Interferometric Swath Bathymetry for Large Scale Shallow Water Hydrographic Surveys

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Abstract

Traditional hydrographic data acquisition techniques for large-scale shallow water survey projects are typically inefficient and costly. Technological advancements to Phase Differencing Bathymetric Sonar (PDBS) systems, or interferometric sonar, have overcome the efficiency and cost obstacles associated with traditional surveying methods. PDBS systems provide a significantly wider swath in shallow water (depth less than 35 meters) compared to Multibeam Echo Sounders (MBES). The increased number of phase detection arrays found in some systems has also proven to significantly improve the accuracy. Additionally, some manufacturers have found methods for closing the nadir gap which has historically plagued the efficiency of these sensors. These recent improvements paired with the wider swath coverage observed by these systems place interferometric sonars at the forefront of acoustic technology. Utilization of these systems allow for fewer sweeps across the survey area resulting in decreased data acquisition time and cost. For many applications, the wider swath coverage eliminates requirements of deploying the survey system close to the shoreline thus increasing keel clearance for safe deployment. Furthermore, some PDBS systems offer a platform for providing simultaneous, co-registered, three-dimensional (3D) bathymetry and side scan sonar imagery in a single unit. This considerably improves the integrity of feature detection for navigation and mapping purposes, while reducing processing time for co-registering imagery to the bathymetric data. This paper analyzes the efficacy of utilizing a technologically advanced PDBS system, such as the EdgeTech 6205, to perform large-scale shallow water survey operations.

Introduction

Traditionally, Multibeam Echo Sounders (MBES) have been the canonical system for providing swath bathymetry, but with the latest technological advancements within the Phase Differencing Bathymetric Sonars (PDBS) systems industry this may no longer be the case. PDBS systems, also known as interferometric sonars or bathymetric side scans, have long been considered for meeting the surveying requirements but their shortcomings, such as excessive depth ambiguities associated with noisy range and angle observations and the lack of coverage within the nadir region, significantly limited the efficacy of the technology. Furthermore, the size and weight inherent to the design of these systems have limited their applicability within the shallow water survey environment for which they were designed.

Today, PDBS systems are a focal point of product development among sonar manufacturers. This technology is rapidly evolving as new sensors, practices, and users emerge. This evolution has been driven largely by the lack of availability of survey tools and significant inefficiencies afforded by other technical approaches combined with an increased demand of shallow water mapping. Hydrographers and their respective clients have particular interest in ensuring that the survey methods meet the specifications, needs, and requirements of the organization. In addition to the data quality, the feature detection capabilities and low cost of ownership are integral to achieving their demands. The use of these new types of PDBS systems is a promising tool for achieving these objectives in the shallow water environment. This paper takes a closer look at the state of the technology and provides a broad overview of the efficiency gains afforded by these advanced PDBS systems; particularly the performance, cost benefit, and additional advantages of utilizing these systems to support shallow water navigation and broad scale mapping requirements in 35 meters of water or less.

State of the Technology

PDBS systems can be considered a multi-stave side scan, collecting a wide swath of bathymetry and sonar amplitude data with the angle of arrival of the seabed returns determined by phase comparisons between the receive staves. PDBS systems have always been appealing because they are capable of obtaining high resolution side scan data that is precisely co-registered to the three-dimensional (3D) point data. This property often proves valuable in reconciling uncertain point data that would otherwise be debatable. The hydrographer is often questioned about the validity or presence of particular shoals and apparent seafloor features and the complimenting side scan imagery can improve the confidence of bathymetry strike integrity and validation.

Historically, the problem with PDBS systems has been their lack of data at nadir, unknown and insufficient accuracy, form factor, and large data volumes. Until recently there has not been a technology readily available that provides the coverage and accuracy to meet the strict International Hydrographic Organization (IHO) standards while providing the same benefits that interferometers are known to provide. Unlike its predecessors, the EdgeTech 6205 is the first of its kind to offer complete bathymetric coverage of the seafloor, even at nadir. Combining this kind of coverage with accuracy that exceeds IHO Special Order requirements provides the hydrographer with a tool that can safely and efficiently survey within the shallow water environment.

A New Kind of PDBS

The EdgeTech 6205 Swath Bathymetric and Simultaneous Dual Frequency Side Scan Sonar System (EdgeTech 6205) is a combined, fully integrated system that produces real-time high resolution 3D maps of the seafloor while providing co-registered simultaneous dual frequency side scan and bathymetric data. The high number of channels employed by the system enables enhanced rejection of multi-path effects as well as reverberation and acoustic noise. EdgeTech's Full Spectrum® processing techniques have been proven to provide complete coverage in the nadir region, while meeting IHO Special Publication No. 44, National Oceanic and Atmospheric Administration (NOAA) and United States Army Corps of Engineers (USACE) specifications for feature detection.

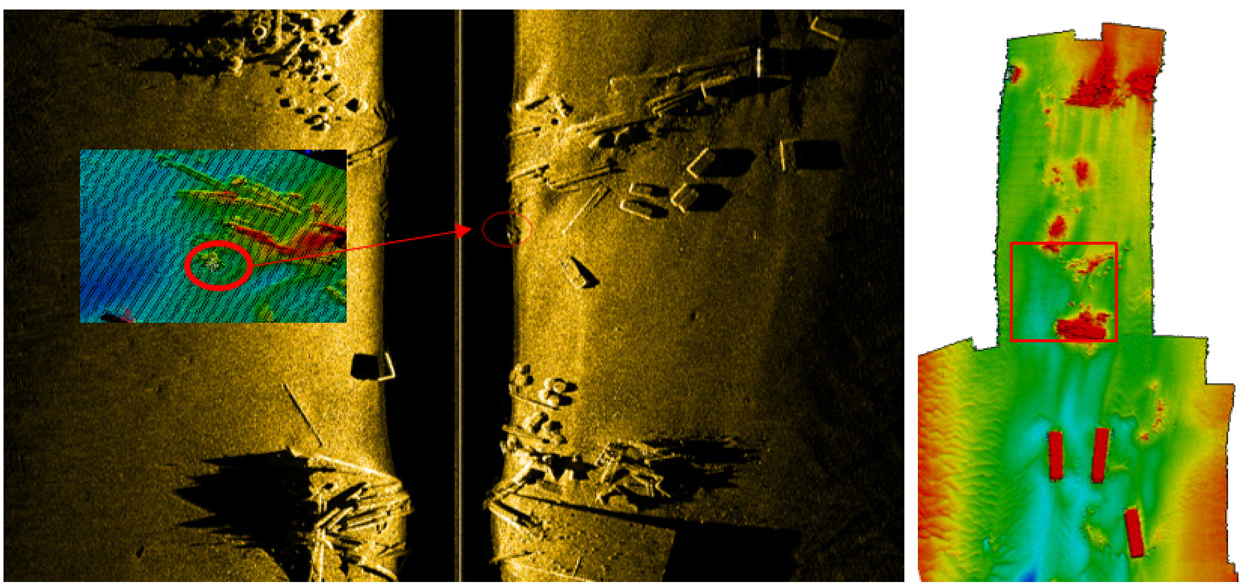

Figure 1: Co-registered side scan imagery and bathymetric data showing obstruction at nadir.

Performance

The overall performance of the chosen sonar system must first be examined before any survey planning can commence. Once the specifications and performance metrics are understood, than budgets, time scales, line planning, etc. can be estimated. This section provides a brief overview of the typical performance achievable by the EdgeTech 6205.

A Closer Look

Statistical techniques for analyzing and optimizing the performance of swath bathymetry systems have been used for several decades, especially in the analysis of MBES systems. A well-used technique is to compare a single line of test data against a reference surface to determine the sonar depth repeatability and consistency across the swath. Statistical analysis of the difference between the reference surface and the test line provides a good indication of the accuracy and repeatability of the sonar and its ancillary sensors in a single pass as a function of 3D positional accuracy across the entire swath. The benchmarking and accuracy assessments utilizing this method require the use of high quality sensors to correct the geo-referenced data so that the true errors from the sonar system can be evaluated. Due to the expanded swath coverage of PDBS systems, the core suite of sensors used to directly geo-reference the bathymetry includes high-end inertial navigation systems that utilize dual frequency carrier-phase GNSS receivers with tidal correction capabilities and heading determination, while providing highly accurate measurements for roll, pitch, and heave. These ancillary sensors minimize positioning errors of the directly geo-referenced bathymetry point data, especially in the outer swath regions, as most of the corrections are angular in nature. [1, 2]

In late 2013, these techniques were applied to analyze the performance of a pole-mounted EdgeTech 6205. Figure 2 shows the EdgeTech 6205 mounted aboard the USACE Survey Boat SB-46.

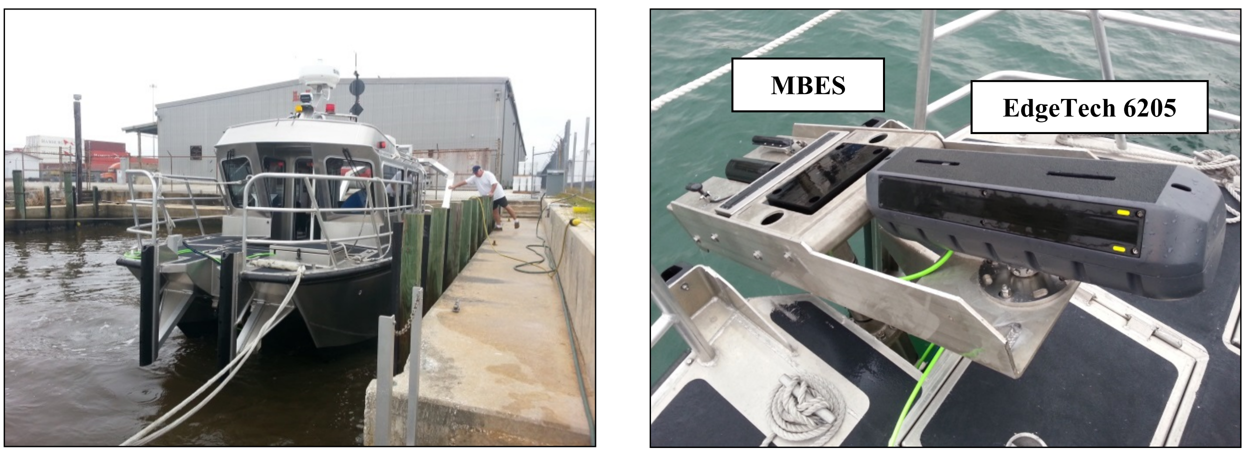

Figure 2: Survey vessel SB-46 (left) and bow mounted EdgeTech 6205 and MBES (right)

The area chosen was a nominally flat navigational channel, which was in approximately 10 meters of water, sheltered from swell and weather, and was of sufficient size to allow 16 orthogonal sets of 200 meter lines at 15 meter spacing. Repeat surveys were run over the dredged navigation area with a MBES in the St. John's River, Jacksonville, FL, with the aim of generating a reference bathymetric surface. The MBES reference surface was acquired using 200% coverage with a boustrophedonic lattice pattern, consisting of 16 N-S lines and 16 E-W lines, and only logging the highest quality data, or 90 degree swath. A test line was then collected over this reference surface using the EdgeTech 6205. The test line was acquired using the full field of view (200°) which amounts to 12 times water depth or more.

A patch test area to the northwest of the survey area was identified. It consisted of a flat area and a channel edge which enabled roll, pitch, yaw, and latency calibrations. The final surfaces were corrected for tides, delayed heave, and sound velocity variations within the water column and are presented in Figure 3 and Figure 4.

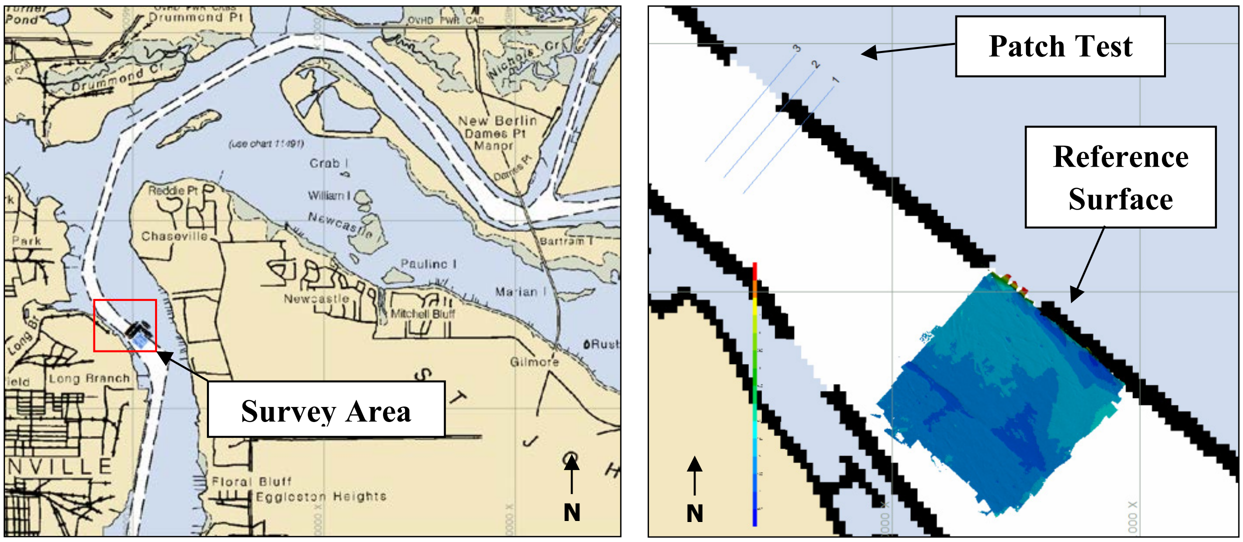

Figure 3: The survey area showing the reference surface and patch test area (left) and enlarged view of these areas (right).

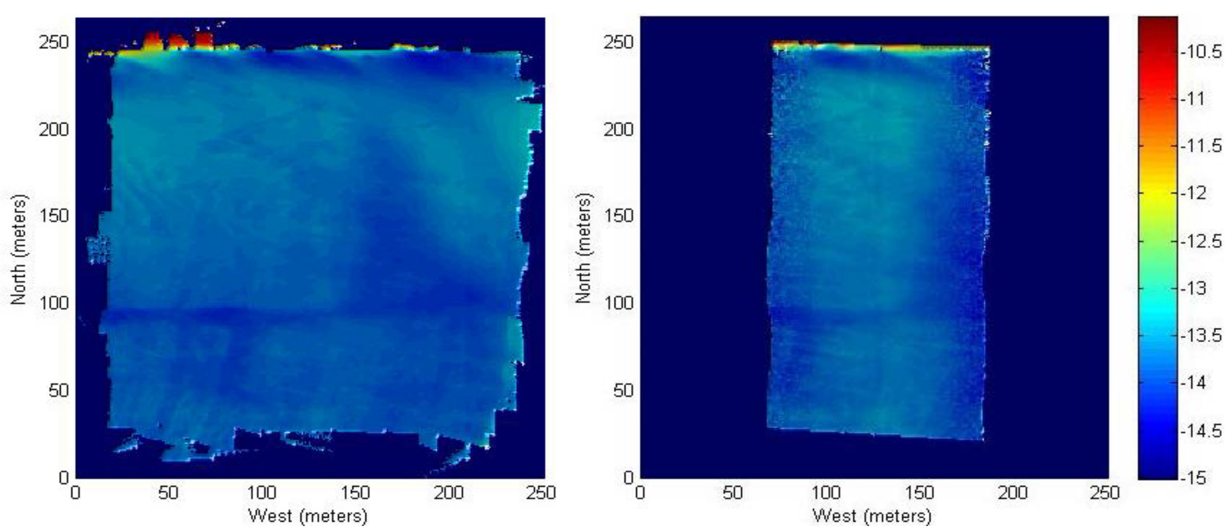

Figure 4: MBES reference surface (250m x 250m) gridded to 1m cells (left); the EdgeTech 6205 250m test line, untouched, gridded to 1m, and collected at 12 x water depth (right). Both have been plotted using the same color scale shown on the right and rotated counter clockwise so that cross profiles are perpendicular to the vessel's track.

To compare the reference surface with the EdgeTech 6205 test line, a mean difference surface was created and exported as a separate DTM (Figure 5). Notice the color scale has changed and the mean difference oscillates around zero.

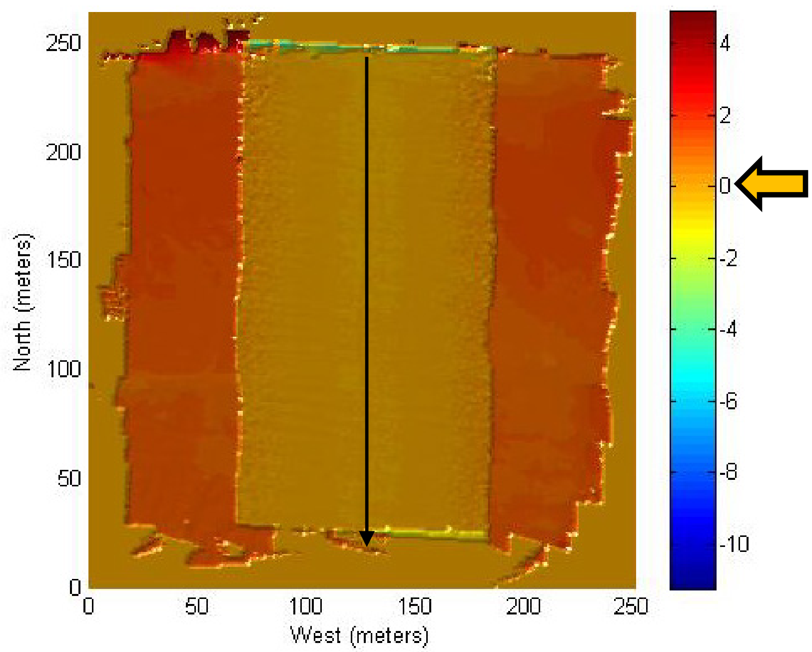

Figure 5: Top view of the EdgeTech 6205 test line differenced from the MBES reference surface with the vessel's track designated by the arrow. Notice the new color scale representing the difference surface. Mean difference oscillates around zero (light orange).

Analysis

The above methods provided a set of profiles across the test swath which revealed the difference between the test line and the reference surface. These profiles were analyzed to find the mean and standard deviation of the differences between the test line and reference surface. The 95% confidence interval was then computed from two times the standard deviation.

In order to aid in determining whether or not the system can meet hydrographic standards the IHO Special Order criterion was used as the performance metric. According to the IHO Standards for Hydrographic Surveys, 5th Edition, Special Publication N°44, the Total Vertical Uncertainty (TVU) is computed as

$$TVU = \pm\sqrt{a^2 + (b \times d)^2} \quad \text{Eq. 1}$$

where, *a* represents that portion of the uncertainty that does not vary with depth,
b is the coefficient which represents that portion of the uncertainty that varies with depth,
d is the depth, and

(b x d) represents that portion of the uncertainty that does vary with depth.

The maximum allowable uncertainty in depth includes all inaccuracies due to residual systematic and system specific instrument errors. This includes the speed of sound in water, static vessel draft, dynamic vessel draft, heave, roll, and pitch, and any other sources of error in the actual measurements process, including the errors associated with water level (tide) variations (both tidal measurement and zoning errors). [3]

For IHO Special Order surveys in 10 meters of water, the variables a and b are defined as a = 0.25 meters and b = 0.0075. Using the equation above and the variables stated previously, the TVU in 10 meters of water was calculated as +/- 26.1 centimeters.

To demonstrate the overall system performance of the EdgeTech 6205, the 95% confidence level was plotted as a function of water depth (Figure 6). A blue line was fitted to these values for visualization purposes and the TVU for IHO Special Order surveys was drawn in red.

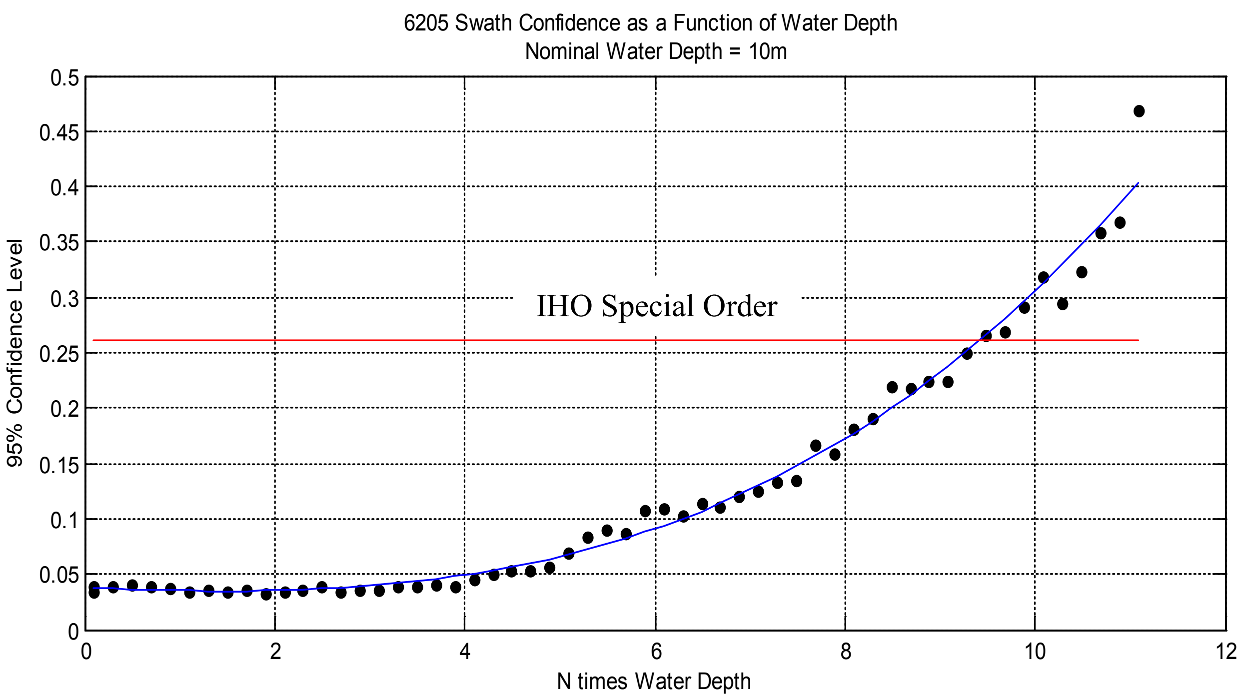

Figure 6: EdgeTech 6205 Swath confidence as a function of water depth for a nominal water depth of 10m. IHO Special Order standard is indicated by the red line.

Based on the above plot it can be said that the EdgeTech 6205 can produce IHO Special Order quality data out to approximately 9.5 times water depth. To be conservative, 8 times water depth will be used to analyze the cost benefits of using a system such as the EdgeTech 6205 in large-scale shallow water surveys. [4]

Cost Analysis

When surveying in shallow water with specifications dictating 100 percent or more of bathymetry coverage, survey costs can increase exponentially with decreased seafloor depth. This is due to the fact that to an extent, effective swath width is directly proportional to water depth.

MBES vs. PDBS

In the case of the MBES the effective swath width is limited by the swath angle gate utilized for mapping. Effective swath width of a MBES system is computed as

$$SW_{MBES} = 2 \times d \times \tan\left(\frac{a}{2}\right), \qquad \text{Eq. 2}$$

where, SW_{MBES} is the swath width for MBES systems,
d is the water depth, and
a is the effective MBES swath sector.

In the case of PDBS systems the sonar always maintains an open field of view. Effective swath width is constrained linearly (vs. angularly in the case of the MBES) by gating the effective swath as follows:

$$SW_{PDBS} = d \times z, \qquad \text{Eq. 3}$$

where, SW_{PDBS} is the swath width obtainable by PDBS systems,
d is the water depth, and
z is the effective swath (i.e. 8 times water depth).

Cost Estimation

As seen in the formulas above, effective swath width and water depth are essential considerations for project cost estimation. To determine the overall acquisition cost for a survey, the daily coverage rate and number of days necessary to complete the job are required.

The daily coverage rate can be determined by,

$$C = SW \times v \times t, \qquad \text{Eq. 4}$$

where, SW is the effective swath width,
v is the survey speed, and
t is the amount of time the crew can survey in a day.

Once the total survey area is known, the number of days is computed as

$$n = \frac{A}{C}, \qquad \text{Eq. 5}$$

where, A is the total area of the survey location and C is the daily coverage rate.

The results are then used from Equation 4 and Equation 5 to calculate the overall acquisition cost of the survey.

$$Acquisition\ Cost = n \times R \qquad \text{Eq. 6}$$

where n is the number of days required to complete the survey and R is the daily rate.

No Nadir Gap

Coverage within the nadir region of the sonar is crucial to capitalizing on the efficiency gains of PDBS systems. While the wider swath afforded by PDBS systems is valuable, lack of nadir coverage hinders the overall efficiency gains due to the required additional passes to cover the nadir gap. There are, however, certain systems available today that have found a way to retain this efficiency by providing real acoustic data at nadir, while also providing the wide swath capability inherent to PDBS systems. The EdgeTech 6205 is one such system and is used in the following sections to perform the cost analysis.

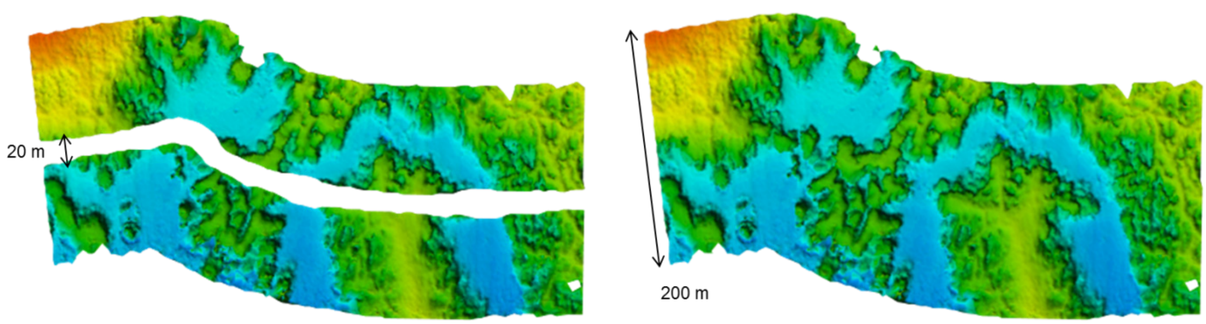

Figure 7: Historical performance at nadir (left) and nadir coverage produced by some current PDBS systems like the EdgeTech 6205 (right).

Florida Harbors

Florida has over 40 harbors located along its coastlines requiring routine surveys performed at least four times a year. Using traditional surveying MBES methods this can prove to be very expensive. Often these harbors are neglected due to lack of funding within the government sector. Using a PDBS system, such as the EdgeTech 6205, can address this problem by drastically reducing costs thereby providing well maintained waterways. To illustrate the efficiency gains of a no nadir gap PDBS system over typical MBES systems scenarios, three different harbors and an EdgeTech 6205 were used. Table 1 below illustrates the harbors' characteristics and properties.

Harbor	Maintained Depth (m)	Average Depth (m)	Length (m)	Width (m)	Area (km^2)
Palm Beach Harbor	9.75	7.8	3,500	310	1.09
Jacksonville Harbor	12.8	10.24	42,500	300	12.75
Tampa Bay Harbor	12.2	9.76	100,000	300	30.00

Table 1: Attributes for three Florida harbors.

Looking closely at one example, the Jacksonville Harbor's maintained channel depth and coverage rates are designated by the arrow in Table 2. This table illustrates the effective swath width and daily coverage rates by utilizing the EdgeTech 6205 (green) versus that of a typical MBES (red). Table 2 shows the daily coverage rate achievable by the EdgeTech 6205 is more than double that attainable by a typical MBES system (approximately 5 km^2 versus 2 km^2 respectively).

This information can then be converted to a project cost by using the actual acquisition time per day as 6 hours and a typical day rate of $5,500. Table 3 compares the typical cost per unit area using the EdgeTech 6205 (green) versus a traditional MBES (red). Here the table illustrates the EdgeTech 6205 cost is approximately $1,000 per km^2, whereas the MBES system cost is approximately $2,400 per km^2. Again, showing the same harbor survey acquired by a typical MBES system is roughly twice as expensive as one collected by the EdgeTech 6205 PDBS.

Depth (m)	Swath Width PDBS (m)	PDBS Survey Coverage (km^2) (Daily)	PDBS Survey Coverage Area (Acreage) (Daily)	Swath Width MBES (m)	MBES Survey Coverage (km^2)	MBES Survey Coverage Area (Acreage)
2	16	0.89	219.67	6.93	0.38	95.12
4	32	1.78	439.33	13.86	0.77	190.24
6	48	2.67	659.00	20.78	1.15	285.36
8	64	3.56	878.67	27.71	1.54	380.47
10	80	4.44	1098.33	34.64	1.92	475.59
12	96	5.33	1318.00	41.57	2.31	570.71
14	112	6.22	1537.67	48.50	2.69	665.83
16	128	7.11	1757.33	55.43	3.08	760.95
18	144	8.00	1977.00	62.35	3.46	856.07
20	150	8.33	2059.38	69.28	3.85	951.19
22	150	8.33	2059.38	76.21	4.23	1046.30
24	150	8.33	2059.38	83.14	4.62	1141.42
26	150	8.33	2059.38	90.07	5.00	1236.54
28	150	8.33	2059.38	96.99	5.39	1331.66
30	150	8.33	2059.38	103.92	5.77	1426.78
32	150	8.33	2059.38	110.85	6.16	1521.90
34	150	8.33	2059.38	117.78	6.54	1617.01
36	150	8.33	2059.38	124.71	6.93	1712.13

Table 2: EdgeTech 6205 daily coverage calculations assuming a linear kilometer of survey as 55.56, a survey speed of 5 knots, a PDBS swath coverage of 8 times water depth achieving a maximum swath width of 150m, and a MBES swath coverage of 120° (or approximately 3.5 times water depth).

PDBS Coverage (Acres per Day)	Cost Per Acre	PDBS Coverage (km^2 per Day)	Cost Per km^2	MBES Coverage (Acres per Day)	Cost Per Acre	MBES Coverage (km^2 per Day)	Cost Per km^2
219.67	$25.04	0.89	$6,187.01	95.12	$57.82	0.38	$14,288.28
439.33	$12.52	1.78	$3,093.50	190.24	$28.91	0.77	$7,144.14
659.00	$8.35	2.67	$2,062.34	285.36	$19.27	1.15	$4,762.76
878.67	$6.26	3.56	$1,546.75	380.47	$14.46	1.54	$3,572.07
1098.33	$5.01	4.44	$1,237.40	475.59	$11.56	1.92	$2,857.66
1318.00	$4.17	5.33	$1,031.17	570.71	$9.64	2.31	$2,381.38
1537.67	$3.58	6.22	$883.86	665.83	$8.26	2.69	$2,041.18
1757.33	$3.13	7.11	$773.38	760.95	$7.23	3.08	$1,786.04
1977.00	$2.78	8.00	$687.45	856.07	$6.42	3.46	$1,587.59
2059.38	$2.67	8.33	$659.95	951.18	$5.78	3.85	$1,428.83
2059.38	$2.67	8.33	$659.95	1046.30	$5.26	4.23	$1,298.93
2059.38	$2.67	8.33	$659.95	1141.42	$4.82	4.62	$1,190.69
2059.38	$2.67	8.33	$659.95	1331.66	$4.13	5.39	$1,020.59
2059.38	$2.67	8.33	$659.95	1426.78	$3.85	5.77	$952.55
2059.38	$2.67	8.33	$659.95	1521.90	$3.61	6.16	$893.02
2059.38	$2.67	8.33	$659.95	1617.01	$3.40	6.54	$840.49
2059.38	$2.67	8.33	$659.95	1712.13	$3.21	6.93	$793.79

Table 3: EdgeTech 6205 daily coverage calculations assuming a survey speed equal to 5 knots, efficiency is equal to 6 hours of actual acquisition and survey rate is equal to $5,500. Coverage per acre fields computed as in Table 2.

To further demonstrate the cost saving capabilities of the EdgeTech 6205 Table 2 and Table 3 were applied to the three different Florida harbors presented in Table 1. These results are presented in Figure 8.

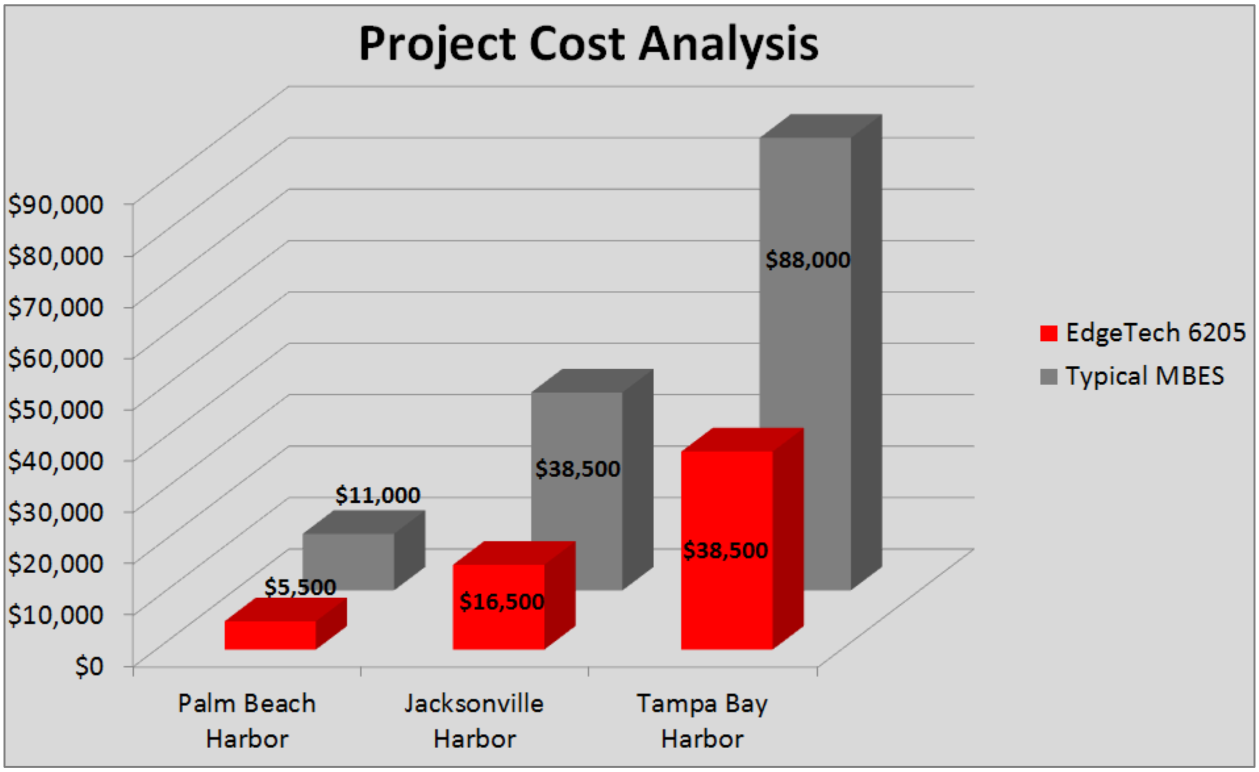

Figure 8: Project cost analysis for three of Florida's harbors using both a PDBS system like the EdgeTech 6205, and a typical MBES.

The bar graph in Figure 8 shows that by utilizing the EdgeTech 6205 to survey these harbors the government saves the taxpayers over 50%, or approximately $77,000 per quarter. Implementing these surveying techniques across all deep and shallow draft projects provides the potential for huge cost savings passed down to the taxpayers.

Additional Benefits

There are several additional cost saving benefits in using some of today's advanced PDBS systems over the traditional MBES. This section provides an overview of the three most common advantages provided by such a system, the EdgeTech 6205; single deployment, true side scan imagery, and simultaneous dual frequency operation.

Single Deployment

Traditionally, survey efforts involving the acquisition of both side scan imagery and seafloor bathymetry require the deployment of two individual sensors. While this technique has been accepted and utilized for a number of years, there are complications and inefficiencies associated with both the acquisition phase and the data processing workflow. Acquisition inefficiencies are associated with differing deployment techniques of the two sensors, whereas the data processing workflow is hampered by positional discrepancies of the two data sets along with the lack of consolidated workflow procedures. Using a combined system that provides bathymetry and high resolution side scan imagery significantly reduces the time it takes to complete those surveys that require both data sets, and since the side scan is directly co-registered with the bathymetric point data, there is no downtime trying to render the two sets together.

Figure 9 provides an example of a dredged seafloor collected using six survey lines. Note the perfect alignment of the dredge cutter head markings between bathymetric and side scan data. The exact orientation of these features would not be possible without the precise co-registration of these two data sets achievable by only PDBS systems.

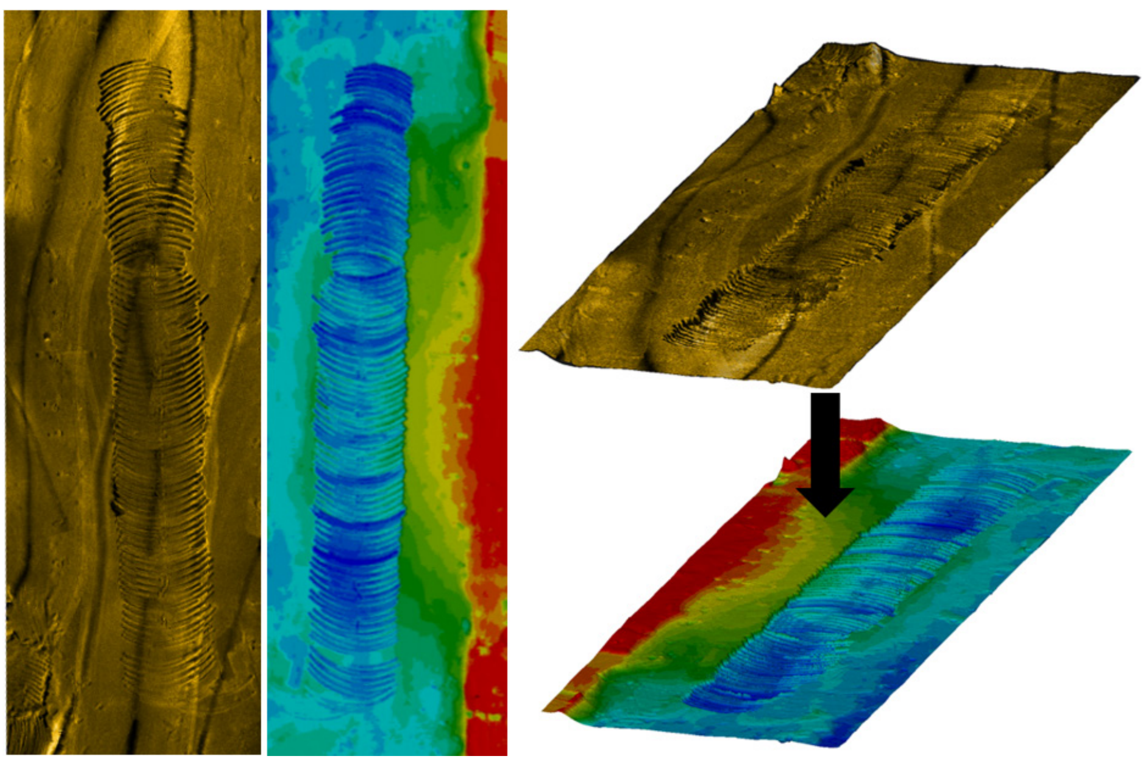

Figure 9: Side scan mosaic (left) and bathymetry map (right) representing an area surveyed with an EdgeTech 6205 using six passes.

True Side Scan

An additional benefit of using a PDBS system is its capability of providing true side scan imagery that is directly co-registered to the bathymetric point data. Using true side scan imagery can aid in feature and target localization as it provides shadow information, as opposed to a MBES backscatter plot of the seafloor. These shadows are used as visual cues to allow the hydrographer to identify small vertical objects that may be proud of the seafloor. These small vertical objects are often missed by or edited from the bathymetry. Therefore, the co-registered side scan sonar imagery allows surveyors and data processors to cross reference and verify features or targets when cleaning the bathymetry data to be certain real features are not deleted from the data set.

Simultaneous Operation

With the current technological advancements in today's PDBS systems some manufacturers have taken this feature a step further by providing dual frequency side scan imagery, and even simultaneous dual frequency side scan operation. By offering the simultaneous dual frequency capability, the frequency selection tradeoffs with regard to efficiency and resolution no longer exist. For example, the EdgeTech 6205 550/1600 kHz Swath Bathymetric and Dual Frequency Side Scan System can achieve a maximum swath width equal to 150 meters of bathymetry and a maximum swath width equal to 300 meters for the low frequency side scan and 70 meters for the high frequency side scan. In applications where maximum water depth does not exceed 15 meters, a frequency combination of 550 kHz and 1600 kHz is a good choice as the lower frequency is used for long range feature detection, while the higher frequency is used for target characterization and classification. Furthermore, in water depths where the range scale of the high frequency side scan frequency becomes limited, the hydrographer can always rely on the low frequency imagery since both the 550 kHz and 1600 kHz side scan channels are simultaneously collecting seafloor imagery.

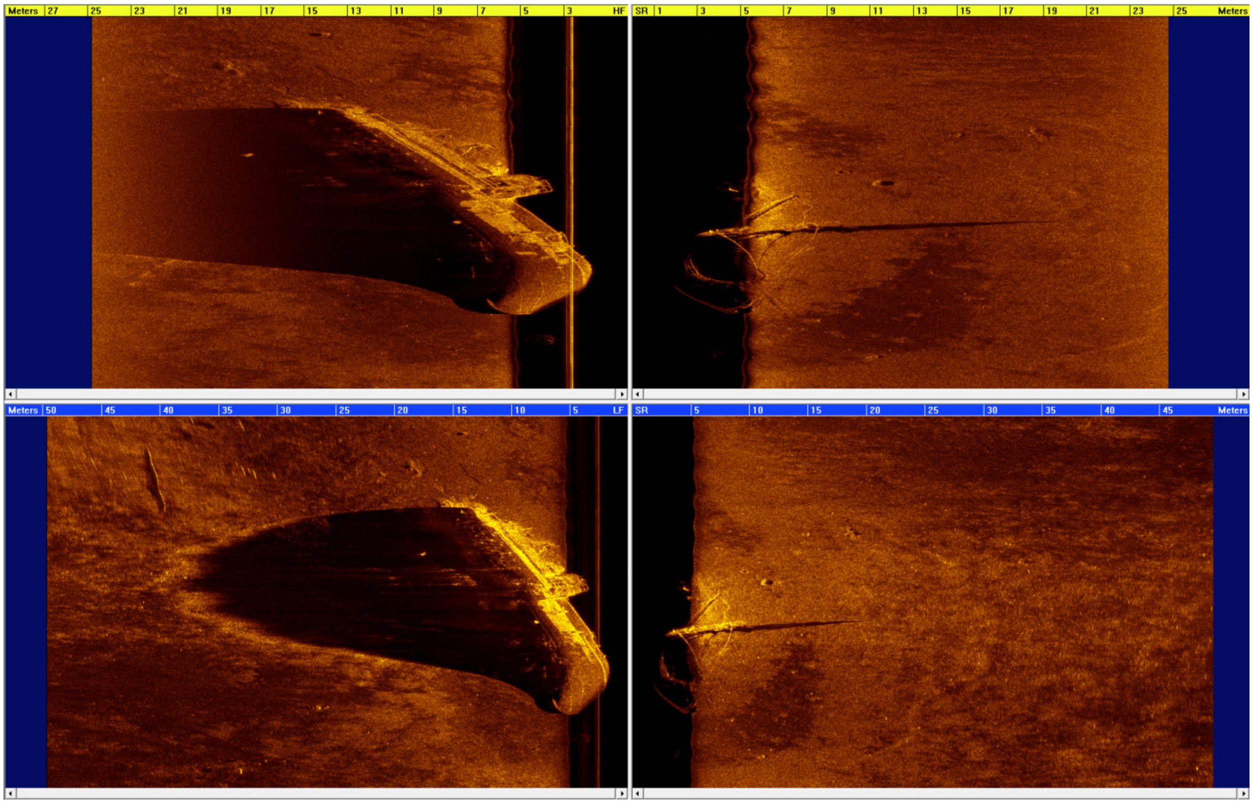

Figure 10: Simultaneous operation of both high (top) and low (bottom) frequency side scan channels of the EdgeTech 6205 550kHz/1600kHz system.

Conclusion

In summary, this paper presents the state of the technology, performance capabilities, and cost benefits afforded by some of today's PDBS systems. One such system is the EdgeTech 6205 Swath Bathymetric and Simultaneous Dual Frequency Side Scan Sonar System. This advanced PDBS system has shown to considerably increase efficiency and safety for near shore and shallow water hydrographic surveys by providing wide swaths of 2 to 3 times that of MBES systems, while achieving IHO Special Order standards out to at least 8 times water depth. Furthermore, a cost analysis involving surveying three Florida harbors showed the difference between traditional MBES surveys versus those obtainable by the EdgeTech 6205. The results were significant and proved to not only save taxpayers over 50% but also to drastically reduce the amount of time survey crews must spend on large-scale operations. In addition, the EdgeTech 6205 can provide co-located simultaneous dual frequency side scan imagery to eliminate frequency selection tradeoffs, always providing the highest resolution for the water depth at hand. Finally, this co-located side scan imagery compliments the bathymetry solutions and provides the hydrographers and data processers with increased confidence when it comes to feature detection, target classification, and data cleaning.

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Author Biographies

Ms. Lisa N. Brisson is the lead Bathymetry Product Engineer at EdgeTech with experience in Underwater Acoustics and Hydrographic Surveying. Brisson graduated with a M.S. in Ocean Engineering in 2010 from Florida Atlantic University and has been developing and analyzing swath bathymetric sonars for the last 4 years.

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Mr. Matthew Staley is the Senior Geodesist for the US Army Corps of Engineers Jacksonville District Hydrographic Surveying and Mapping Branch with experience in Geodesy and Hydrographic Surveying. His duties include acquisition, training, and installation of advanced surveying equipment and vessels. Staley has also helped write several key chapters of the Hydrographic Surveying Manual (EM 1110-2-1003).

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