Evaluation of Surf Zone Survey Systems during Calm and Rough Sea States

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Abstract: Surveys collected with a 10-m-long lighter amphibious resupply cargo (LARC) vessel and a 3.3-m-long jetski are evaluated by comparison with surveys using the 11-m-tall coastal research amphibious buggy (CRAB) in calm and rough sea states representing the lower and upper operational bounds when considering safety and data quality. The centimeter-level accuracy of CRAB surveys, performed since 1981, is well established. The field test consisted of repetitively surveying two cross-shore profile lines from near the shoreline to 6-m water depth, 700 m offshore. The survey lines were repeated four times by the CRAB and nine to ten times by the LARC and jetski. The CRAB data were averaged to define a reference cross-shore elevation and profile shape to serve as ground truth to determine the accuracy of the LARC and jetski surveys. The two systems compare best with the CRAB surveys on the mildly sloping shoreface, seaward of the nearshore sandbar, where alongshore currents were weakest, depth-limited breaking waves were infrequent, and small-scale morphological features that may not be resolved by the CRAB were minimal. The root mean square (RMS) elevation error between the LARC measurements and the CRAB mean profile was 0.03 m under calm conditions and 0.05 m under rougher conditions, whereas the jetski RMS was 0.09 and 0.10 m, respectively.
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Introduction

As populations within the US coastal zone continue to expand, the importance of monitoring coastal morphology has become paramount. This growth creates additional demand for state and federal funding to protect coastal development, shoreline habitats, recreational beaches, and economies (Houston 2018). To manage coastal resources effectively, accurate and repetitive coastal surveys that provide insight into trends of shoreline movement are required. In addition, these data also prove critical in developing, testing, and refining numerical models of coastal hydrodynamics and morphologic change; in the design and monitoring of beach nourishment; and in determining regional sediment budgets.

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Since 1981, the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Field Research Facility (FRF) has been conducting monthly or more frequent detailed surveys of the beach topography and nearshore bathymetry. These long-term survey datasets provide scientists, engineers, and coastal communities with information critical to understanding coastal processes and coastal evolution on a range of temporal and spatial scales. The surveys require vertical accuracy on the order of a few centimeters to resolve small volume changes over the length of a survey line. The nearshore (including the surf zone) is particularly challenging to survey due to breaking waves that make it difficult and dangerous to navigate, with the potential for vessel capsizing. Breaking waves also entrain air, producing bubbles that attenuate and reflect acoustic signals, making it harder to detect the bottom. Additionally, the seafloor in shallow nearshore waters can vary significantly at small spatial scales, causing potential for vessel grounding. Although many accurate beach and nearshore surveying methods have been developed (Birkemeier and Mason 1984; Morton et al. 1993; Dugan et al. 1999; MacMahan 2001; Bernstein et al. 2003; Forte et al. 2017; Bak et al. 2023), little attention has been devoted to evaluating the relative accuracy of these methods under a range of sea states. Here, the measurement accuracy of two surf zone surveying platforms is compared with coastal research amphibious buggy (CRAB) surveys (Fig. 1) during two different sea states. In addition, high spatial resolution observations with a multibeam system show complex morphology that changes in both time and space, demonstrating why certain areas of the surf zone are difficult to assess.

Experimental Design and Methods

Survey Platforms

The CRAB is a unique three-wheeled 11-m-tall amphibious vehicle that remains on its tires as it is driven along the beach and seafloor (Birkemeier and Mason 1984). The CRAB is equipped with RTK

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Fig. 1. (Color) Photograph of the LARC (left), CRAB (middle), and jetski (right) surveying in rough water conditions on October 17, 2023. The vehicles are in about 5-m water depth. (Image courtesy of Erin Diurba.)

GPS, has a top speed of 3.2 km/h, and is designed to operate safely in 2-m waves. The CRAB's height allows accurate topographic surveys to extend offshore to a depth of 9 m. The GPS antenna is mounted a known distance directly above and centered between the back two wheels and thus provides an estimate of the elevation of the seafloor that is an average over the 7.6 m separation distance between the wheels. The CRAB is not influenced by waves or currents, nor by bubbles caused by breaking waves because it does not use acoustics for measurement. The lighter amphibious resupply cargo (LARC) is also an amphibious vehicle equipped with RTK GPS, a 200 kHz Knudsen singlebeam echosounder, and a TSS motion reference unit, and it is designed to both drive on land (on its tires) and navigate on the water (floating once the water is sufficiently deep). The LARC is 10-m-long and diesel powered, with four-wheel drive, and capable of speeds of 15 km/h in water and 48 km/h on land (Forte et al. 2017). With the 2023 rough water survey, an additional Norbit 400 kHZ multibeam system was mounted on the LARC. This all-in-one tightly integrated broadband multibeam offers high resolution bathymetry over a wide swath (depth dependent). The sonar is coupled with the Applanix WaveMaster inertial navigation system embedded into the unit, providing high quality attitude measurements for accurate surveys in dynamic conditions. The jetski is a 2009 Seadoo GTX, a 3.3-m-long personal watercraft. It is equipped with a custom-built 198 kHz single beam sonar, a KVH GyroTrac for measuring pitch and roll, a thermistor to measure surface water temperature, and a Trimble R7 GNSS receiver for positioning, and it has an operating speed when surveying of 10–12 km/h. Positioning of the jetski was done with postprocessing kinematics (PPK) using data from the jetski's onboard GNSS receiver and the NGS Continuously Operating Reference Station (CORS) located on the FRF property. Although the jetski participated in the initial test in 2016, it was not included in the prior analysis and technical report (Forte et al. 2017).

Field Test

The field test consisted of repetitively surveying two shore perpendicular transects approximately 700 m in length and spaced 45 m apart in the alongshore. The survey lines were repeated four times with the CRAB and 9–10 times with the LARC and jetski over a 2-h period. The LARC transited the two profiles repetitively from land to sea (into the waves) and then from sea to land (with the waves) by traveling seaward on one line and back toward shore on the other (which is typical to maximize survey efficiency). Jetski data often are retained only when transiting with the waves (from sea to land) when the operator can remain behind the wave crest avoiding the steep faces of breaking waves. This approach limits the number of waves encountered by the jetski, thus reducing the error induced by pitching (MacMahan 2001). However, to compare all systems under similar conditions, here both seaward transiting and landward transiting data are analyzed. The first survey test was collected on July 11, 2016, under ideal conditions [wave height = 0.5 m and wind speed = 2 m/s. Table 1, Fig. 2(a)], with the second survey test occurring on October 17, 2023, during rougher conditions [wave height = 1.4 m and wind speed = 8 m/s, Table 1, Fig. 2(b)] that represent the upper limit for surveying when considering safety and data quality.

Multiple sound velocity profiles were measured during each survey (Fig. 3) and were used in postprocessing to minimize error associated with spatially variable sound velocity in the LARC single beam acoustic data. The jetski uses a different approach by applying a single speed of sound value based on the surface water temperature measured with the onboard thermistor and a set salinity for the entire water column. For this study site, a salinity value of 30 ppt was used.

Data Processing and Analysis

The CRAB data were processed using a FORTRAN routine that computed the elevation of the CRAB by subtracting the height of the GPS antenna from the GPS elevation data and then correcting for a cross-shore tilt that is derived from the elevation change between survey points to determine a slope.

The LARC estimates of the seafloor elevation are computed by combining the RTK-GPS, echosounder, and motion sensor data streams using a FORTRAN routine that does the following:

Table 1. Environmental conditions during test days observed from CDIP 433 (waves), FRF AWAC 11 m (currents), and NOAA Station 8651370 (winds)

	Waves			Currents		Winds	
Survey date	Hs (m)	Tp (s)	Dir (degrees)	Speed (m/s)	Dir	Speed (m/s)	Dir (degrees)
20160711	0.54	9.72	94	0.05	191°	1.94	119
20231023	1.43	6.01	25	0.21	163°	8.34	341

Note: Shore normal is 72°.

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Fig. 2. (Color) Photographs of the LARC and jetski in 4-m water depth during: (a) calm conditions in 2016 (image by authors); and (b) rough conditions in 2023 (image courtesy of Erin Diurba).

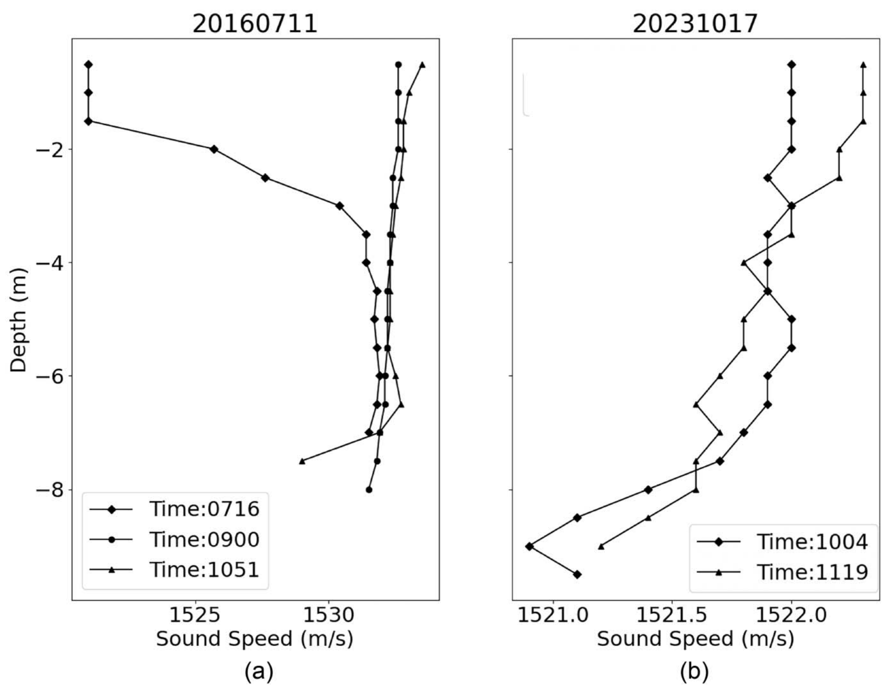

Fig. 3. Speed of sound as a function of water depth obtained in: (a) 2016; and (b) 2023. The times (local) of the measurements are given in each panel.

1. Separates and cleans the RTK-GPS and echosounder data streams by removing outliers and erroneous points;
2. Adjusts echosounder data for the speed of sound profile;
3. Corrects the echosounder data for any drift of the data collection computer clock;
4. Separates topographic (over land) points from bathymetric (in water) points;
5. Matches an echosounder reading for each bathymetric RTK-GPS point; and
6. Optimizes the match between the RTK-GPS and echosounder data in time.

Processing the jetski data (mostly with MATLAB routines) consisted of the following:

1. Postprocessing the GNSS data collected at the jetski with the FRF CORS data using NovAtel's GrafNav post-processing software;
2. Time syncing the PPK GPS data with the gyro, sonar, and temperature data;
3. Filtering to remove poor PPK solutions and points with pitch or roll $> 10°$;
4. Adjusting for the measured water temperature and a given salinity (30 ppt for this survey); and
5. Removing spurious data points by hand before applying a final moving median filter with a window size of ± 1 m.

To compute elevation statistics, the original data were linearly interpolated onto a 1-m spatial grid that oversamples the LARC and jetski surveys and slightly undersamples the CRAB surveys. The 1-m spacing is close to the 0.6-m spacing of the CRAB data, and thus it produces a mean profile from the CRAB data repetitions that resolves the shape of the profile. Statistics including standard deviations and root mean square elevation (RMSE) differences relative to the CRAB were computed at each 1-m cross-shore location (Forte et al. 2017).

Multibeam Data Processing and Analysis

The multibeam data were processed using Qimera—QPS software (Qimera 2025), which adjusts for vessel motion (heading, heave, pitch, roll), sound velocity, and RTK GPS vertical corrections. A 0.25-m continuous grid was derived from the soundings from each of the 10 repetitions. The swath width was typically 9 m in the shallowest parts of the survey (0.6 ≤ depth ≤ 2.0 m), expanding to 20 m at depths > 2 m. The data collected traveling from landward to seaward (into the waves) encountered issues with breaking wave generated bubbles that prevented bottom returns from the sonar. In addition, the bottom tracking algorithm was limited; resetting after bubbles from each breaking wave would cause the sonar to lose the bottom. Due to the many sonar dropouts, the morphologic features within the surf zone were not well resolved, and those multibeam data are not considered here. Conversely, when traveling from seaward to landward (with the waves) the morphologic features were resolved, especially in the surf zone because the breaking waves hit the stern of the vessel, whereas the multibeam sensor was located on the bow, and thus the bottom tracking algorithm had better performance.

Results

The analysis procedure (Forte et al. 2017) assumes that each pass along the profile line is a valid representation of the actual profile shape and examines (1) the variation from multiple passes of each profile; and (2) the difference between each survey platform and the CRAB reference profile that is the mean of four repetitions.

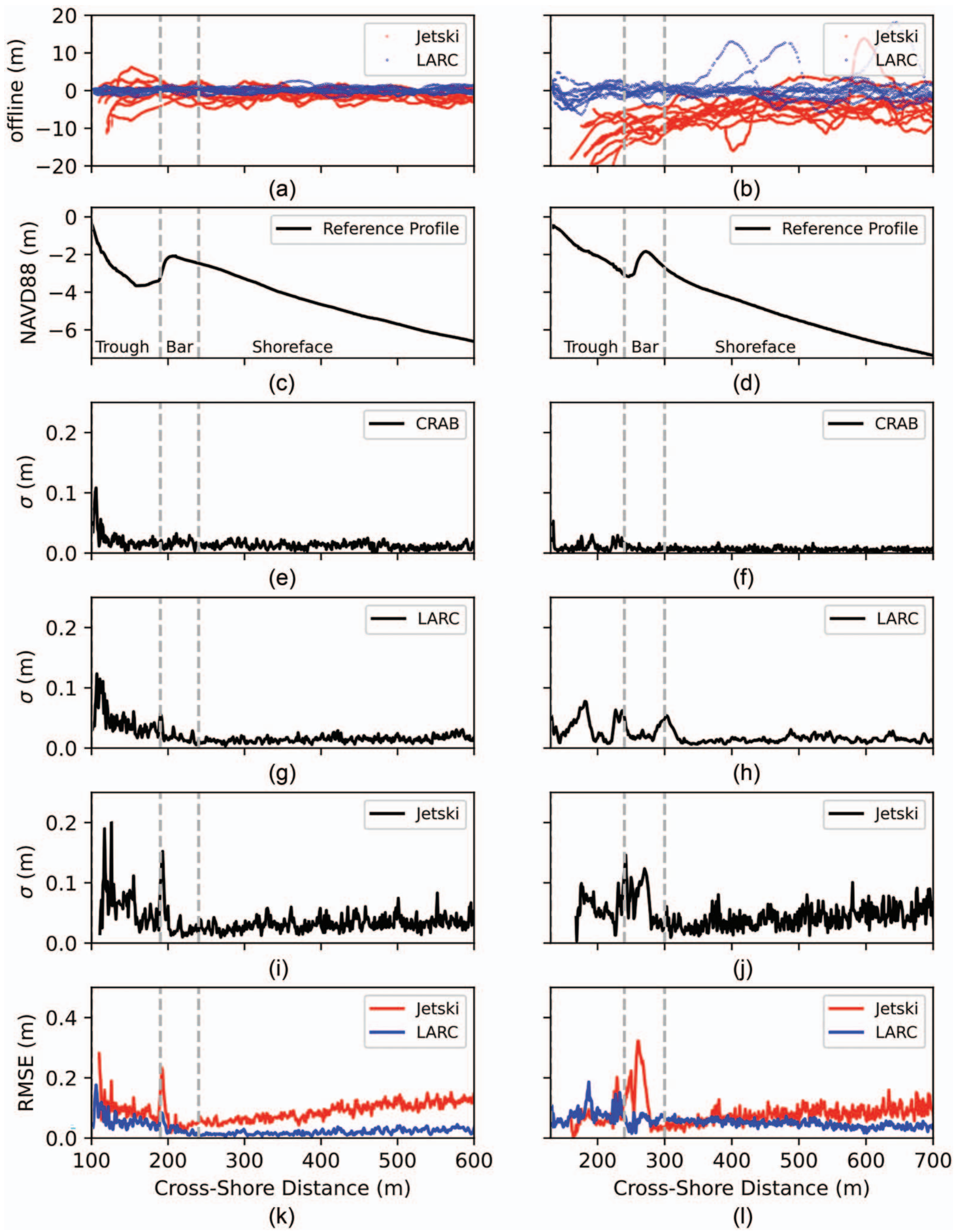

Fig. 4. (Color) While surveying landward to seaward (LARC) and seaward to landward (jetski): (a and b) distance from the predetermined transect; and (c and d) seafloor elevation relative to NAVD88; standard deviations of the repeated survey transects for (e and f) CRAB; (g and h) LARC; and (i and j) jetski; and (k and l) RMSE relative to the CRAB survey for the jetski (red curves) and LARC (blue curves) versus cross-shore distance for calm (2016, left column) and rough (2023, right column) conditions.

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When repeating transects, vessels stayed within 10 m [calm conditions, Figs. 4(a) and 5(a), Table 2] and 20 m [rough conditions, Figs. 4(b) and 5(b), Table 2] of the target transect line at all times. The analysis is based on the predefined cross-shore transects, and all points are treated as though they are on that line. Only the amphibious LARC and CRAB were able to survey both the seafloor and the dry beach, and thus the onshore extent of the comparisons is determined by the shallowest jetski survey data.

To adjust the acoustics for temporal changes in the speed of sound, multiple sound velocity casts (Fig. 3) were collected throughout the day during each survey. In 2016 the water column was stratified during the first part of the survey and then transitioned to a well-mixed water column later in the day [Fig. 3(a)]. In 2023, sound velocity was uniform throughout the water column, which is typical of a well-mixed water column often seen at this site during higher winds, with the speed of sound varying by less than 2 m/s from the surface to 9 m depth [Fig. 3(b)].

Results are presented for surveys going into the waves (landward to seaward, Fig. 4) and with the waves (seaward to landward, Fig. 5). During calm conditions, the survey tracks are relatively uniform and within 10 m of the target transect line [Figs. 4(a) and 5(a)], whereas during the rough water survey the vessel tracks deviated up to 20 m from the line [Figs. 4(b) and 5(b)], demonstrating the effects and difficulty of navigating along a known line in the

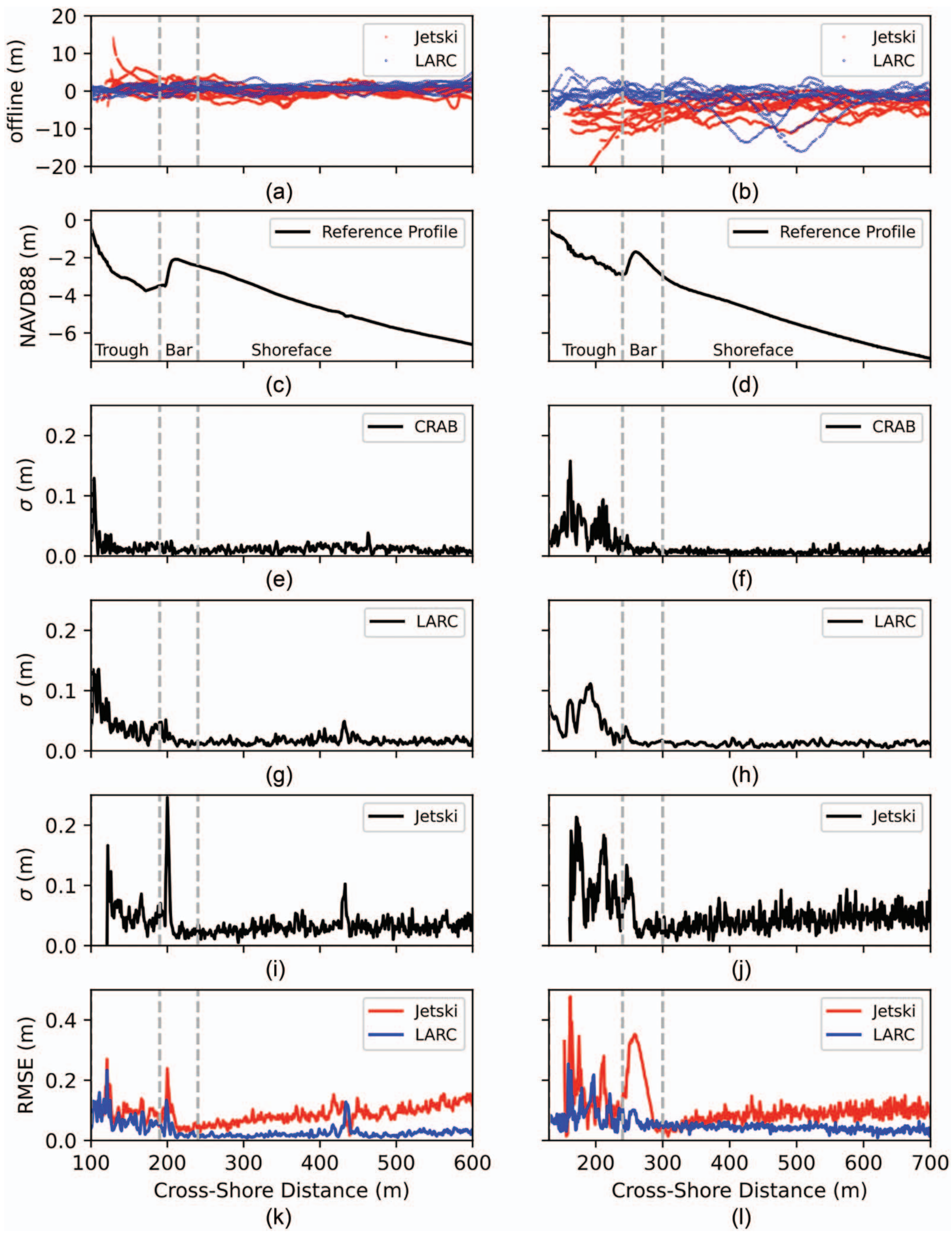

Fig. 5. (Color) While surveying seaward to landward: (a and b) distance from the predetermined transect; and (c and d) seafloor elevation relative to NAVD88; standard deviations of the repeated survey transects for (e and f) CRAB; (g and h) LARC; and (i and j) jetski; and (k and l) RMSE relative to the CRAB survey for the jetski (red curves) and LARC (blue curves) versus cross-shore distance for calm (2016, left column) and rough (2023, right column) conditions.

Table 2. Offline statistics in meters for each platform. $\bar{x}$ = average

	2016 (calm)		2023 (rough)	
Platform	$\bar{x}$ offline	x mean range	$\bar{x}$ offline	x mean range
CRAB	0.45	0.55	−0.34	4.01
Jetski	−0.33	10.33	−4.99	17.36
LARC	0.49	2.05	−0.94	14.56

presence of alongshore surface currents, oblique waves, and NW winds. The distance offline of the jetski steadily increased toward the shoreline [red curves in Figs. 4(b) and 5(b)] owing to both increasing surface currents and breaking waves. Safety considerations are the main contributor to offline errors inside the breakers. Even small breakers on a calm day can roll a jetski if taken beam-on. The ability of the vessels to traverse along a predetermined transect line is quantified by the mean alongshore difference between actual and target transects and the range of the differences calculated by subtracting the maximum from the minimum value of the deviations from each 1-m cross-shore location computed from the repetitions (9 in 2016 and 10 in 2023) and then taking the mean (Table 2). The data demonstrate that navigation of the survey line becomes more difficult in rougher conditions, with the survey platforms having an average range of lateral shifts in position up to 4 m for the CRAB, 15 m for the LARC, and 17 m for the jetski (Table 2).

Although the general shapes of the cross-shore profiles are similar between test days, there were slight differences in the shape and width of the trough and the cross-shore position of the sandbar [Figs. 4(c and d) and 5(c and d)]. During calm conditions, the root mean square (RMS) differences between the repetitive surveys are a few centimeters when traveling in either direction for the CRAB [Figs. 4(e) and 5(e)] and LARC [Figs. 4(g) and 5(g)], except near the shoreline. The RMS was slightly larger for the jetski onshore and seaward of the bar and was largest near the onshore face of the bar [Figs. 4(i) and 5(i)]. During rough conditions the CRAB RMS differences were similar to those during calm conditions [Figs. 4(f) and 5(f)], except onshore of the bar trough, where the RMS was as big as 0.15 m [Fig. 5(f)]. In contrast, during rough conditions, both the LARC [Figs. 4(h) and 5(h)] and jetski [Figs. 4(j) and 5(j)] had bigger deviations between repetitive surveys. The overall RMS differences between CRAB and LARC [blue curves in Figs. 4(k and l) and 5(k and l)] are similar during both calm and rough conditions (0.03 to 0.05 m, Table 3), with slightly higher values near and onshore of the sandbar (Table 3). The overall RMS differences between CRAB and jetski [red curves in Figs. 4(k and l) and 5(k and l)] also were similar during both calm and rough conditions (0.08 to 0.11 m, Table 3), with higher values near the sandbar and trough, especially during rough conditions (Table 3).

In both tests, the jetski shows a gradual offshore increase in RMS differences with the CRAB surveys that may be attributed to errors associated with applying a single sound speed for the entire water column. Similarly, slight changes with cross-shore location in the RMS between LARC and CRAB surveys also may be related to uncertainties and spatial differences in the speed of sound.

With the addition of the mutibeam data in 2023, morphology on 9–20 m (depth-dependent) spatial scales was resolved. The zones with the largest differences relative to the CRAB surveys had the most small-scale variations in bathymetry that included sand waves (megaripples) with amplitudes ranging from 0.05 to 0.30 m and wavelengths from 0.5 to 7.0 m throughout the bar and trough region of the surf zone [Fig. 6(a)]. The seafloor bedforms extended from the bar tough to the shoreline [Fig. 6(b)]. During the 2 h spanning the surveys, the bedforms migrated [Fig. 6(c)], with up to ±0.1 m changes in elevation along the transect [Fig. 6(d)]. The differences in the seafloor caused by migrating bedforms (Fig. 6) could explain some of the RMS differences between repeat surveys in areas shallower than the sandbar crest.

Discussion

The stable platform of the CRAB allows operation in conditions with waves as large as 2 m and strong currents. In contrast, both the LARC and jetski typically are restricted to operate in milder conditions, with waves less than 1 m, and their data and the corresponding estimates of the seafloor elevation deteriorate as the sea state increases. However, surveys with the much slower moving CRAB take about twice as long as surveys with the LARC or jetski.

The highest standard deviations and RMSE values from all platforms were found in the trough and sandbar regions (Table 3), likely owing to both the complex seabed morphology (e.g., bedforms, Fig. 6) and the difficulty in traversing the exact same cross-shore transect. As sea state increases, it becomes more difficult to navigate vessels repeatedly over the same predetermined transect line (Table 2), increasing the errors between repeated surveys and the errors relative to the CRAB-provided ground truth (Table 3). Inaccurate estimates of the speed of sound also can result in errors, especially as the water depth increases. For example, the errors between jetski and CRAB surveys are somewhat larger during the calm conditions than during rough conditions [Table 3, and compare the red curves in Figs. 4(k) and 5(k) with the red curves in Figs. 4(l) and 5(l) offshore of the sandbar], possibly owing to the stratified water during the calm conditions [Fig. 3(a)]. When traversing seaward on the LARC, the operator is able to pause movement while on tires before floating and time oncoming waves. This may have contributed to the lower RMS values as opposed to traveling landward where the operator must keep forward motion until

Table 3. Elevation z statistics in meters from jetski and LARC compared with the CRAB

		Overall		Trough		Bar		Shoreface	
Platform/date	Direction	RMSE	$\bar{z}$	RMSE	$\bar{z}$	RMSE	$\bar{z}$	RMSE	$\bar{z}$
Jetski 2023	Landward	0.11	0.07	0.15	0.04	0.19	0.07	0.08	0.07
LARC 2023	Landward	0.05	0.04	0.09	0.03	0.06	0.05	0.04	0.04
jetski 2016	Landward	0.09	0.08	0.10	0.09	0.07	0.05	0.09	0.08
LARC 2016	Landward	0.03	−0.01	0.07	−0.04	0.04	0.01	0.02	−0.01
jetski 2023	Landward	0.08	0.06	0.07	−0.02	0.13	0.10	0.08	0.07
LARC 2023	Seaward	0.05	0.05	0.08	0.06	0.06	0.04	0.05	0.04
jetski 2016	Landward	0.09	0.08	0.10	0.06	0.06	0.05	0.09	0.08
LARC 2016	Seaward	0.03	−0.01	0.05	−0.06	0.04	−0.01	0.02	−0.01

Note: RMSE for each platform relative to CRAB and $\bar{z}$ = average difference between platform and CRAB.

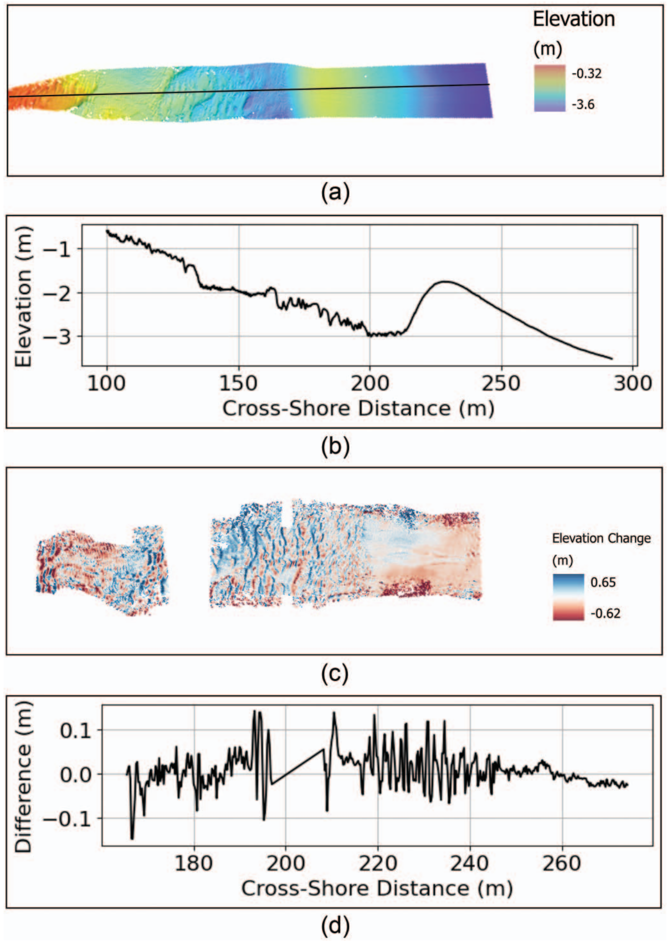

Fig. 6. (Color) Multibeam observations of (a) seafloor elevation (color scale on the right); (b) elevation along the cross-shore transect indicated by the black horizontal line in panel (a); (c) change in seafloor elevation over 2 h (scale on the right); and (d) difference in elevation over 2 h versus cross-shore distance.

landing on the shoreline otherwise risk vessel broaching in the surf zone.

Conclusions

Seafloor bathymetry estimated with surface vessels (a LARC and a jetski), both equipped with RTK and PPK GPS and acoustic echosounders, was compared with ground truth surveys obtained with the amphibious CRAB tripod during two sea states to determine their relative accuracy in varying conditions. Across the 700-m-long cross-shore transects, overall RMS differences with the CRAB surveys were about 0.03 to 0.05 m for LARC surveys and about 0.08 to 0.11 m for jetski surveys. As the sea state increased, the accuracy relative to CRAB surveys decreased by 0.01 to 0.02 m RMSE, and the navigation of the survey transect became more difficult, with offline distances nearly doubling between calm and rough conditions.

Differences were largest onshore of the sandbar, from the trough to the shoreline, possibly partially owing to evolving bedforms (detected with multibeam observations) with amplitudes as large as 0.3 m, and with ±0.1 m vertical changes over the 2-h-long surveys. Additionally, when the vessels are offline of the transect, they may not be measuring the exact location on the seafloor in relation to the CRAB ground truth.

Data Availability Statement

All data and code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

Michael F. Forte: Conceptualization; Formal analysis; Methodology; Project administration; Writing – original draft; Writing – review and editing. Levi Gorrell: Writing – review and editing. Steve Elgar: Funding acquisition; Resources; Writing – review and editing. Britt Raubenheimer: Funding acquisition; Resources; Writing – review and editing. Patrick J. Dickhudt: Resources; Writing – review and editing. J. R. Mitchell: Methodology; Writing – review and editing.

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