.9118 | 122.3752 | 0 | 100 | 0 | 0 | 2.07 | 0.24 | 0.21 | 0.46 | 0.25 | 4.68 |
| 2 | 2/1/2007 22:21 | 47.9117 | 122.3752 | 0 | 100 | 0 | 0 | 2.12 | 0.23 | 0.23 | 0.48 | 0.35 | 3.69 |
| 3 | 2/1/2007 22:27 | 47.9137 | 122.3752 | 0 | 100 | 0 | 0 | 2.48 | 0.18 | 0.18 | 0.42 | -0.05 | 3 |
| 4 | 2/1/2007 22:35 | 47.9163 | 122.3753 | 0 | 100 | 0 | 0 | 2.47 | 0.18 | 0.42 | 0.65 | -0.21 | 2.38 |
| 5 | 2/1/2007 22:36 | 47.9164 | 122.3753 | 0 | 100 | 0 | 0 | 2.59 | 0.17 | 0.41 | 0.64 | -0.14 | 2.18 |
| 6 | 2/1/2007 22:39 | 47.9184 | 122.3753 | 0 | 93.6 | 5.1 | 1.3 | 2.55 | 0.17 | 1.69 | 1.3 | 2.15 | 13.11 |
| 7 | 2/1/2007 22:43 | 47.9207 | 122.375 | 0 | 100 | 0 | 0 | 2.17 | 0.22 | 0.3 | 0.55 | -0.6 | 4.13 |
| 8 | 2/1/2007 22:45 | 47.9228 | 122.3741 | 0 | 100 | 0 | 0 | 2.29 | 0.2 | 0.16 | 0.4 | 0.22 | 2.98 |
| 9 | 2/1/2007 22:48 | 47.925 | 122.3729 | 0 | 100 | 0 | 0 | 2.15 | 0.23 | 0.12 | 0.35 | 0.79 | 6.59 |
| 10 | 2/1/2007 23:02 | 47.9272 | 122.3711 | 0 | 100 | 0 | 0 | 2.21 | 0.22 | 0.22 | 0.46 | -0.88 | 6.38 |
| 11 | 2/1/2007 23:05 | 47.9287 | 122.3689 | 0 | 100 | 0 | 0 | 2.15 | 0.23 | 0.08 | 0.28 | -0.31 | 3.15 |
| 12 | 2/1/2007 23:09 | 47.9304 | 122.3666 | 0 | 100 | 0 | 0 | 2.11 | 0.23 | 0.12 | 0.35 | 1.84 | 10.75 |
| 13 | 2/1/2007 23:12 | 47.9317 | 122.3641 | 0 | 100 | 0 | 0 | 2.05 | 0.24 | 0.08 | 0.28 | 0.66 | 4.81 |
| 14 | 2/1/2007 23:17 | 47.9333 | 122.3617 | 0 | 100 | 0 | 0 | 2.05 | 0.24 | 0.08 | 0.28 | 0.3 | 4.41 |
| 15 | 2/1/2007 23:19 | 47.9355 | 122.3599 | 0 | 100 | 0 | 0 | 1.97 | 0.25 | 0.11 | 0.33 | 0.63 | 3.87 |
| 16 | 2/1/2007 23:28 | 47.9376 | 122.3582 | 0 | 100 | 0 | 0 | 2.34 | 0.2 | 0.29 | 0.54 | -0.08 | 2.84 |
| 17 | 2/1/2007 23:41 | 47.9093 | 122.3756 | 0 | 98.1 | 1.9 | 0 | 2.14 | 0.23 | 0.28 | 0.53 | 1.09 | 5.87 |
| HP-1 | 2/28/2007 18:17 | 47.9339 | 122.3652 | 0 | 96.4 | 2.7 | 0.9 | 2.55 | 0.17 | 1.04 | 1.02 | 3.8 | 23.66 |
| HP-2 | 2/28/2007 18:20 | 47.9335 | 122.3647 | 0 | 100 | 0 | 0 | 1.63 | 0.32 | 0.27 | 0.52 | 0.62 | 5.05 |
| HP-3 | 2/28/2007 18:26 | 47.9332 | 122.3637 | 0 | 100 | 0 | 0 | 1.63 | 0.32 | 0.21 | 0.46 | 0.34 | 5.33 |
| HP-4 | 2/28/2007 18:31 | 47.9327 | 122.3623 | 0 | 100 | 0 | 0 | 1.93 | 0.26 | 0.09 | 0.31 | 1.8 | 11.53 |
| HP-5 | 2/28/2007 18:33 | 47.9323 | 122.3623 | 0 | 100 | 0 | 0 | 2.05 | 0.24 | 0.1 | 0.31 | 1.61 | 10.74 |
| HP-6 | 2/28/2007 18:35 | 47.9319 | 122.362 | 0 | 100 | 0 | 0 | 2.24 | 0.21 | 0.16 | 0.4 | 0.44 | 4.24 |
| HP-7 | 2/28/2007 18:37 | 47.9317 | 122.3613 | 0 | 100 | 0 | 0 | 2.31 | 0.2 | 0.22 | 0.47 | 0.9 | 5.03 |
| TN-1 | 2/28/2007 18:47 | 47.9221 | 122.3761 | 0 | 71 | 23.9 | 5.2 | 3.76 | 0.07 | 3.71 | 1.93 | 1.46 | 4.82 |
| TN-3 | 2/28/2007 19:00 | 47.9217 | 122.374 | 84.3 | 15.7 | 0 | 0 | -2.75 | 6.75 | 3.73 | 1.93 | 1.71 | 4.38 |
| TN-4 | 2/28/2007 19:04 | 47.9217 | 122.3734 | 0 | 100 | 0 | 0 | 2.03 | 0.24 | 0.35 | 0.59 | -0.34 | 3.92 |
| TN-5 | 2/28/2007 19:06 | 47.9213 | 122.373 | 0 | 100 | 0 | 0 | 2.02 | 0.25 | 0.36 | 0.6 | -0.01 | 3.14 |
| TS-1 | 2/28/2007 19:11 | 47.9203 | 122.3762 | 57.5 | 41.8 | 0.6 | 0 | -0.97 | 1.95 | 6.37 | 2.52 | 0.52 | 1.63 |

**Table C1.** Locations and grain-size parameters for samples collected at Possession Point. —Continued.

| Station ID | Collection Date | Latitude (deg N) | Longitude (deg W) | Gravel % | Sand % | Silt % | Clay % | Mean (phi) | Mean (mm) | Variance | Std. Dev. | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TS-2 | 2/28/2007 19:13 | 47.9201 | 122.3758 | 0 | 94.8 | 3.8 | 1.4 | 2.7 | 0.15 | 1.35 | 1.16 | 3.24 | 18.74 |
| TS-4 | 2/28/2007 19:14 | 47.9202 | 122.3755 | 0 | 92.9 | 5.3 | 1.8 | 2.67 | 0.16 | 1.66 | 1.29 | 3.36 | 16.61 |
| TS-5 | 2/28/2007 19:17 | 47.9203 | 122.3751 | 0 | 96.9 | 2.2 | 0.8 | 2.32 | 0.2 | 1.06 | 1.03 | 3.52 | 23.6 |
| TS-6 | 2/28/2007 19:19 | 47.9201 | 122.3745 | 0 | 100 | 0 | 0 | 2.04 | 0.24 | 0.3 | 0.55 | -0.18 | 3.36 |
| TS-7 | 2/28/2007 19:22 | 47.92 | 122.3737 | 0 | 100 | 0 | 0 | 1.79 | 0.29 | 0.34 | 0.58 | 0.24 | 3.93 |
| TS-8 | 2/28/2007 19:24 | 47.9202 | 122.3731 | 0 | 100 | 0 | 0 | 1.8 | 0.29 | 0.45 | 0.67 | -0.14 | 2.99 |
| TS-9 | 2/28/2007 19:27 | 47.9201 | 122.3739 | 17.8 | 82.2 | 0 | 0 | 0.89 | 0.54 | 3.84 | 1.96 | -1.34 | 3.36 |
| G22-1A | 3/22/2007 15:47 | 47.9042 | 122.3778 | 13.2 | 86.8 | 0 | 0 | 1.11 | 0.46 | 2.67 | 1.63 | -1.56 | 4.66 |
| G22-1B | 3/22/2007 15:47 | 47.9042 | 122.3778 | 41 | 59 | 0 | 0 | -0.34 | 1.27 | 5.61 | 2.37 | -0.22 | 1.44 |
| G22-2A | 3/23/2007 16:10 | 47.9219 | 122.3747 | 62.3 | 37.7 | 0 | 0 | -1.37 | 2.59 | 4.7 | 2.17 | 0.44 | 1.65 |
| G22-2B | 3/23/2007 16:10 | 47.9219 | 122.3747 | 53.6 | 46.4 | 0 | 0 | -0.91 | 1.88 | 4.32 | 2.08 | 0.11 | 1.54 |
| G22-3A | 3/24/2007 16:24 | 47.9203 | 122.3752 | 0 | 95.5 | 3.3 | 1.2 | 2.52 | 0.17 | 1.22 | 1.1 | 3.92 | 23.28 |
| G22-3B | 3/24/2007 16:24 | 47.9203 | 122.3752 | 0 | 96 | 2.9 | 1.1 | 2.53 | 0.17 | 1.09 | 1.05 | 3.94 | 24.68 |
| G22-4 | 3/25/2007 16:38 | 47.933 | 122.3632 | 0 | 100 | 0 | 0 | 1.68 | 0.31 | 0.15 | 0.39 | -0.3 | 3.46 |
| G22-5 | 3/26/2007 16:47 | 47.9332 | 122.3641 | 0 | 100 | 0 | 0 | 2.04 | 0.24 | 0.15 | 0.38 | -0.14 | 2.4 |
| AP-1 | 4/19/2007 20:25 | 47.9334 | 122.3638 | 0 | 100 | 0 | 0 | 1.77 | 0.29 | 0.15 | 0.39 | 0.84 | 5.43 |
| AP-2 | 4/19/2007 20:30 | 47.9334 | 122.3635 | 0 | 100 | 0 | 0 | 1.82 | 0.28 | 0.16 | 0.4 | 0.41 | 3.25 |
| AP-3 | 4/19/2007 20:40 | 47.9337 | 122.3645 | 0 | 100 | 0 | 0 | 1.77 | 0.29 | 0.17 | 0.41 | 1.54 | 7.15 |
| AP-4 | 4/19/2007 20:45 | 47.9337 | 122.3642 | 0 | 95.8 | 3 | 1.3 | 2.59 | 0.17 | 1.25 | 1.12 | 3.66 | 21.55 |
| AP-5 | 4/19/2007 20:52 | 47.9342 | 122.3634 | 0 | 100 | 0 | 0 | 1.64 | 0.32 | 0.14 | 0.37 | 0.68 | 4.83 |
| AP-6 | 4/20/2007 20:30 | 47.9218 | 122.3742 | 22.5 | 77.5 | 0 | 0 | 0.74 | 0.6 | 4.37 | 2.09 | -1.06 | 2.61 |
| AP-7 | 4/20/2007 20:33 | 47.9214 | 122.3744 | 32.1 | 67.9 | 0 | 0 | -0.15 | 1.11 | 5.24 | 2.29 | -0.58 | 1.77 |
| AP-8 | 4/20/2007 20:40 | 47.9218 | 122.3745 | 27.5 | 72.5 | 0 | 0 | 0.23 | 0.85 | 3.3 | 1.82 | -0.79 | 2.3 |
| AP-9 | 4/20/2007 21:15 | 47.9201 | 122.3759 | 5.7 | 86.3 | 6.2 | 1.8 | 2.61 | 0.16 | 3.61 | 1.9 | -0.4 | 8.16 |

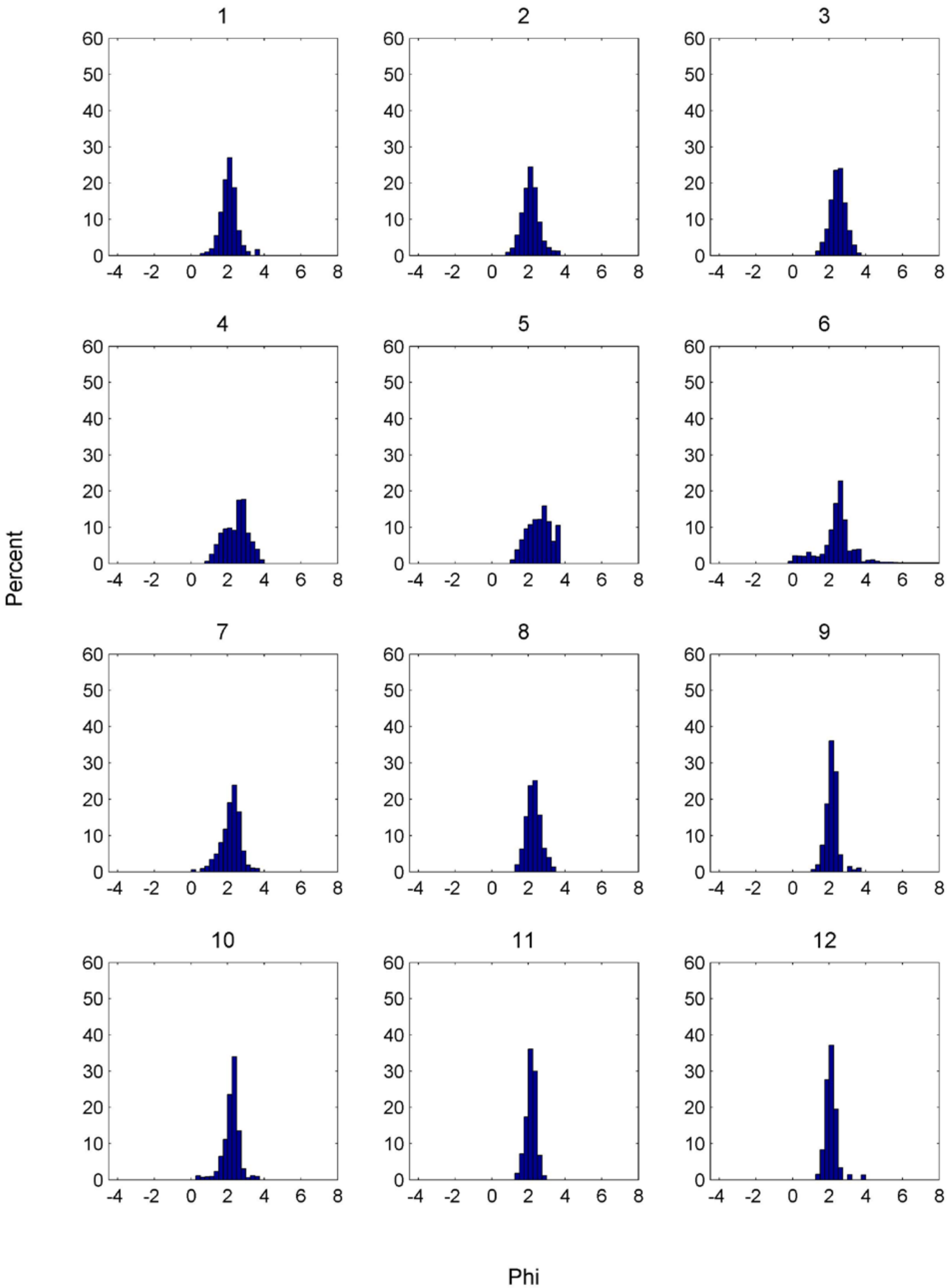


**Figure C1.** Sediment grain-size distribution (weight percent) for samples 1 through 12 from Possession Point. See table C1 for locations of samples.

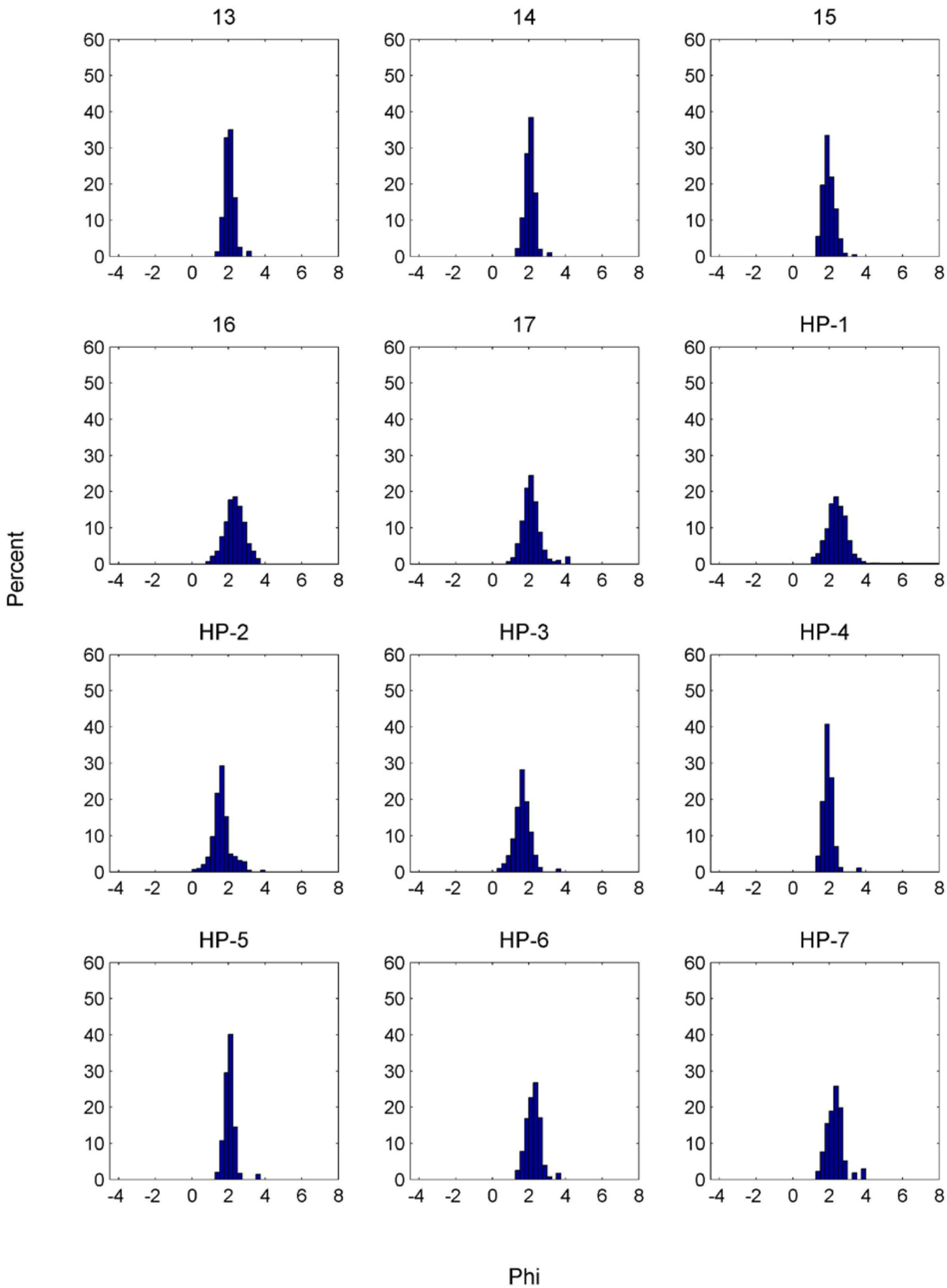


**Figure C2.** Sediment grain size distribution (weight percent) for samples 13 through HP-7 from Possession Point. See table C1 for locations of samples.

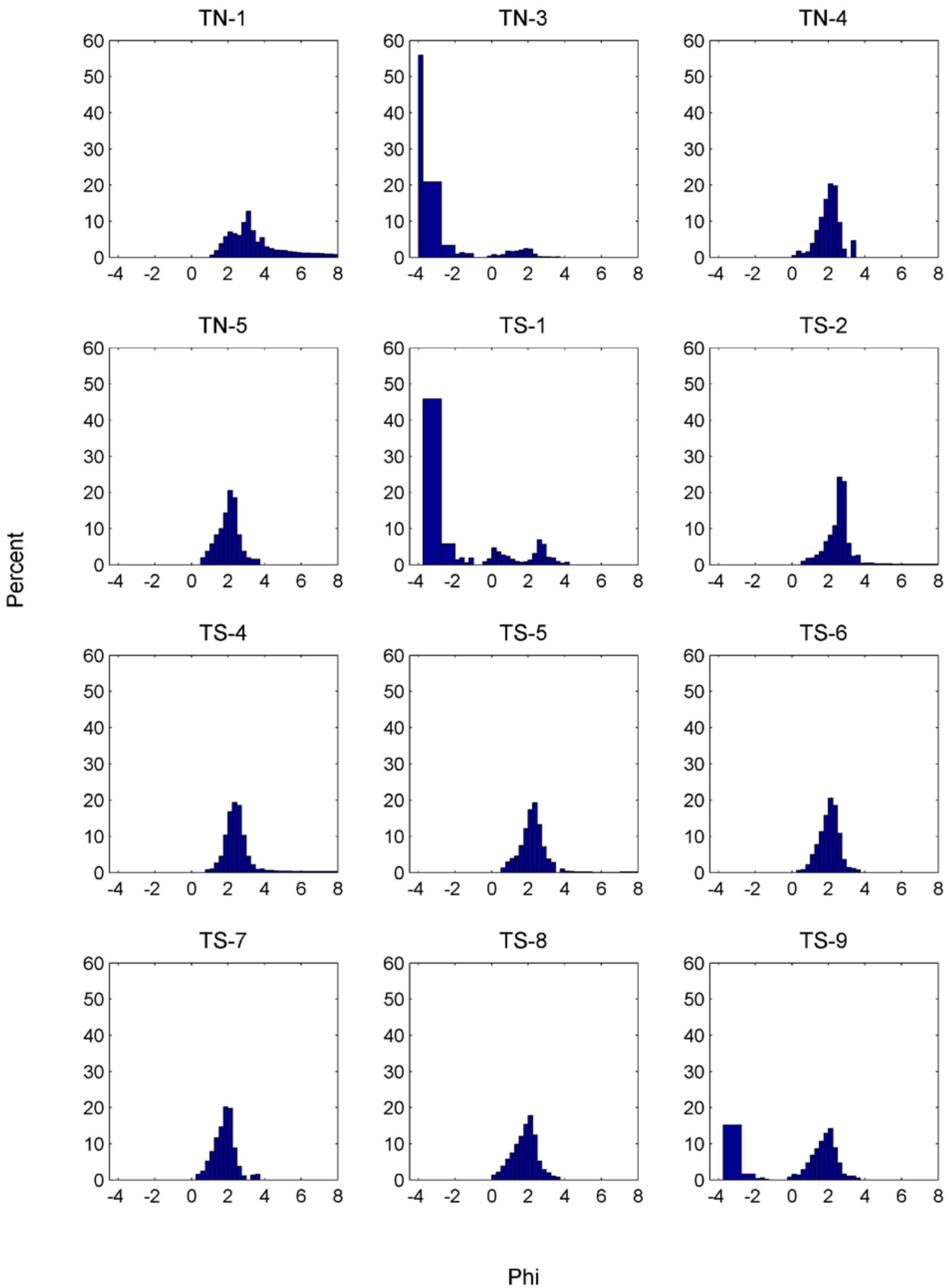


**Figure C3.** Sediment grain size distribution (weight percent) for samples TN-1 through TS-9 from Possession Point. See table C1 for locations of samples.

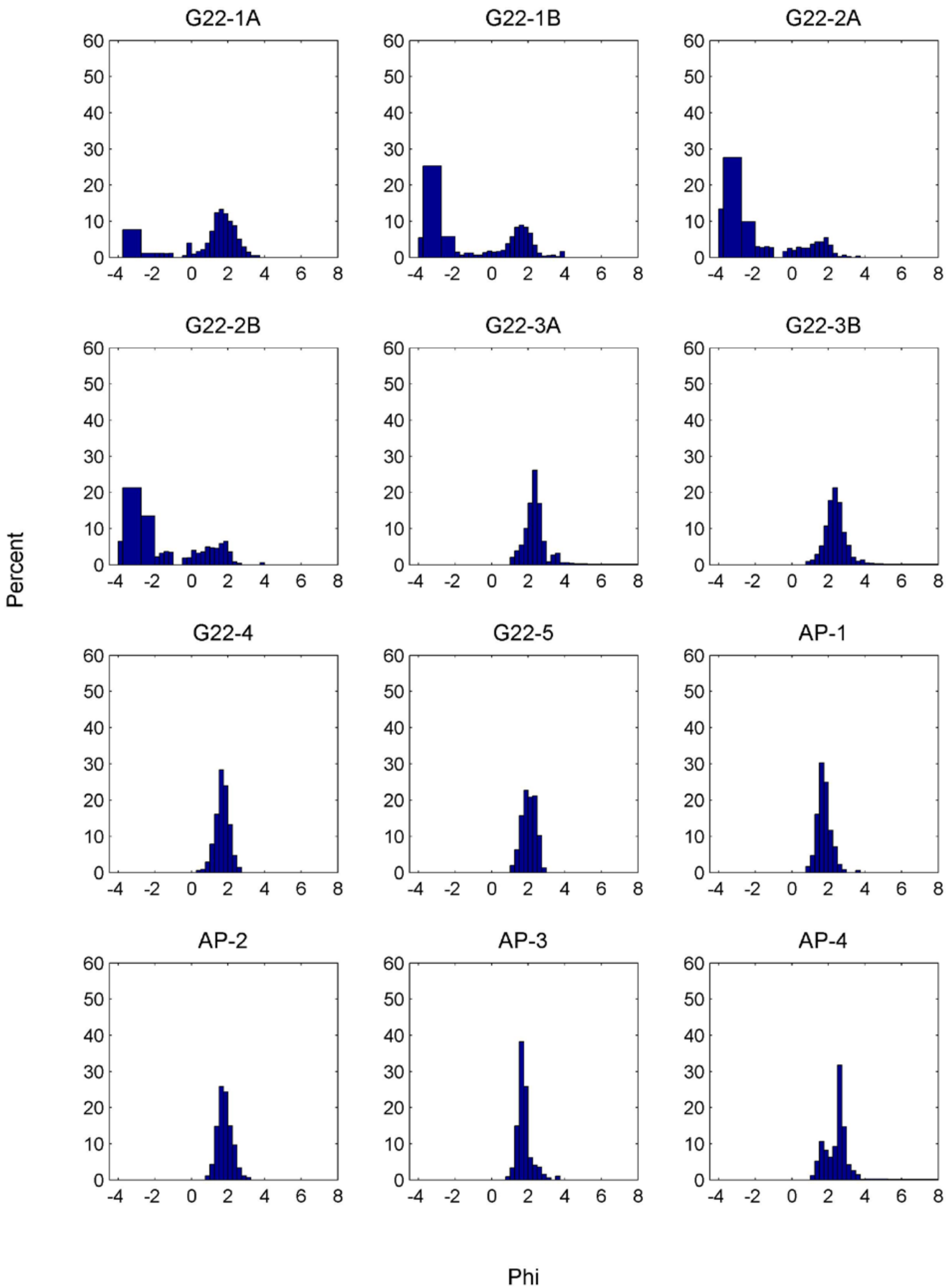


**Figure C4.** Sediment grain size distribution (weight percent) for samples G22-1A through AP-4 from Possession Point. See table C1 for locations of samples.

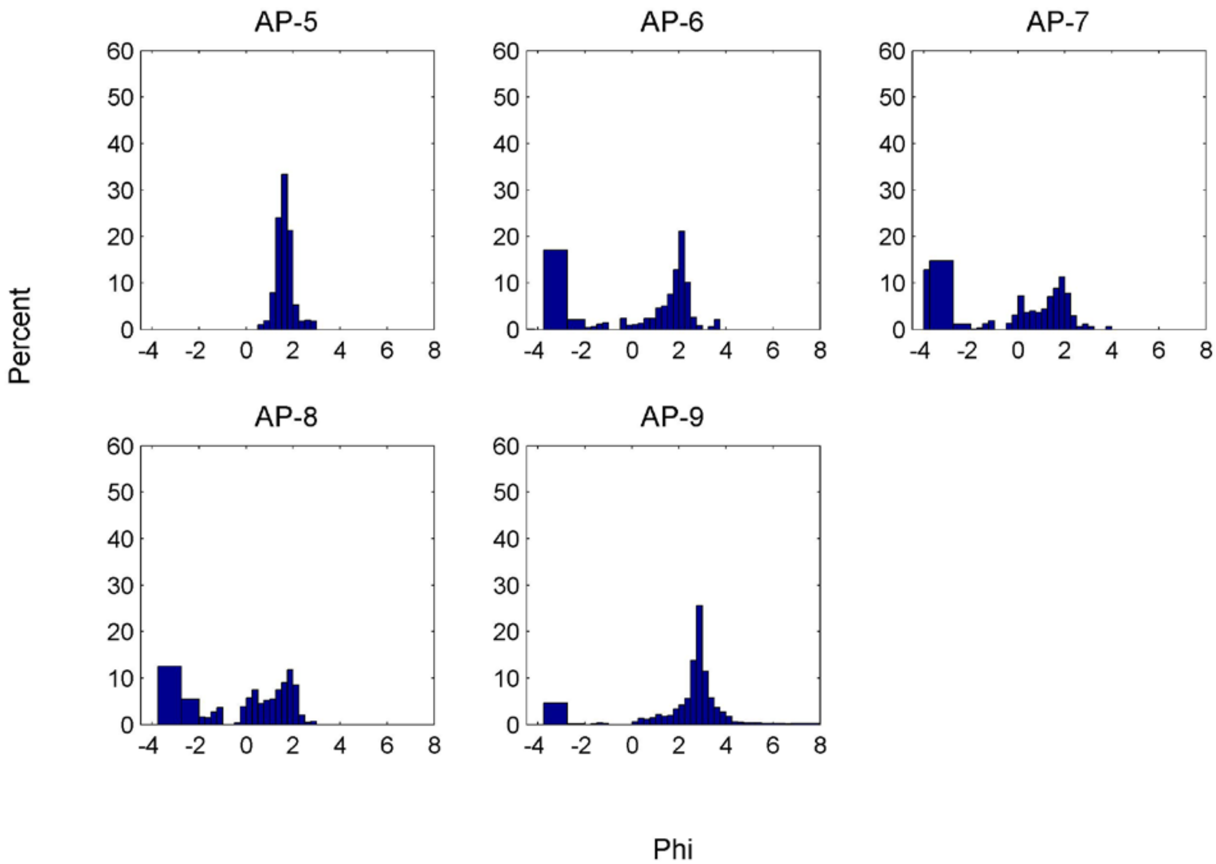


**Figure C5.** Sediment grain size distribution (weight percent) for samples AP-5 through AP-9 from Possession Point. See table C1 for locations of samples.

Stevens and Others—**Evaluation of a Single-Beam Sonar System to Map Seagrass at Two Sites in Puget Sound**—Scientific Investigations Report 2008–5009