NOAA Test and Evaluation of Interferometric Sonar Technology

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Abstract:

NOAA currently spends a large portion of its overall hydrographic survey effort obtaining bathymetric data in waters shoaler than 20m. Interferometric sonar systems are one tool that may be capable of significantly improving the safety and efficiency of hydrographic survey operations in shoal waters. Interferometers provide high-resolution wide-swath bathymetry in shallow water with swaths of 10-15 times instrument altitude; a significant improvement over the typical 3-5 times water depth capability of shallow water multibeam.

Recent advances in electronics and phase deconvolution algorithms and techniques have improved interferometric data quality and the shift away from using discrete soundings towards a surface based approach makes the noise levels inherent in interferometric data less of an issue. NOAA's Office of Coast Survey is seeking to ascertain whether today's interferometric sonar technology is capable of meeting NOAA's stringent nautical charting hydrographic survey requirements for shallow water and nearshore survey work, and if so, to integrate interferometers into the existing data acquisition and processing pipeline.

Data were acquired with a very high resolution shallow water multibeam system and three commercially available interferometric systems over an area with sonar targets of known size and orientation as well as over areas with sloped and vertical features running up to the land-water interface. Comparisons were made between the multibeam and test datasets using IVS 3D Fledermaus.

*Interferometric technology appears capable of resolving ~1*m^3 *sonar targets on the seafloor and sloped and vertical features up to, or slightly above, the draft of the instrument. The technology was also shown to improve coverage efficiency by approximately two times that achievable with shallow water multibeam in waters shoaler than 10m. Preliminary results are promising enough that NOAA is moving forward with system integration and operational test and evaluation aboard a NOAA hydrographic survey vessel during the 2006 field season.*

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Introduction:

NOAA spends a large amount of its overall nautical charting hydrographic survey effort obtaining bathymetric data in waters shoaler than 20m. Not only does it take more time and effort to survey a given amount of area in shoal waters relative to deeper waters, but these regions are also frequently the most dangerous areas that we require our hydrographic survey teams to work in. In the nearshore waters of Alaska both visible and submerged rocks are prevalent and currents can be strong. In the shallow and turbid waters of the Gulf of Mexico submerged pipeline terminations and other obstructions rising to within a few feet of the surface are common. Waters of these depths are typically considered navigationally significant and must be surveyed in an accurate and methodical fashion.

While multibeam echosounders (MBES) are known to provide very accurate bathymetric information and are used throughout many the world's hydrographic offices, their data acquisition capability is typically limited to 3-5 times water depth when maintaining the rigorous data quality standards required for nautical charting. This does not become a major limiting factor until working in waters shoaler than 10-15m where it can be difficult to efficiently attain full bottom coverage. In many of these areas water turbidity or resolution requirements preclude the use of lidar and there are few alternatives for obtaining bathymetry in an efficient manner.

Interferometric sonar systems are one tool that may be capable of significantly improving the safety and efficiency of hydrographic survey operations in shoal waters. Interferometers, also referred to as phase differencing bathymetric sonar (PDBS) systems, provide high-resolution wide-swath bathymetry in shallow water with swaths of 10-15 times instrument altitude; a significant improvement over the typical 3-5 times water depth capability of MBES.

While the bathymetric data from phase differencing sonar systems has been historically of suspect quality, with bathymetric resolution limited to 2-3% of water depth (DeMoustier 1993), recent advances in electronics and phase deconvolution techniques and algorithms have markedly improved their precision and reliability (Griffiths *et al* 1997, Kraeutner and Bird 1999, Wilby 1999). These improvements, combined with NOAA's ongoing conversion to surface based nautical charting hydrographic survey deliverables (Smith, *et al* 2002), make the use of PDBS a potentially beneficial tool for NOAA's nautical charting survey program.

Preliminary testing conducted as part of a graduate level research project at the University of New Hampshire indicated that PDBS tended to produce data with higher standard deviation than that derived from MBES but that surfaces generated from the data were similar (Gostnell 2005). This similarity in surfaces is what would be expected based on high density data being distributed normally about the true surface as described by Hiller and Lewis (2004). It was also found that discrete features were reproduced with fidelity, that the average difference between PDBS and MBES surfaces was less than 0.1m and that PDBS was capable of accurately resolving sandwaves as small as 0.1m in amplitude (Gostnell 2005). Based on these findings a formal evaluation of interferometric technology was recommended to determine whether it is appropriate for NOAA to incorporate PDBS into the numerous technologies it uses for nautical charting hydrographic survey work. This series of tests is the result of that recommendation.

Methods:

The goal of these tests was to ascertain the current state of interferometric technology to determine if it would be advisable for NOAA's Office of Coast Survey to integrate PDBS into the suite of tools used to acquire nautical charting hydrographic survey data. Several test sites were selected to test the capability of PDBS to accurately model features of known size as well as their ability to resolve sloped and vertical features and to more accurately estimate what, if any, real world efficiency gains are achievable.

Data Acquisition –

Data were acquired with MBES, SSS, and each of three commercially available PDBS systems over the period of four weeks during the summer of 2005. MBES data were acquired with a Reson SeaBat 8125 while SSS data were acquired with a Klein 5500. PDBS data were acquired with each of the following three systems: GeoAcoustics GeoSwath, SEA SWATHplus, and Teledyne Benthos C3D. The first week was spent preparing the study sites and acquiring baseline data with MBES and SSS and then one week was spent acquiring data with each PDBS system. All data were acquired aboard the NOAA S/V Bay Hydrographer in and around the mouth of the Patuxent River in Chesapeake Bay, MD. Water levels were obtained from NOAA's Solomons Island tide station in 6 minute intervals. Water column sound speed was measured at least every 4 hours during survey operations using a Sea-Bird Electronics 19 SEACAT CTD. Vessel motion correctors and position were provided by Applanix POS/MV V 4 except with the GeoSwath which employed a TSS DMS2-05 motion sensor at the sonar head.

Study Sites –

Four study sites were developed to test specific system capabilities (Figure 1). The first site was developed to test the ability of PDBS to accurately and repeatedly identify small objects of known size and shape. This site was located at the mouth of the Patuxent River, measured 250m x 500m, and had a relatively flat bottom with numerous oyster beds to provide relief. The average depth of the area was approximately 7m. Sonar targets were constructed from 30, 55, and 85 gallon drums wrapped in wire mesh to create an irregular surface and encourage marine growth. The targets were connected at 10m spacing using polypropylene line and deployed in the southern portion of the area. In addition to a standard survey of the area, a tight search pattern was run over the targets; the same search pattern lines were used with each system.

The second site was designed to test the ability of PDBS to accurately resolve sloped features running up to the land water interface. This area was located adjacent to the East Patuxent Basin on the southern shore of the Patuxent River and measured approximately 300m x 500m. The area was relatively flat to approximately 150m from shore, had a moderate slope from 150m offshore to 20m from shore, and had a steep incline from 20m from shore to the land water interface. Survey lines were run parallel to the shoreline and the same nearshore line was run with each system.

The purpose of the third site was to evaluate PDBS capability to resolve vertical features, something that interferometers have historically had difficulty with but which recent advances have worked to address (Kraeutner and Bird 1999). The site was located under the Thomas Johnson Bridge, ranged from 20m to 40m in depth, and included two cylindrical bridge abutments with diameters of approximately 9m. Lines were run on four sides of the abutments to model their entire circumference.

The final study site was used to ascertain potential efficiency gains achievable with PDBS over MBES in waters shoaler than 10m. The efficiency test covered a baseline region of 1350m x 500m over a fish haven as depicted in Figure 1. Six hours of acquisition were conducted with each system with a vessel speed of 5 knots and one sound speed cast conducted at approximately the 3 hour mark. Different line plans were run with each system to maximize coverage capability. Comparisons were made between the area covered with the MBES and PDBS systems in the allotted amount of time.

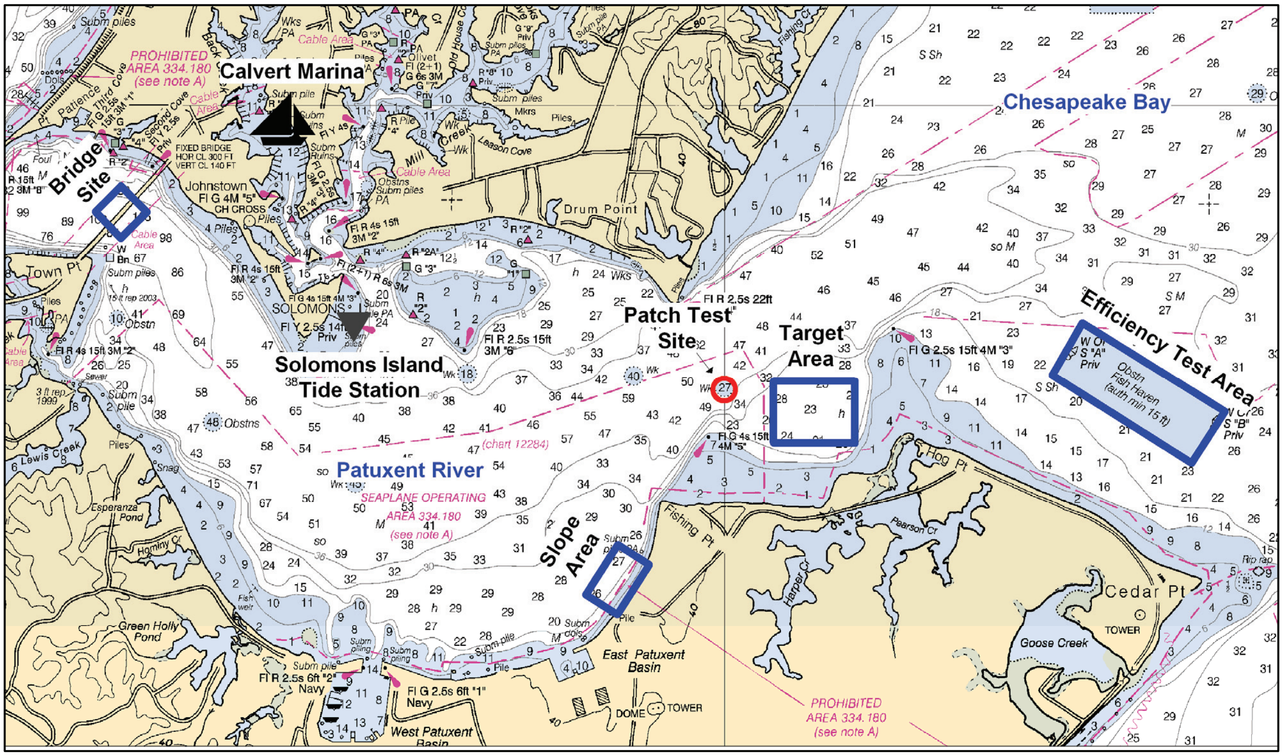


Figure 1 – Data acquisition was conducted in each of the four study sites shown. Water levels were measured at the Solomons Island Tide Station which was directly adjacent to the study sites. (NOAA Nautical Chart 12264, soundings in feet).

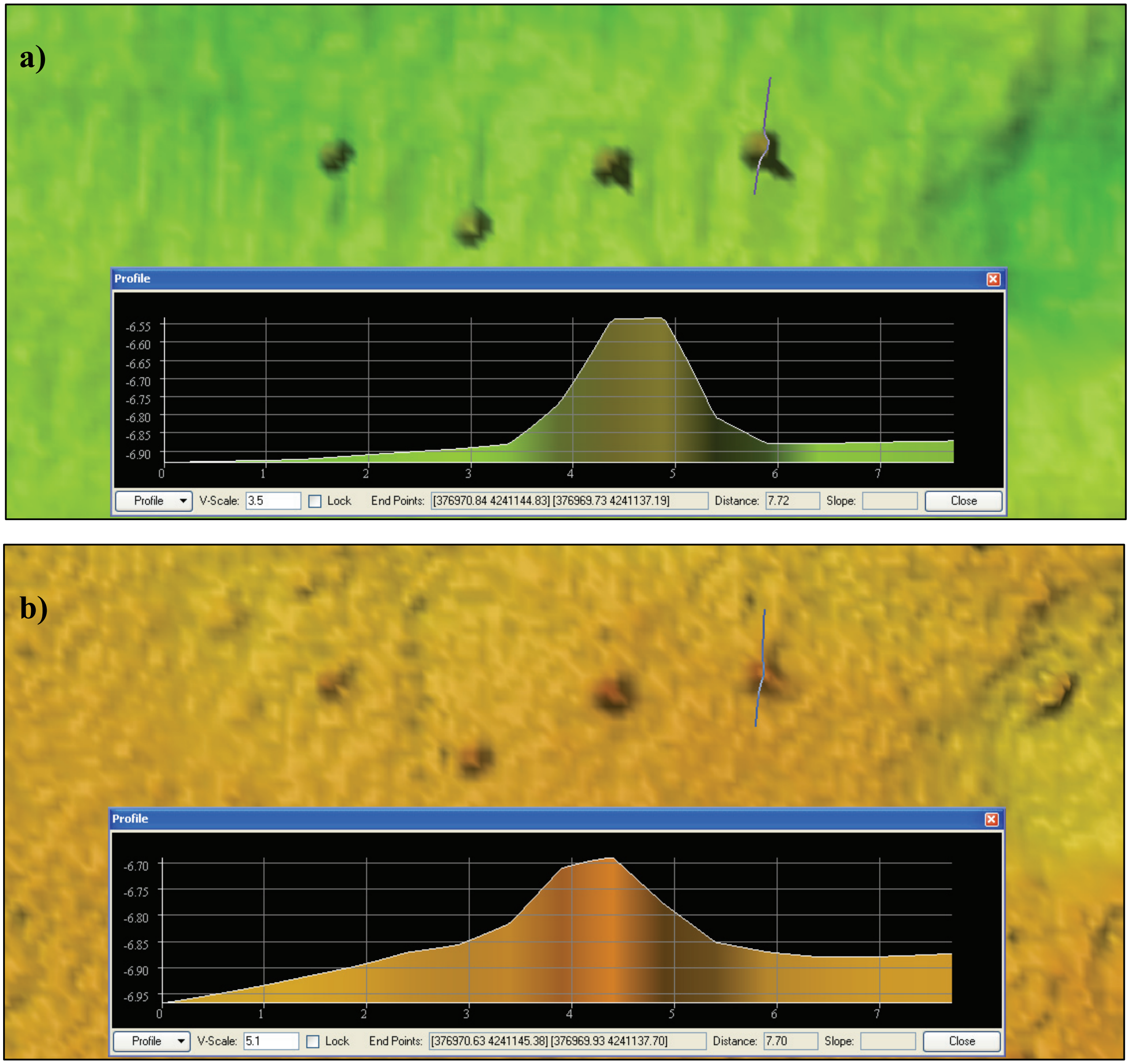
Data Processing –

MBES data were fully processed within Caris HIPS/SIPS software package while PDBS data were processed within each vendor's proprietary or recommended software package. All data had vessel motion, sound speed, and water level correctors applied. Data were then imported into IVS 3D's Fledermaus data visualization package using similar conversion parameters for comparison and evaluation. All grids were created at 1m resolution using a weighted moving average and a weight diameter of 3. Point and surface PDBS data were then compared to MBES and SSS data covering similar regions and features.

Results:

Target Detection –

The targets were resolved by both MBES and PDBS and are clearly visible as shown in Figure 2. The cross section shown is over the largest target, which had a real world height of 1.04m. After binning, which tends to smear small, discrete objects (Jensen 1996), the target had a vertical presence of 0.34m in the MBES data and 0.18m in the PDBS data. In the sample datasets of the target area, the standard deviations of the unbinned data were 0.65 for the MBES and 1.32 for the PDBS. While there were small differences in the heights of the targets between datasets, other small features, such as 0.2m amplitude oyster beds, were similarly modeled in both.



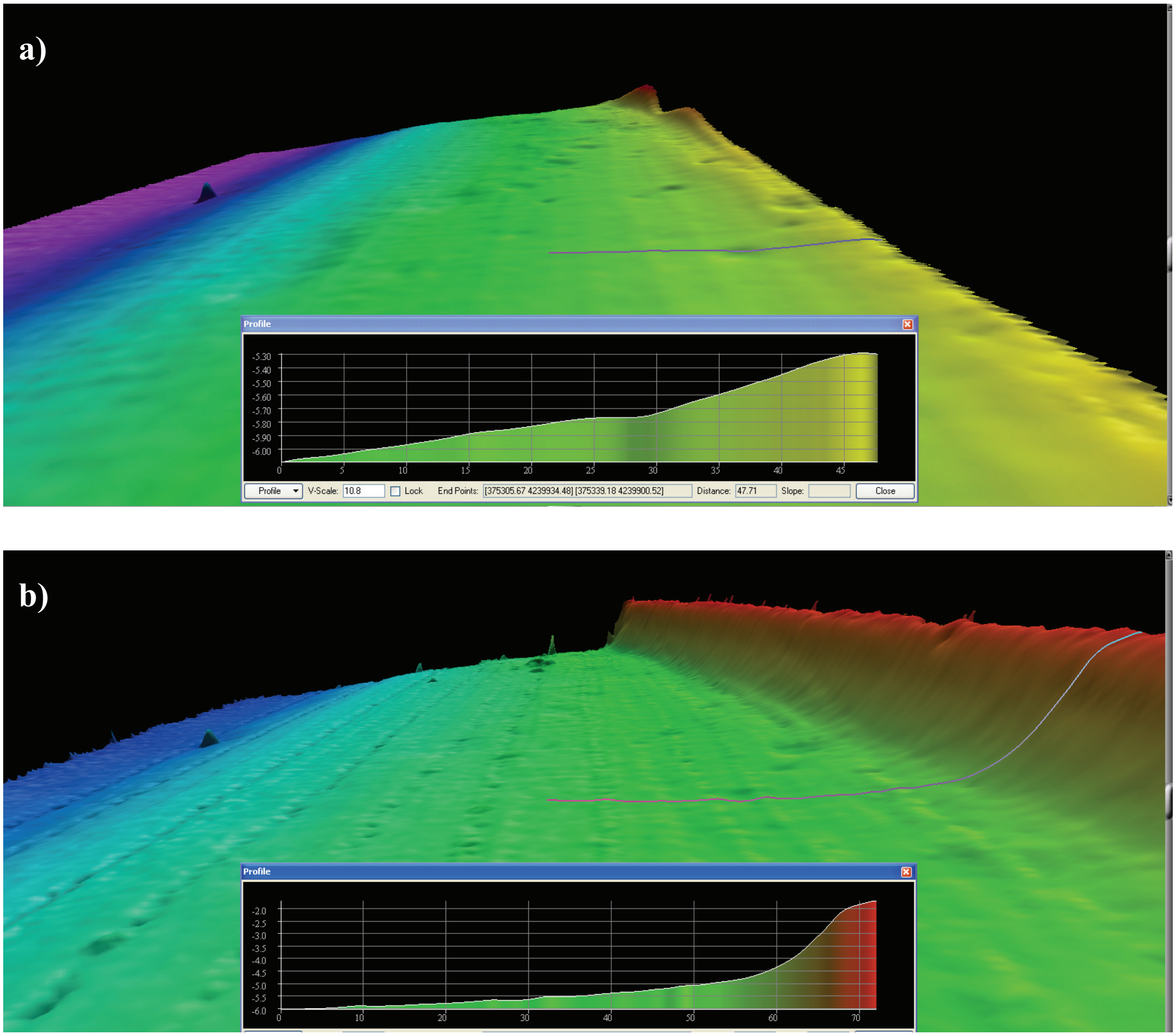
a) V-Scale: 3.5 ☐ Lock End Points: [376970.84 4241144.83] [376969.73 4241137.19] Distance: 7.72

b) V-Scale: 5.1 ☐ Lock End Points: [376970.63 4241145.38] [376969.93 4241137.70] Distance: 7.70

Figure 2 – Sonar targets as gridded from a) MBES data and b) PDBS (GeoAcoustics GeoSwath) data. Note that the gridding process has reduced the height of the target in both datasets and that while the effect is more dramatic in the PDBS data the targets remain readily visible. Data are shown with a vertical exaggeration of 6.

Slope Area –

PDBS appears fully capable of resolving sloped features up to a depth of slightly shoaler than the instrument itself. As shown in Figure 3, the PDBS captured an additional 20m laterally of the steep slope running up to the land-water interface while running the same nearshore line as with the MBES. In this case the systems were mounted approximately 2m below the surface and it is expected that bringing them closer to the surface would yield additional data (Figure 3).



V-Scale: 10.8
End Points: [375305.67 4239934.48] [375339.18 4239900.52]
Distance: 47.71

Figure 3 – Sample data from slope area. Shown are a) MBES data and b) PDBS data (GeoAcoustics GeoSwath). The same nearshore line was run with all systems but the PDBS was capable of resolving the slope 20m farther laterally, providing significantly more information about the slope itself. Note that while the PDBS data is noisier than the MBES it was still capable of capturing the small feature in the upper left portion of the data and the small depressions along the base of the slope. The along track artifacts are on the order of 0.1m in amplitude. Data is shown with a vertical exaggeration of 6.

Bridge Site –

Both MBES and PDBS resolved the bridge abutments at the appropriate locations and with the correct diameter. The MBES was able to resolve the abutments to a minimum depth of ~ 5.5m while PDBS was capable of resolving them to ~ 2.0m. The MBES provided denser, more regularly spaced sounding coverage on the features resulting in the gridded representations of the abutments appearing to have more significant vertical presence in the MBES data (Figure 4).

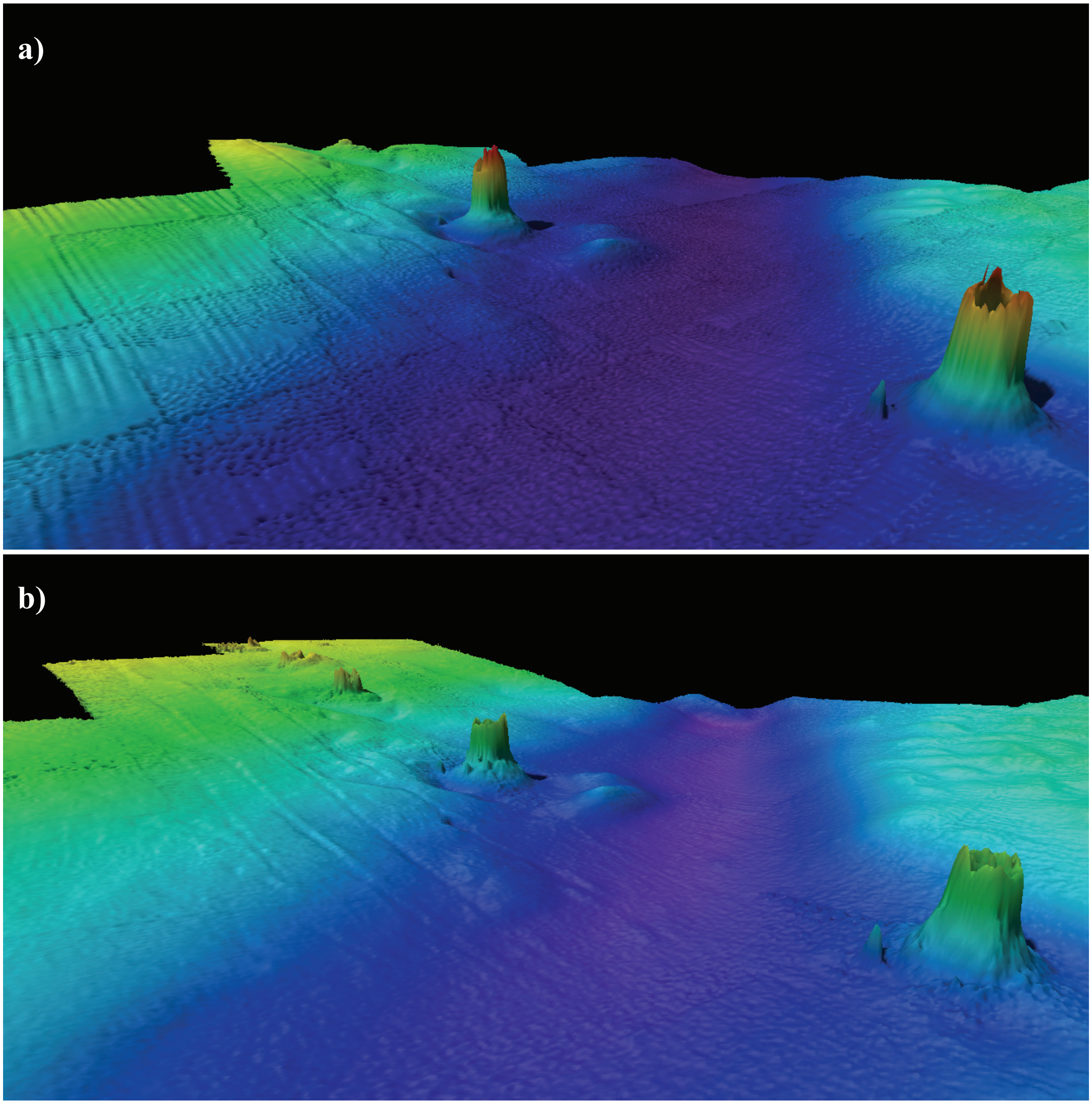


Figure 4 – Shown are bridge abutments with a diameter of ~ 9m as modeled from a) MBES and b) PDBS (GeoAcoustics GeoSwath) data; both technologies resolved the bridge abutments, however, MBES tended to provide denser, more regularly spaced measurements at shoal depths resulting in the MBES gridded representation appearing to have a greater vertical presence. Note the submerged cable trenches running parallel to the bridge and the remnant of a cofferdam at the base of the abutment in the lower right corner of each image. The motion artifacts clearly visible in the MBES data were the result of pole motion which was exaggerated by outgoing tidal flow beneath the bridge. Data are shown without vertical exaggeration.

Efficiency Test –

In six hours of operations at 5 knots the MBES provided approximately 0.44snm of coverage. PDBS yielded as much as 0.96snm in the same amount of time with the same vessel operating parameters; an efficiency gain of better than 100% in waters shoaler than 10m (Figure 5).

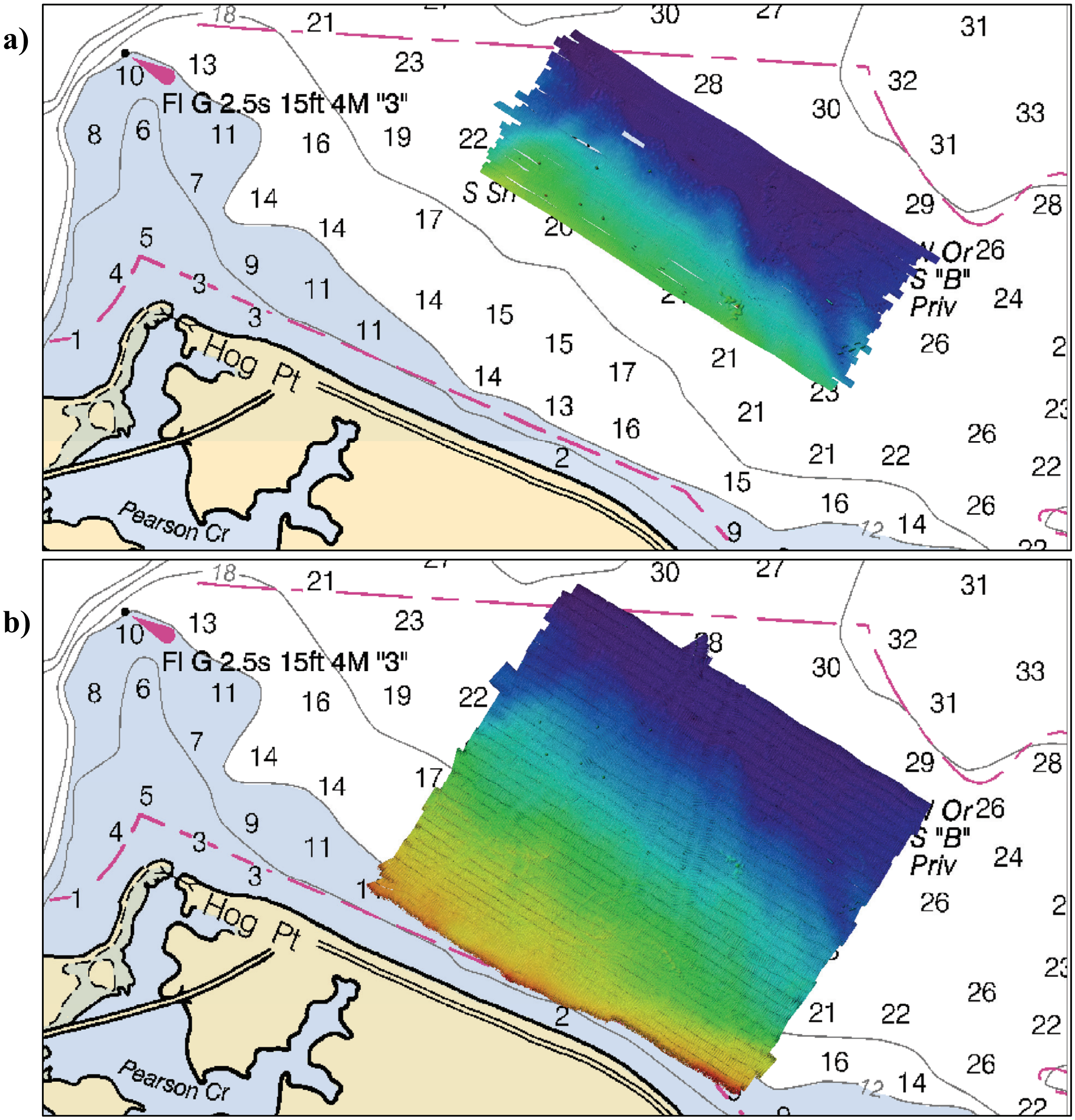


Figure 5: Coverage comparison between a) MBES and b) PDBS (SEA SWATHplus) coverage. Each dataset was acquired in six hours of vessel operations with speed maintained at or near 5 knots; the cross-lines visible in the PDBS data were not collected as part of the efficiency test. MBES covered 0.44 SNM while PDBS covered up to 0.96 SNM. Motion artifacts visible in both datasets are primarily due to pole motion and do not reflect on the capabilities of the sonar systems themselves. The motion artifacts in the PDBS data are exaggerated at the edges because of the wider swath and are on the order of 0.1-0.2m. Note the small data gaps at the shoal end of the MBES data due to reduced swath width.

Discussion:

Target Detection –

The sonar targets in this study were resolved by both MBES and PDBS, however, once the data were binned to a resolution of 1m the target heights in data from both technologies were significantly reduced from their acquired values. In the MBES data the targets appear slightly less than half their actual height and in the PDBS data they are reduced by half again. While a portion of this effect is due to gridding the data at a bin size greater than half the diameter of the targets (Nyquist 1928), the point data from the PDBS did not tend to provide as dense a sampling of soundings on the targets as MBES did, and those soundings did not necessarily represent the shoal depths. In other instances PDBS did resolve similar features with fidelity, indicating that at least a portion of the problem may reside in the data filtering techniques applied and not necessarily with the data or technology itself. Over relatively flat areas, large objects, and areas of more gradual or consistent change this did not seem to be an issue and in general the soundings and surfaces vary little between MBES and PDBS.

Resolving Slopes –

PDBS technology appears quite adept at yielding quality data on sloped surfaces. As shown in Figure 3, the wide swath of bathymetry enabled significant additional data to be acquired along the representative slope than was feasible with MBES. In this example the PDBS provided a shoreward swath of 4-6 times as wide as that feasible with the MBES on the shoreward most line. This ability to acquire significantly more data affords the survey team several options; they have the ability to acquire additional data that they would not have been able to without PDBS or they can stand back farther off of dangerous features while still acquiring the same amount of data that would have been feasible with MBES. In Alaska, where the slopes running up to the land water interface are very steep, it can be nearly impossible to safely obtain such data with MBES. The ability to stand off by 20m while acquiring bathymetry up to 2m water depth would dramatically improve the safety and efficiency of operations in such areas. Safety from the perspective of the vessel operator is discussed further in a later section.

Resolving Vertical Features –

The current evolution of PDBS appears fully capable of resolving vertical features (Figure 4). The use of multiple receive elements affords PDBS the ability to handle several simultaneous returns from different angles making this feasible (Bird and Mullins 2005). In this example, the PDBS resolved the bridge abutment to approximately 2m, the same depth as the instrument altitude, while the MBES was limited to ~ 65° off nadir (i.e., 65° to each port and starboard), yielding data to 5m below the surface. The MBES data was, however, more regularly spaced and denser on the vertical structure itself than was the PDBS data resulting in the gridded feature appearing to have a more significant vertical presence. In the real time acquisition display the PDBS data appeared to be much denser than was realized after the data had been cleaned so it is feasible that the data were capable of supporting denser coverage over the abutments and that the sparse data were the result of the data cleaning process and that improved techniques would allow for more accurate data filtering.

Changes in Charting Deliverables –

Several years ago it would not have been feasible to consider using PDBS data for nautical charting because of the high standard deviation of the data. NOAA's move away from discrete soundings and toward surfaces as a final survey deliverable from the United States' domestic nautical charting survey fleet, however, makes the use of PDBS data feasible today. With a standard deviation approximately twice that of MBES, using discrete soundings from PDBS may not yet be advisable but may become possible as algorithmic advances are made and/or confidence is built in the technology through use over time. In the interim it will most likely remain necessary to continue to acquire development data over discrete hazards to navigation with MBES, vertical beam echosounder (VBES), or other proven means.

Efficiency Gains –

As is visible in the coverage shown in Figure 5, PDBS is capable of more than doubling the amount of area that can be covered in a given amount of time in waters shoaler than 10m. The MBES data were acquired using the maximum line spacing feasible while still achieving full bottom coverage resulting in small holidays towards the inshore edge of the data. Under real world surveying conditions it would have been necessary to tighten up the line spacing to ensure that no significant objects were missed which would have further reduced the amount of area covered. The PDBS acquisition, on the other hand, was run with a relatively narrow range scale and at a line spacing enabling better than 200% coverage to ensure that there was adequate coverage to demonstrate the viability of the technology. Under operational acquisition it is likely that the line spacing would be greater, and thus yield additional areal coverage.

Enhanced Safety of Operations –

The nearshore area can be one of the most challenging areas to operate a survey vessel. Surveys are typically required in these areas because there is no accurate, up to date bathymetric data available. Navigating a vessel in such areas often requires a boot-strap survey where the vessel slowly works its way towards shore, navigating only in the waters which it has surveyed immediately beforehand. In the shallow waters typical to nearshore areas, multibeam echosounder systems are limited by their cross track range meaning that safely navigating shoreward can require survey line spacing of 10m or less. This often takes an inordinate amount of time and can be extremely difficult to execute when currents are present. While side scan sonar is capable of providing the required cross track range, it does not yield bathymetry, making it difficult to know where the water becomes too shallow for the vessel to safely operate. By providing wide swath bathymetry, interferometric sonar appears to be a viable solution to this problem.

The slope area depicted in Figure 3 provides an excellent anecdotal example of the issues described above with regards to nearshore survey work. NOAA S/V Bay Hydrographer's sonar mount extends approximately 2m below the water's surface, making identifying a 2m shoal a delicate proposition. Bay Hydrographer first surveyed the area with side scan sonar and the shoal was identified by its increased intensity of reflection, however, without bathymetry it was not possible to delineate the cutoff for safe vessel navigation. As the vessel approached the area near the shoal during MBES acquisition, line spacing was decreased to 7 meters. As Bay Hydrographer does not have a data acquisition display on the bridge the acquisition team was tasked to alert the bridge verbally of any shoaling as it became visible in the data. Once shoaling was evident the vessel was maneuvered to deeper water.

During MBES acquisition it was feasible to see 5-7m shoreward to provide the operator with warning of shoaling. With the interferometric sonar systems the acquisition team was able to monitor the bathymetry 20-30m shoreward of the vessel. This extra coverage allowed the acquisition team to monitor not only the distance to shoal water, but how fast the vessel was approaching it. This, in turn, enabled the vessel operator to confidently maneuver the vessel in the near vicinity of the shoal without endangering the vessel or her crew.

The wide swath bathymetry provided by the interferometric sonar systems that were tested are also seen as having a potential advantage for port and harbor surveys. Such surveys often require the survey vessel to acquire data in slips and along pier faces. The additional bathymetric coverage afforded by interferometers enables the survey vessel to stand farther off from submerged pilings and piers and other dangers, thus more safely and efficiently delivering full bathymetric coverage of an area.

Future Studies –

While many aspects of this study were successful and a number of the suggestions from prior work were integrated (Gostnell 2005) there are several things that could be done to make future comparisons of this nature more robust. Motion artifacts were visible in much of the data and had a significant effect on the bathymetric data quality. This was largely attributable to pole motion caused by a loose joint on the NOAA S/V Bay Hydrographer's sonar arm which was slightly damaged immediately prior to this series of tests. In any future tests or operational deployments it is strongly recommended that rigid mounts be used, particularly for PDBS systems whose wider swaths of bathymetry tend to exaggerate any motion at their outer limits.

To maintain further consistency throughout the data and afford the evaluator more control over its processing and cleaning, it is recommended that in any future studies all datasets be fully processed within a single software package. This is nearly feasible today as the PDBS manufacturers continue to work with data processing software vendors that are already capable of working with MBES data. Processing in a single software package will allow for all datasets to be cleaned using the same techniques and to have all correctors applied in an analogous way to further limit any differences in the data to the capabilities of the systems used to collect them.

Summary and Conclusions:

The NOAA hydrographic survey fleet spends a significant portion of its overall survey effort working in shallow and nearshore waters; areas that frequently contain dangerous rocks, wrecks, and obstructions making them particularly hazardous to work in. While multibeam echosounders (MBES) provide high quality bathymetric data, their limited swath width in shallow water makes them less than ideal for work in these areas. Interferometric, or phase differencing bathymetric (PDBS), sonar systems are capable of providing significantly wider swaths than MBES in waters shoaler than 10-15m, however, the technology has not yet been approved for use in NOAA's nautical charting hydrographic survey program. This series of tests was conducted to determine whether PDBS technology has advanced to a point where it is appropriate to integrate PDBS systems into NOAA's inventory of hydrographic survey equipment for operational test and evaluation.

Several study sites were designed to evaluate the current capability of PDBS to resolve small targets of known size, sloped and vertical features, and to ascertain achievable efficiency gains over MBES in waters shoaler than 10-15m. It was shown that PDBS technology appears capable of resolving ~1m^3 sonar targets on the seafloor and sloped and vertical features up to the draft of the instrument. PDBS was also shown to improve coverage efficiency by better than two times that achievable with shallow water multibeam in waters shoaler than 10m. While the noise levels inherent to PDBS technology make the individual soundings provided slightly suspect, NOAA's shift away from using discrete soundings towards a surface based deliverable makes the noise levels associated with discrete measurements less of an issue. Surfaces generated from MBES and PDBS data resolve small targets, slopes, and vertical features similarly making PDBS a viable candidate for use in acquiring nearshore and shallow water data.

Preliminary results are promising enough that NOAA has begun to move forward with system integration and operational testing and evaluation aboard a NOAA hydrographic survey vessel. As binning at scales fine enough to identify navigationally significant objects but coarse enough to maintain the data at a manageable size tends to reduce the overall height of small, discrete objects, using surfaces is not the best method for measuring shoal depths over small obstructions to navigation. It is therefore advised that PDBS technology initially be used solely for charting generalized bathymetry and item detection with developments run over objects considered to be hazardous to surface navigation with vertical beam echosounder or MBES until additional advances and further testing has improved confidence in PDBS measurements over discrete objects.

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