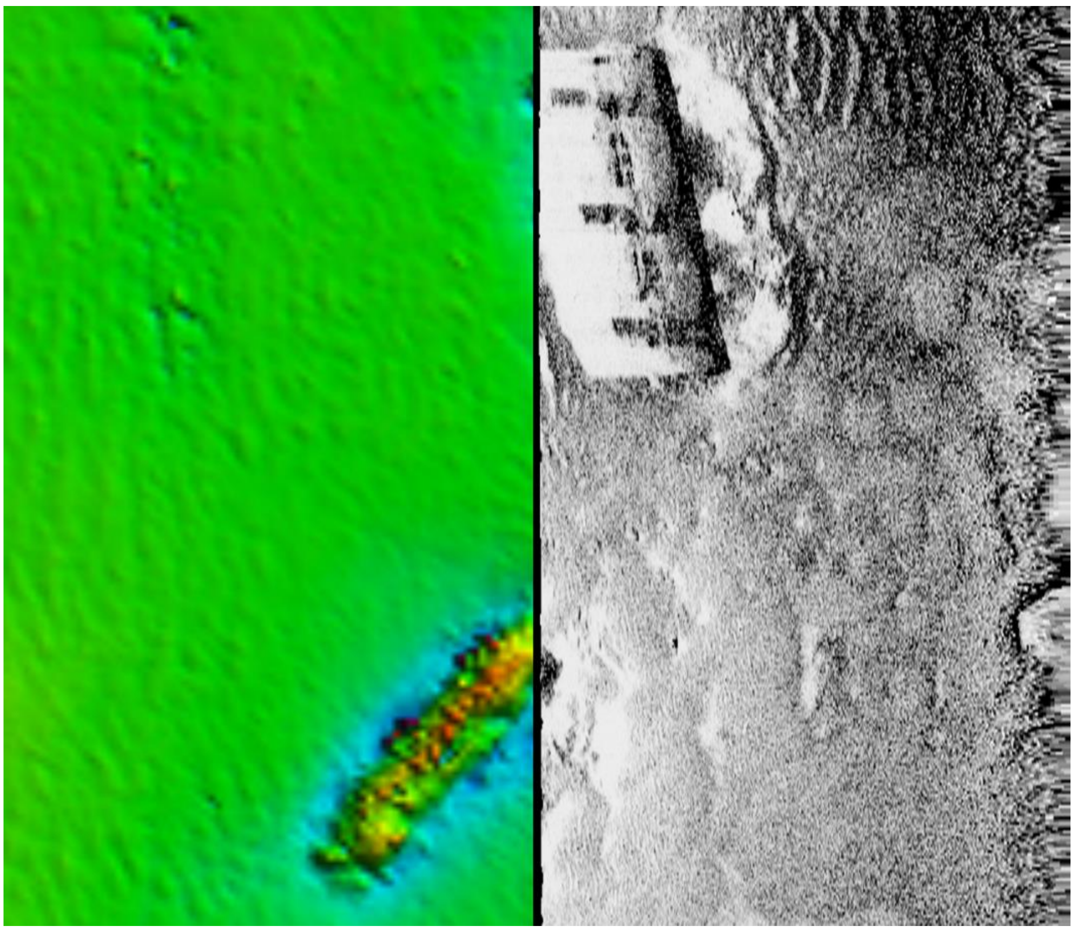
Storm Response Surveying with Phase-Measuring Bathymetric Sidescan Sonar

Kevin Jerram and Val Schmidt

Center for Coastal and Ocean Mapping

Durham, New Hampshire



Two sunken subway cars and adjacent bedforms at Redbird Reef, offshore Delaware, are revealed in this composite image of phase-measuring bathymetric sidescan (PMBS) sonar data collected from an autonomous underwater vehicle (AUV) shortly after Super Storm Sandy. The seafloor depth is 26 m and the subway cars protrude roughly 2 m; the AUV altitude was 6 m. PMBS systems produce co-located depth estimates (left) and sidescan imagery (right) which may be analyzed together to potentially improve survey efficiency in response scenarios. The bathymetric surface includes data from multiple overlapping survey lines gridded at 30 cm without manual editing; the sidescan imagery depicts one side of a 45 m-wide swath from one survey line. The presence of the southern (lower) subway car is suggested by detection of its corner in the sidescan imagery (dark anomaly near swath limit) and confirmed in bathymetry from additional survey lines.

Contents

Background

Post-storm acoustic surveys in coastal regions represent a challenging balance between the needs of rapidly reopening ports and harbors while ensuring effective detection of storm-related seafloor changes and hazards to navigation. Whenever possible, surveys conducted in response scenarios should also support routine hydrographic charting efforts. Multibeam echosounders (MBES) have traditionally been employed in both routine and response survey scenarios to provide high-accuracy bathymetry, with incorporation of sidescan sonar in some cases to provide acoustic backscatter imagery for visual analysis of the seafloor and navigational hazards.

Another class of sonar technology, called phase-measuring bathymetric sidescan (PMBS), combines the bathymetric data of MBES and backscatter imagery of traditional sidescan sonar in a single system. PMBS sonars feature wider angular swath widths than MBES systems, offering potentially increased swath coverage and survey line spacing for a given echosounder frequency and altitude above the seafloor. PMBS sonars of various manufacturers and models have been evaluated by NOAA over the previous decade [e.g., *Gostnell et al.*, 2006; *Brodet et al.*, 2010]. Adoption of PMBS technology during this period has been hindered by insufficient post-processing software support for the relatively dense and large datasets produced by PMBS systems; ongoing development of echosounder uncertainty models; lack of an established method for angular offset calibration (i.e., 'patch testing'); and difficulty in identifying bottom returns and object features amidst raw datasets with higher density and large vertical distributions than typical MBES data.

Many of these initial challenges to PMBS adoption have been addressed in recent years. For instance, CARIS HIPS post-processing software readily handles PMBS datasets from several manufacturers; uncertainty models are in development or have been implemented for many PMBS echosounder models [*Parent*, 2011; *Dodd*, 2013]; a 'patch-test' method has been demonstrated for these systems [*Eisenberg et al.*, 2011]; and statistical gridding techniques traditionally applied for MBES data have been shown to reduce 'noise' and preserve objects of many sizes in PMBS bathymetric surfaces [e.g., as described in 'Object Detection with Phase-Measuring Bathymetric Sidescan Sonar Depth Data' available at *sandy.ccom.unh.edu*]. These developments have prompted renewed consideration for PMBS systems, especially in survey scenarios where operational efficiency for the detection of navigationally significant objects or seafloor changes are of primary significance.

Purpose

The purpose of this document is to investigate potential survey efficiency gains using PMBS sonars alone or in combination with MBES systems to effectively provide full acoustic survey coverage of a storm response site. This document describes the relative advantages and drawbacks of both echosounder types, examines PMBS data from a Super Storm Sandy-impacted area to demonstrate the value of co-located bathymetry and sidescan imagery, and outlines protocols to increase survey efficiency in response environments.

Fundamentals of MBES and PMBS Systems

MBES and PMBS systems intended for shallow water operations share similar frequency ranges and form factors, but these echosounders differ in several important ways. As a primary consideration, depth estimates on the seafloor and other objects are estimated by fundamentally different approaches (described later in this document). In addition to bathymetric soundings, many MBES systems yield co-located backscatter measurements which may be useful for seafloor characterization. Likewise, PMBS systems produce sidescan amplitude imagery which are typically of high value for object identification but not necessarily equivalent to MBES backscatter amplitude. PMBS output natively include two to ten water column data points per range sample by sampling almost immediately after transmission; by contrast, MBES water column data are collected across hundreds of beams at each range sample. While both types of sonar are routinely employed for surveys planned with significant swath overlap, their differences may be leveraged to provide full acoustic coverage of the seafloor for object detection at all times and additional scrutiny for object development as necessary.

Soundings from ranges and angles

Each depth estimate acquired by sonar requires a range and angle from the echosounder to the seafloor or other acoustic target, such as marine debris. MBES and PMBS systems employ nearly opposite approaches to arrive at these soundings. In effect, MBES systems search for the range to the seafloor for each of many angles across a swath, while PMBS systems estimate the angle from the echosounder to the seafloor for each of many range samples in a swath.

For both MBES and PMBS systems, the ping cycle begins with emission of a transmit pulse in a fan shape that is broad in the acrosstrack (port-starboard) direction and narrow in the alongtrack (fore-aft) direction. The transmit swath ensonifies a 'slice' of the water column, produced in one pulse from a single transmit array or in separate pulses from independent arrays on the port and starboard sides. Single-array transmitters, such as those for most (single-head) MBES systems, are typically limited to a transmit swath angular width of 160° or less in the acrosstrack direction whereas independent transmit arrays facing the port and starboard directions (such as those employed by PMBS and dual-head MBES) enable wider angular swath widths up to 220°. In some systems, independent transmitters may operate on an alternating basis to reduce port-starboard interference; single-transmitter systems may utilize several frequency-encoded sectors of the swath to achieve similar reduction in port-starboard interference. After transmission, the receiver array commences sampling for returns of the transmitted signal; these samples naturally include all other acoustic noise incident on the receiver and internal electronic noise.

MBES systems determine the travel times from the echosounder to the estimated seafloor positions in many directions ('beams') across a swath (Fig. 1). The beam angles from the echosounder to the seafloor are fixed and the range to the seafloor is estimated along each beam. These beam angles represent directions of receiver sensitivity formed by post-processing signals from many transducer elements in the receive array and applying time delays or phase shifts to the individual signals. Along each beam, the echosounder searches in near-real-time for the return of the transmitted signal from the seafloor. The search for the bottom along each beam is accomplished by identifying high-amplitude returns that are likely to represent a strong reflection from the seafloor. Alternatively, and especially when high amplitudes do not clearly indicate the bottom returns, the seafloor may be identified by examining patterns in phase of the arriving signals which correspond to the transmit pulse moving across the beam's projected area (or 'footprint') on the seafloor. MBES systems often employ a combination of amplitude- and phase-detection methods and record the sounding most likely to be reliable from either method (or no sounding when neither method yields a suitable result). Beamwidth and beam spacing may both be as small as 0.5°, yielding hundreds of seafloor depth estimates per swath. Furthermore, most MBES systems offer adjustable beam spacing to achieve equal distribution of soundings in angle or in acrosstrack distance on the seafloor.

PMBS systems, by contrast, estimate up to five angles of arrival for acoustic signals measured at every range sample. These systems typically employ two or more receiver arrays in each acrosstrack direction (port and starboard) to measure phase differences between signals from each direction at each receiver. For each range sample, the wavefront arrival angle relative to the echosounder is deduced from the phase differences of the signal at each receiver. A potential ambiguity in angle calculation arises due to the wide range of possible angles of arrival and the geometry of the wavelength, array size, and receiver spacing. Various post-processing methods are employed among PMBS manufacturers to resolve this phase ambiguity. One method (employed by GeoAcoustics and L3-Klein) resolves one angle of arrival for each range sample. With additional elements, another method (employed by Benthos, SEA Swathplus, and EdgeTech) may resolve multiple angles of arrival, such as simultaneous returns from the seafloor and a large structure or wall (Fig. 1). Resolution of these angle measurements is on the order of 0.01-0.1°; however, the angular resolution is not equivalent to accuracy of the measurement because, as with all sonar systems, PMBS angle data are degraded by acoustic and electronic noise. Furthermore, PMBS resolution is not equivalent to MBES beam spacing, as PMBS sonars resolve only one to five angles of arrival per range sample over the entire angular swath width of 110-120° in each direction (port and starboard). Due to the dual-head design inherent in PMBS systems and lack of control over spacing between soundings, acrosstrack data density is typically lowest near nadir; with some models, no soundings are produced within 15-30° of nadir.

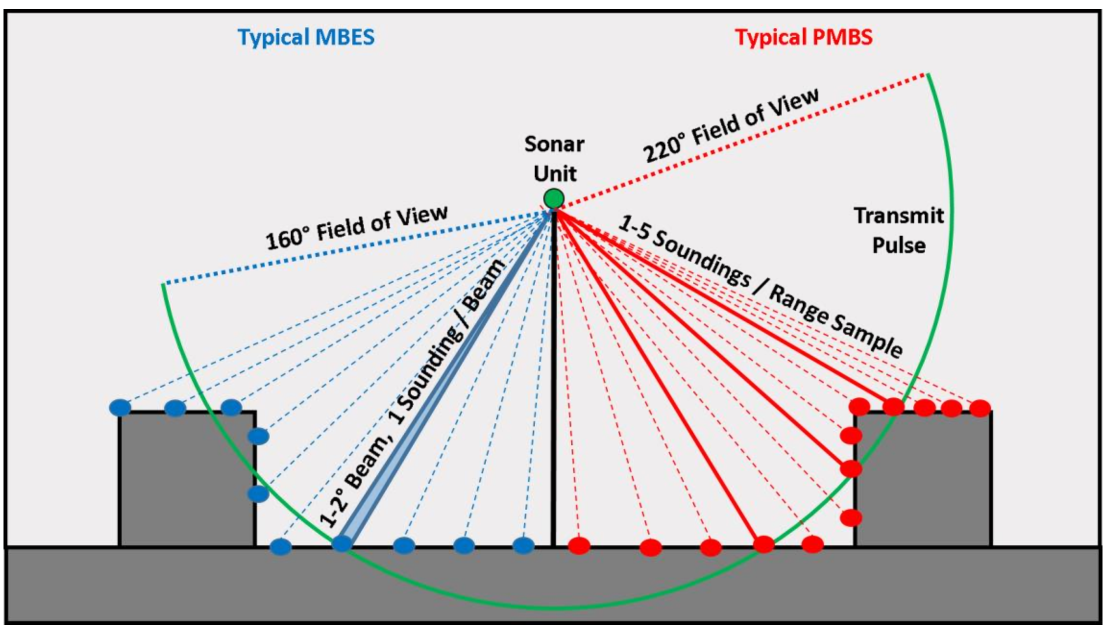


Figure 1. Schematic of MBES and PMBS strategies for estimating depths (or 'soundings'). MBES systems (left) estimate the range to the seafloor for many angles, typically spaced to achieve equal separation between soundings in either acrosstrack distance or beam angle. The MBES swath width, or field of view, is typically limited to 160° or less for single-head systems. PMBS sonars (right) estimate one to five angles of arrival for targets at each range; in this example, three soundings are estimated at the range indicated (the seafloor, side of the object, and top of the object). PMBS angular swath widths of up to 220° are possible, though no control exists over sounding spacing and data may be sparse or excluded near nadir.

Considerations for Echosounder Selection

The methods for estimating seafloor depths employed by MBES and PMBS systems affect parameters such as angular swath width, range resolution, sounding density, sounding uncertainty, and ability to image certain structures. Table 1 outlines general characteristics of MBES and PMBS systems intended for surveying in shallow waters, with descriptions below of how these characteristics generally impact their consideration for various survey requirements. Example MBES systems include the RESON 7125, Kongsberg 2040, and R2Sonic 2024; example PMBS systems include the GeoAcoustics GeoSwath Plus, EdgeTech 6205, and L3 Klein HydroChart 5000. These models are listed strictly as examples of commonly available echosounders intended for shallow surveying and are not listed out of any endorsement or recommendation for any particular survey purpose. Note that all MBES and PMBS systems require position, attitude, and sound speed inputs for proper georeferencing of depth estimates through target angle calculation, refraction correction, and transformation from the echosounder reference frame to a local or global coordinate system. Likewise, both echosounder types are typically deployable from surface vessels and autonomous underwater vehicles.

The 'effective' swath width is a major consideration for survey efficiency, depending on satisfaction of criteria developed for the survey purpose. These criteria naturally include data quality and utility, such as acrosstrack trends in uncertainty or data density to accurately represent least depths over hazards. Detailed standards exist for NOAA surveys intended to update hydrographic charts [*NOAA*, 2014], which providing a framework for establishing the 'effective' swath width of an echosounder used in this capacity [*Gostnell et al.*, 2006]. Other criteria may be prioritized for response scenarios, perhaps relaxing some data density or uncertainty requirements in order to increase vessel speed and line spacing while maintaining complete acoustic coverage for detection of navigationally significant hazards. These aspects are considered later in the document using PMBS data examples containing many navigationally significant features.

Table 1. Characteristics of typical MBES and PMBS sonar systems intended for shallow water surveying. Maximum swath width is expressed in multiples of echosounder altitude above the seafloor, or approximate water depth (WD).

	MBES	PMBS
Frequency	200-400 kHz	125-550 kHz
Range Resolution (cm)	1-2 cm	1-5 cm
Alongtrack Angular Resolution (°)	1-2°	0.5°
Acrosstrack Angular Resolution (°)	0.5-1°	< 0.1°
Max. Swath Width (°)	160°	220°
Max. Swath Width (Water Depths)	5-6 WD	10-12 WD
Max. Swath Width (m)	400 m	800 m
Max. Depth (m)	200-400 m	200-500 m
Soundings per Swath	200-500	> 1000
Water Column Backscatter	Available	Sidescan Imagery
Seafloor Backscatter	Available	Sidescan Imagery
Power (W)	50-250 W	30-120 W
Deployment	Surface Vessel, AUV	Surface Vessel, AUV

Frequency and range resolution

MBES and PMBS systems intended for shallow water operations typically employ similar frequency ranges on the order of hundreds of kilohertz. These frequencies facilitate short pulse lengths and wide bandwidths to achieve range resolution on the order of centimeters. Because acoustic attenuation scales with frequency, these frequency ranges represent a balance between fine range resolution and extended range capability to maximize acrosstrack swath coverage in shallow survey applications.

For both MBES and PMBS systems, co-located bathymetry data and backscatter amplitude (MBES) or sidescan imagery (PMBS) are collected at a single nominal or center frequency; some systems employ frequency modulation to identify sectors in an MBES swath or directions in a PMBS swath. An exception to this general rule, some EdgeTech PMBS models optionally collect bathymetry at 550 kHz and sidescan imagery at 1600 kHz, enabling higher resolution imagery at the expense of accompanying acoustic attenuation and range limitations.

Assuming that seafloor features and objects of interest are at least ten centimeters in any dimension (e.g., survey specifications typically use 1-m cubes as standards for object detection), the range resolutions of typical shallow-water MBES and PMBS systems are not major factors in their selection. Range capabilities governed heavily by frequency-dependent acoustic attenuation are more significant considerations in echosounder selection and survey planning, as the range limit necessarily impacts maximum survey line spacing and maximum survey depth.

Angular swath width

Angular swath width has significant implications for the geometric limitations to seafloor coverage and capability to image features such as vertical structures and steep embankments. In general, MBES systems are limited to angular swath widths of 160° or less, typically resulting in a geometric constraint to seafloor coverage based on range to the seafloor or maximum range due to acoustic attenuation. PMBS systems feature angular swath widths of up to 220°, enabling seafloor soundings out to ranges limited primarily by attenuation and shallow angles of incidence; within these ranges, the wide field of view enables imaging of surfaces extending toward or above the plane of the echosounder. In this regard, angular swath limits represents a widely recognized advantage of PMBS systems over MBES when swath geometry (not acoustic attenuation) is a limiting factor in total acrosstrack coverage on the seafloor. A particular safety benefit of increased angular swath is the improved capability to survey very shallow regions or objects from greater athwartship distances.

Angular resolution

Alongtrack angular resolution is a function primarily of the transmit swath alongtrack beamwidth, which is typically 1-2° for most MBES systems and typically 0.5° or less for most PMBS systems. Because alongtrack sounding resolution on the seafloor depends on the projected area of the transmit swath, PMBS systems theoretically offer finer alongtrack sounding resolution than MBES at a given echosounder altitude. This does not necessarily represent an advantage of PMBS systems for bathymetry or object detection, however, because alongtrack sounding coverage also depends directly on vessel speed and ping rate (Fig. 2). With characteristically wider alongtrack swath width (i.e., alongtrack beamwidth), an increased MBES ping rate results in increased alongtrack sounding coverage and density as trade-offs of reduced angular swath width compared to PMBS. Some MBES systems produce two transmit swaths per ping cycle; these separate swaths may be steered with some alongtrack angular separation to double the alongtrack sounding density with a balanced alongtrack distribution on the seafloor.

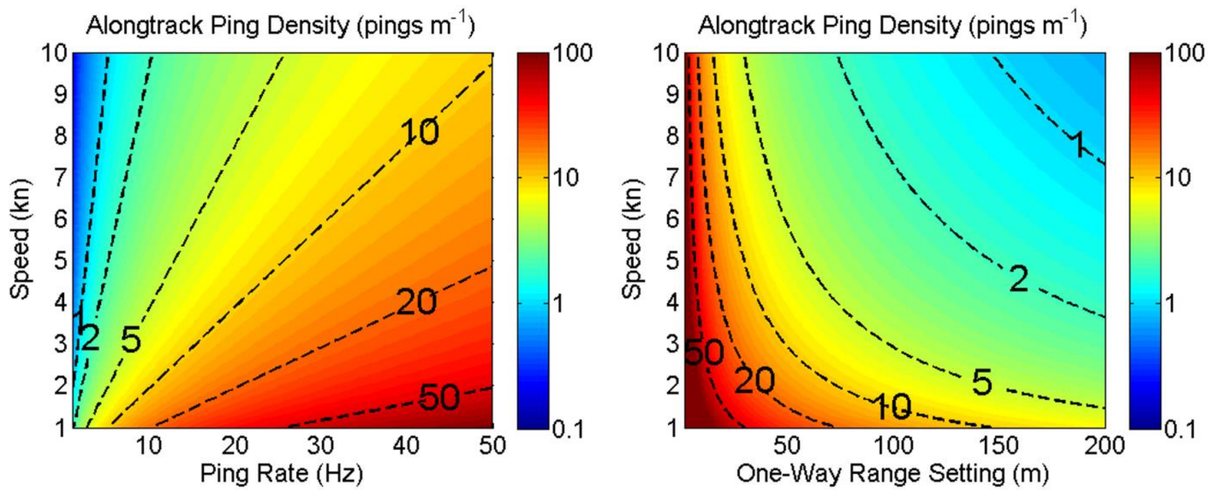


Figure 2. Alongtrack ping density (pings m^{-1}) for MBES and PMBS echosounders based on user-selectable ping rate (left) or maximum one-way range (right). Operating in single-swath mode, alongtrack ping density is equivalent to alongtrack sounding density (soundings m^{-1}). These plots illustrate the trade-offs of increasing survey efficiency through faster vessel speeds, longer ranges for wider swath coverage, and decreased alongtrack sounding density.

As discussed briefly above, acrosstrack angular resolution is not a straightforward metric of comparison between MBES and PMBS due to the fundamentally different methods employed for angle calculation. Whereas MBES systems feature fixed beam angles with known separation, PMBS systems calculate one to five soundings for each range sample with no control over angular separation. The resolution of PMBS angle measurement is on the order of 0.01-0.1°, corresponding to the minimum discrete steps in target angle produced by phase measurement and not directly reflecting the accuracy of the sounding or acrosstrack sounding resolution.

Sounding coverage and maximum depth

The number of PMBS soundings per range sample depends on the method of angle calculation and the amplitudes of distinct arriving signals. While PMBS produce up to an order of magnitude more raw soundings per swath compared to MBES over a given acrosstrack distance, there is no control over angular distribution or acrosstrack density of soundings in the PMBS swath. The nadir region is of particular importance in this regard. Unlike single-head MBES systems, PMBS sonars natively utilize separate arrays for the port and starboard directions; the nadir region is thus located on the inboard limit of the angular swath for each side. This design, coupled with the geometry of intersection between a spherically-spreading wavefront and generally flat seafloor near nadir, typically results in reduced acrosstrack sounding density near nadir. Some PMBS models presently exclude soundings within approximately 30° of nadir region due to these effects; others provide soundings near nadir at reduced acrosstrack density compared to the outer swath. Sounding density near nadir may be a primary consideration in attempting to increase survey efficiency through wider line spacing with less than half-swath overlap.

Though PMBS systems offer generally higher sounding density compared to MBES, the distribution of soundings over an entire survey area also depends on alongtrack sounding density. The PMBS ping rate must be reduced to accommodate its extended range, resulting in reduced alongtrack sounding density for a given survey speed. Coupled with characteristically narrower alongtrack swath width (i.e., transmit beamwidth), a reduced PMBS ping rate may yield gaps in alongtrack sounding coverage. These gaps could be particularly severe near nadir where PMBS sounding density is typically further reduced by geometry of the incident wavefront on the seafloor and methods of angle measurement. Figure 2 illustrates the relationships between alongtrack sounding density and user-selectable ping rate or maximum one-way range, assuming negligible delay between each receive and transmit cycle.

Maximum depth capabilities are heavily governed by acoustic attenuation and are similar for MBES and PMBS systems operating at similar frequencies. PMBS models excluding the nadir region may be further limited in depth due to the geometry of this exclusion zone. In all cases, acrosstrack swath coverage is severely reduced for both MBES and PMBS when surveying near the maximum depth limit. Accordingly, neither system offers a particular maximum depth advantage at a given frequency. Echosounder selection must consider the expected depth ranges and include frequencies yielding a balance between resolution and wide swath coverage without omitting the deepest regions.

Backscatter data

In addition to depth estimates, many MBES and all PMBS systems include co-registered backscatter amplitude data associated with the seafloor and water column. Seafloor backscatter data collected with MBES include the samples contributing to each seafloor sounding. MBES water column data typically include one measurement per range sample for every beam, yielding extremely dense datasets. MBES seafloor and water column backscatter are generally treated as separate data products owing to their different purposes, storage requirements, and post-processing methods. In contrast, PMBS sidescan imagery includes backscatter data from the water column and seafloor in the form of one amplitude value per range sample with no control over the angular separation of these samples.

The relative advantages of MBES and PMBS backscatter data depend on survey needs. Seafloor backscatter from both systems are useful for sediment characterization and detecting objects on the seafloor. The resolution of MBES seafloor backscatter data changes across the swath according to variation in the projected area for each beam on the seafloor; generally, the resolution governed by this projection is finest near nadir and coarsest on the outer beams. Due to swath geometry, acrosstrack resolution of PMBS soundings and backscatter imagery improves with increasing range, from coarsest near nadir to finest in the outer swath. The decreasing resolution of MBES seafloor backscatter data toward the outer swath limits its utility for object identification in the outer beams, whereas PMBS imagery is highly conducive to human visual interpretation at these large swath angles.

MBES water column backscatter data include regularly spaced samples and are indispensable for certain types of surveys, such as fishery assessment. These data are also highly valuable for quantifying least depths over shipwrecks which may include tall or slender features (such as masts or antenna towers) not represented in the single bottom detection for each beam. Like sidescan imagery of the seafloor, PMBS water column backscatter data are irregularly spaced in angle but are readily interpreted by human visual analysis. The co-registered bathymetry data may also correspond to midwater targets, depending on the strengths of their returns. In this regard, the backscatter products required for the survey goals may have direct consequences for echosounder selection.

Effective swath width

Effective swath width is the acrosstrack distance over which soundings are useful for the survey purpose; this distance is typically less than the achievable limits of acrosstrack sounding coverage. With the aim of ensuring useful and accurate representations of seafloor features and hazards to navigation, the effective swath width of a survey system is frequently assessed against criteria relating to the horizontal density and vertical uncertainty of depth estimates. For example, NOAA survey standards for gridded bathymetric products specify, among other criteria, maximum total vertical uncertainty (TVU) according to IHO S-44 Order 1 for waters less than 100 m deep (Fig. 3). Grid resolution requirements also reflect a depth-dependent focus on object detection, calling for grid cell size of half the spatial wavelength of the smallest objects of interest. In waters 20 m deep or shallower, grid sizes must be 0.5 m to meet the spatial Nyquist criterion for 'standard' 1-m target cubes; in waters deeper than 20 m, the grid size scales as 2.5% of water depth. Sounding density in the gridded surface is also specified, in that 95% of grid cells must contain at least five soundings contributing to the final depth estimate.

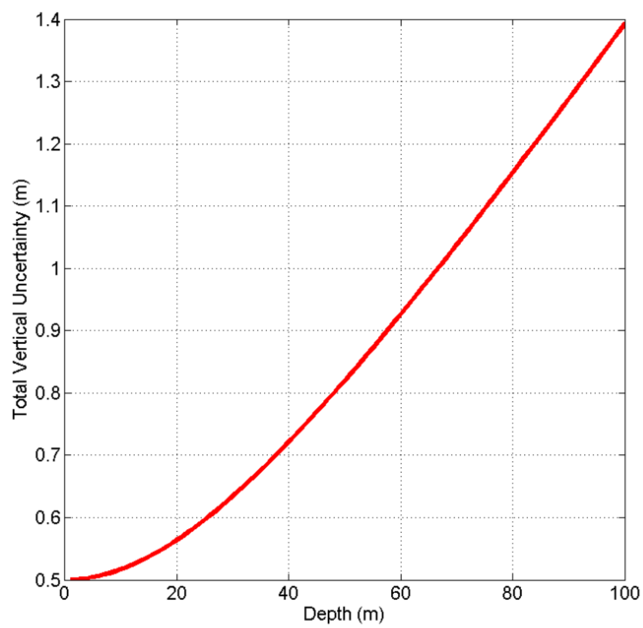


Figure 3. Maximum allowable total vertical uncertainty (m) at the 95% confidence level for NOAA gridded bathymetric products, as specified according to IHO S-44 Order 1 in water depths of 100 m or less.

Acrosstrack swath width on a flat seafloor is often expressed in terms of multiples of water depths (WD), or multiples of echosounder altitude above seafloor. This expression for MBES systems assumes that angular swath width, not acoustic attenuation, is the limiting factor in outer limits to swath coverage over flat seafloor that otherwise meets survey-specific criteria for data density and uncertainty. With angular swath widths approaching or exceeding 180°, attenuation and low backscattering strength due to shallow angles of incidence become limiting factors for achievable bathymetric swath coverage of PMBS systems operating over relatively flat seafloor.

For bathymetric data alone, the difference between 'achievable' and 'effective' swath widths of PMBS sonars may be significant. The calculation of at least one receive angle per range sample yields not only increased PMBS data density compared to MBES output, but also increases the apparent 'noise' in raw PMBS seafloor measurements. Together, the increased density and vertical uncertainty of raw PMBS data (colloquially referred to as 'fluff' by NOAA personnel familiar with data editing) present challenges for manual processing and assessing the useful, or effective, swath coverage of these systems.

Methods for filtering soundings based on range or angle bins typically aid in reducing data density, removing outliers, and improving uncertainty, but these steps are not applied uniformly or consistently across PMBS systems. While MBES uncertainly data have become standard products for most surveys and processing methods, uncertainty models have only recently been implemented for some PMBS sonars and remain in development for others. The importance of total propagated uncertainty (TPU) data in a response scenario depends on the survey objectives, representing a major consideration among echosounders and processing methods.

Because PMBS sonars produce sidescan imagery in addition to depth estimates, the concept of 'effective' swath width in storm response scenarios must incorporate the utility of this additional data product. For instance, the acrosstrack range of sidescan imagery that is useful for detecting objects on the scale of a standard 1-m cube may exceed the bathymetric swath coverage meeting data density and uncertainty criteria for charting purposes. The survey-specific concept of 'effective' swath width using sidescan imagery directly impacts echosounder selection and is examined later using examples from Redbird Reef PMBS data. Effective swath widths of PMBS systems are discussed in the contexts of improving storm response survey efficiency and, where possible, meeting NOAA standards for gridded bathymetric products.

Considerations for full-bottom-coverage surveys

Echosounder selection and effective swath coverage requirements depend directly on survey goals. For example, a survey designed to detect large objects (at least several meters in all dimensions, such as a shipwreck) could very likely fulfill its purpose using either MBES or PMBS with limited swath overlap to more quickly achieve full coverage of the seafloor. This configuration is not likely to yield density or quality of soundings sufficient for hydrographic purposes, but would be useful for detecting hazards for further investigation. Tall, slender features such as masts and radar towers may be poorly represented in the initial gridded results; fortunately, these hazards are associated with much larger objects which would be highly likely to be targeted for additional surveying in greater detail (for example, meeting or exceeding NOAA 'object detection coverage' requirements for data density and uncertainty).

On the contrary, a shallow water survey intended to update hydrographic charts must meet NOAA standards for sounding density, total vertical uncertainty, and grid resolution. By nature of these requirements, such a survey will also be almost certain to detect objects of many sizes, down to 1 m or less in all dimensions. Such a survey could be carried out with either MBES or PMBS, with attendant requirements for swath overlap and survey speed based on the swath width achieved by each system toward satisfying NOAA hydrographic standards. [Note: While all major PMBS manufacturers claim IHO S-44 Special Order survey capabilities, *NOS Hydrographic Surveys Specifications and Deliverables* (April 2014 revision) specifically prohibit PMBS data for nautical charting purposes.]

In all cases, full acoustic coverage of the bottom is required to detect objects and changes to the seafloor. Neither MBES nor PMBS systems facilitate any reduction in this requirement for ensonification of potential hazards. However, the increased 'effective' swath width of PMBS systems incorporating sidescan imagery suggest that post-storm surveys to identify navigationally significant features could be conducted with wider line spacing than expected for MBES. One potential mode would be to conduct PMBS survey lines with minimal overlap to provide an overview of the region with sounding quality and density sufficient to identify regions of interest. The sidescan imagery may of particular value in identifying areas for closer scrutiny, especially in outer swath regions where depth sounding uncertainty increases markedly for PMBS systems. Any objects or hazards requiring additional detail may be surveyed in mid-swath at higher sounding density and quality using PMBS or MBES with lower vessel speed and/or faster ping rate. These options are discussed further in Redbird Reef examples and Survey Protocols below.

Redbird Reef Examples

MBES and PMBS data collected shortly after Super Storm Sandy at the 'Redbird Reef' artificial reef site 30 km offshore Delaware demonstrate potential survey efficiency gains using PMBS for combined bathymetry and sidescan imagery analysis to maximize 'effective' swath width in response scenarios. The survey area includes numerous sunken subway cars and a sunken Navy barge in depths of 24-29 m. Detailed examples of PMBS observations of Redbird Reef objects, large and small, are included in a separate document, 'Object Detection with Phase-Measuring Bathymetric Sidescan Sonar Depth Data' (available at *sandy.ccom.unh.edu*).

The Redbird Reef datasets were acquired using a 200/400 kHz Reson SeaBat 7125 MBES deployed from a surface vessel and a 500 kHz GeoAcoustics GeoSwath Plus PMBS deployed on an AUV. Survey lines were conducted on parallel tracks with fixed separation, oriented east-west and north-south for MBES and PMBS surveys, respectively. Naturally, the survey platforms differed significantly in altitude above the seafloor, with MBES altitude of 24-29 m (the approximate depth from the surface) and PMBS altitude of 6 m (determined by the AUV path). The PMBS maximum range was set to approximately 25 m, yielding typical swath widths of 45 m (7.5 WD) over generally flat terrain.

Figure 4 presents bathymetric surfaces created from MBES and PMBS data in overlapping regions of Redbird Reef. The PMBS data were rapidly processed without manual editing using the CUBE algorithm, as described in 'GeoAcoustics GeoSwath Plus Data Processing with CARIS HIPS 8.1' (available at *sandy.ccom.unh.edu*). Despite different color scales and illumination, it is readily apparent that all navigationally significant objects present in the MBES bathymetry product are represented in the PMBS CUBE surface. More subtle features are also visible, such as scour around the artificial reef objects and large areas of bedforms with amplitudes of 10-20 cm and wavelengths of 1-2 m. Without additional manipulation, the PMBS data gridded at 30 cm in Fig. 4 appear to include outer swath artifacts which might be related to sound speed variability and residuals in the angular offsets applied; vertical offsets are also apparent on some lines, possibly owing to tide errors or drift in the AUV motion sensor record.

Survey efficiency may be improved by achieving wider 'effective' swath coverage, increasing line spacing, and reducing swath overlap between adjacent lines. To simulate various line spacing strategies, PMBS data were reprocessed using all survey lines, every other survey line, and every third survey line (Fig. 5). A major consideration in this dataset is the range setting of 25 m during data acquisition, which limited the swath width to approximately 45 m over flat seafloor. A larger range setting (e.g., 40 m) could have likely provided a wider acrosstrack swath limit (e.g., 12+ WD) to more fully explore the utility of PMBS soundings and sidescan imagery for increasing 'effective' swath widths at very shallow angles of incidence. With approximately 45 m swath width on the seafloor, the full, half-line, and third-line datasets simulated swath overlap of roughly 50%, 12%, and 0% between adjacent survey lines.

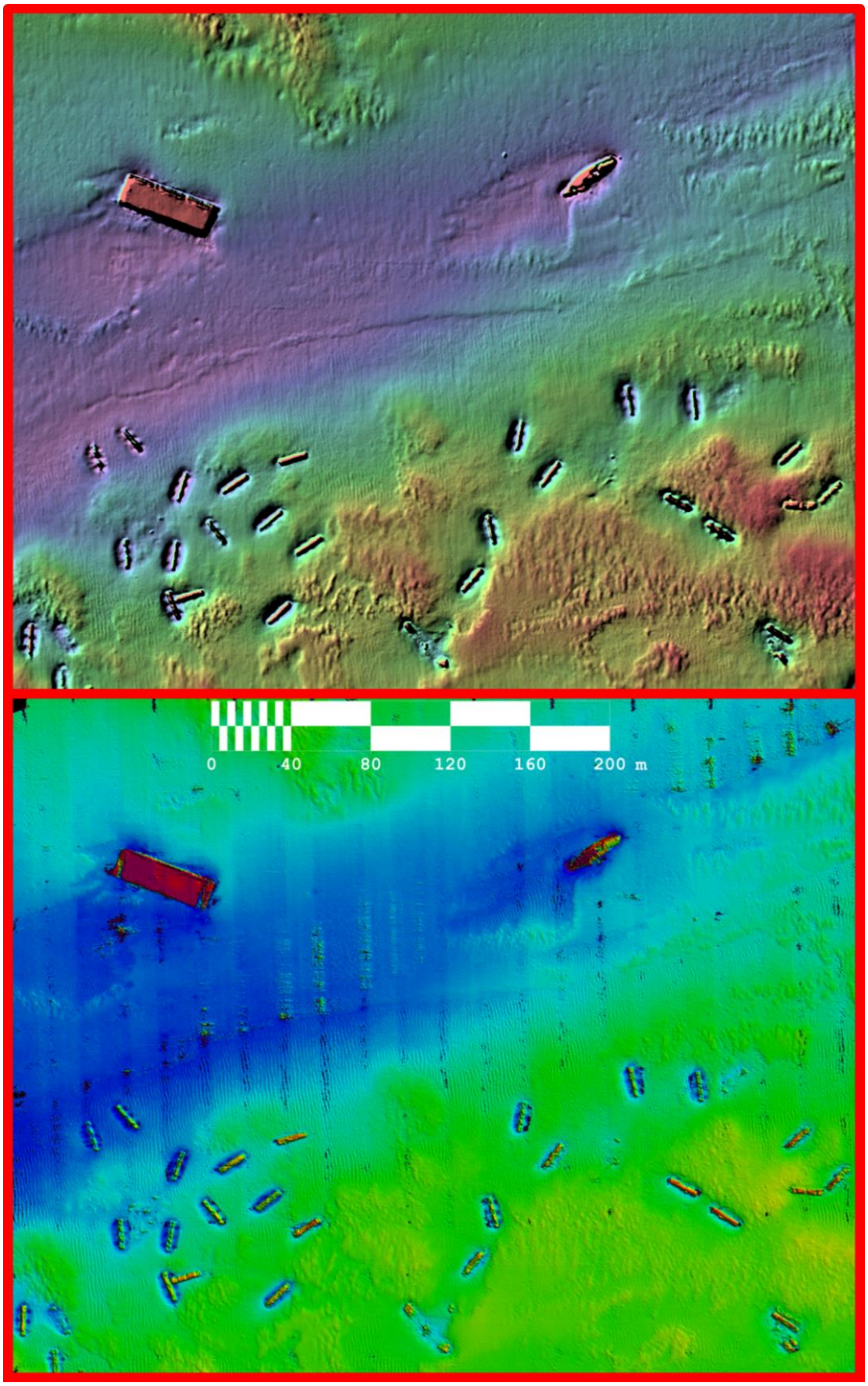


Figure 4. MBES data from a surface ship (top) and PMBS data from an AUV (bottom) appear to include all navigationally significant features, despite differences in color scale and illumination. PMBS data were processed rapidly with a 30 cm grid size using the CUBE algorithm and have not been edited manually. Bedforms with 10-20 cm amplitude and 1-2 m wavelengths are preserved in the PMBS surface, as are depth artifacts in regions with low sounding density (e.g., near nadir). The utility of these PMBS bathymetric data alone depend on survey goals and, at a minimum, support detection of large objects and adjacent areas of seafloor scour which suggest their presence.

Comparison of the CUBE surfaces in Fig. 5 illustrates several considerations for increasing survey efficiency through wider line spacing, given a fixed range setting. Reducing swath overlap from 50% to 12% between adjacent survey lines (Fig. 5, left panel to middle panel) reveals the importance of outer swath data for correcting artifacts near nadir in this particular dataset. Removing all swath overlap (Fig. 5, middle panel to right panel) appears to cause minimal further degradation of the nadir region but increases the prevalence of data gaps (or acoustic 'shadows') behind bedforms in the outer swath (Fig. 5, right panel, eastern border). Because these gaps result from low angles of incidence over ripples in the seabed, it is likely that a higher echosounder altitude above the seafloor and longer range settings during data acquisition would have increased the acrosstrack distance of continuous (i.e., shadow-free) sounding coverage among these bedforms.

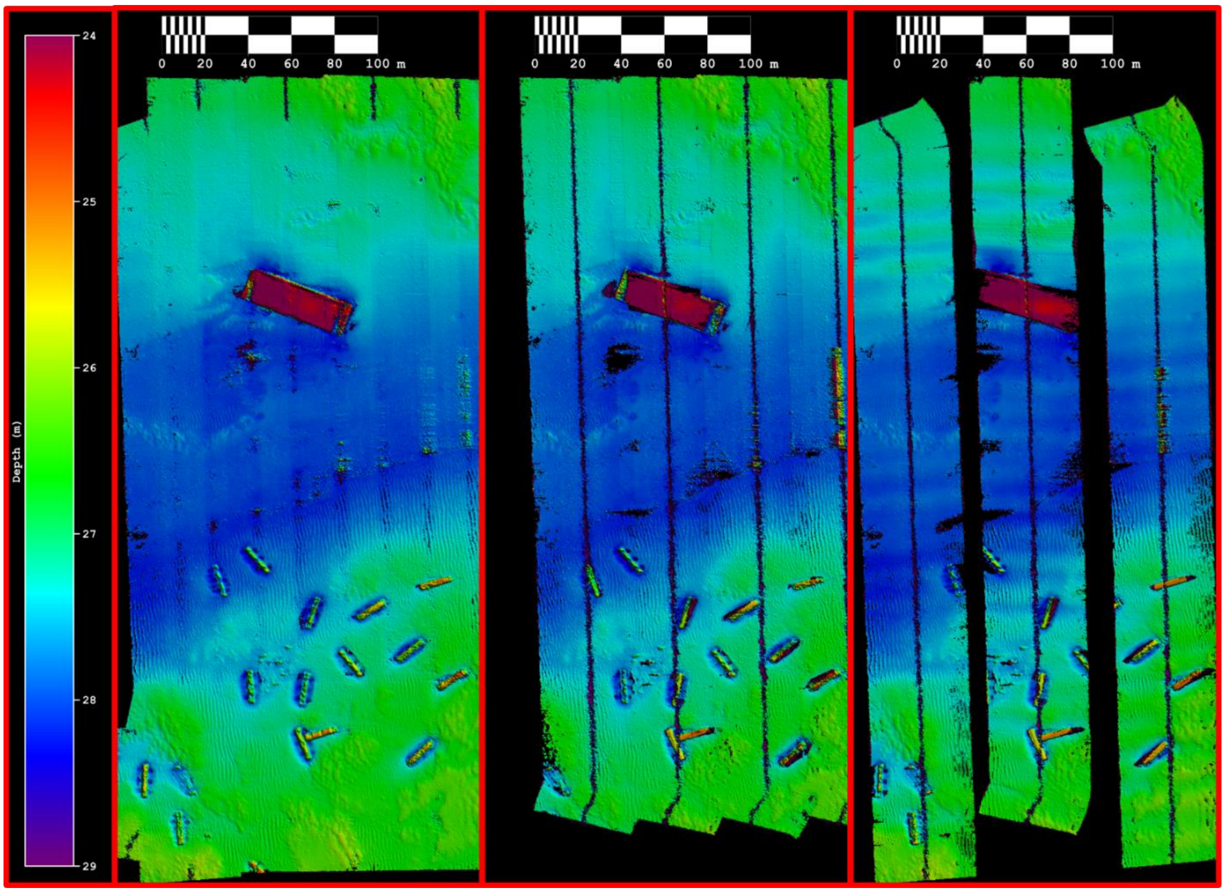


Figure 5. PMBS data collected at Redbird Reef, off the coast of Delaware, were rapidly processed without manual editing in a combination of line spacing strategies to evaluate bathymetric surfaces with various levels of swath overlap (from left: approximate overlap between adjacent survey lines of 50%, 12%, and 0%). The survey was conducted using an AUV at an altitude of 6 m above the seafloor with line spacing of approximately 20 m and a range limit of approximately 25 m, yielding half-swath overlap between adjacent lines over the entire survey area. Under a response scenario with real-time analysis of sidescan imagery, the data quality and representation of reef objects (including scour and bedforms) suggest that the acquisition range limit could likely be extended to 35-40 m with line spacing of approximately 60 m to provide swaths with 10 WD coverage and minimal overlap between adjacent survey lines. The line spacing could potentially be increased proportionally with echosounder altitude (e.g., from a surface vessel) until acoustic attenuation becomes a limiting factor in the swath coverage.

Individual survey lines from the Redbird Reef dataset are useful for evaluating the utility of sidescan imagery for hazard detection, especially in regions poorly represented in the PMBS bathymetry. Figure 6 includes bathymetry and sidescan imagery from one survey line over a sunken barge. While this represents a very large object that will almost certainly be detected from depth data alone, even in outer swath regions, the sidescan imagery provides clear evidence of additional structures not represented in the gridded bathymetry. Some of these structures (Fig. 6, lower panel, red arrows) appear in regions of low sounding density and persistent depth artifacts in the processed surface (e.g., near nadir) or provide context for data gaps on top of the barge (e.g., the large acoustic 'shadow' beyond the westward rail's northern portion). Analysis of this sidescan imagery during the survey (if collected from a surface ship) would strongly suggest to an operator that additional data are necessary to capture all hazards protruding from the barge, likely through tighter line spacing to place the object in non-nadir regions and ensonify its outer vertical surfaces.

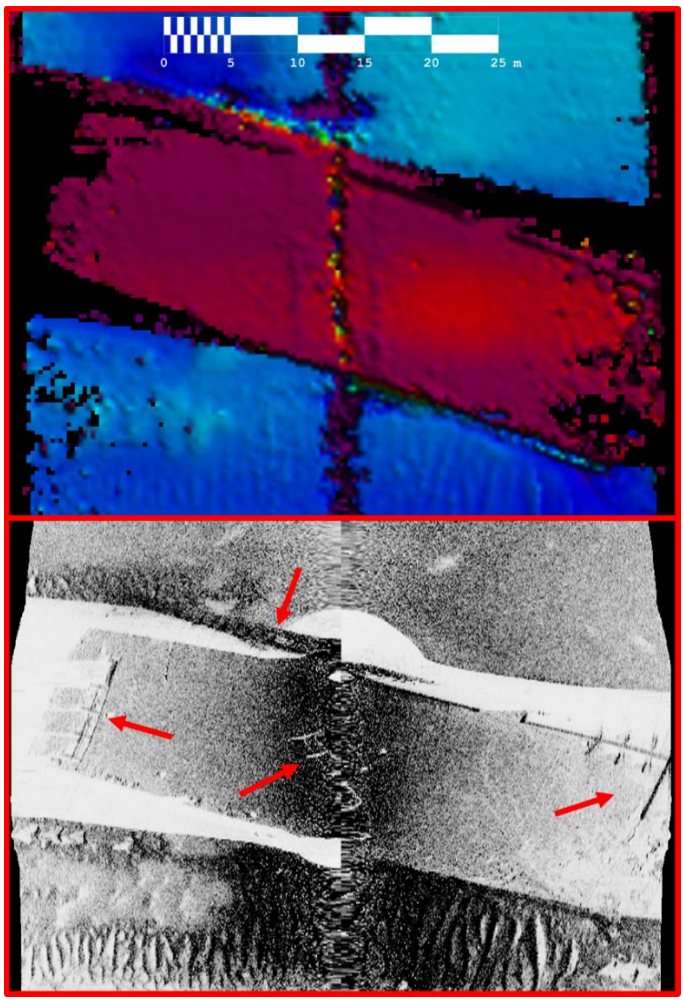


Figure 6. PMBS bathymetry gridded at 30 cm and co-located sidescan data over a sunken barge demonstrate the unique contributions of each type of data for hazard detection. While the soundings alone appear to capture the general shape of the barge and provide depths over much of its surface, the sidescan imagery reveals railings and other vertical structures (red arrows) not well-represented in the bathymetry. The imagery is particularly useful near nadir, where sounding density is lowest due to hardware configuration and the geometry of transmit pulse intersection with the barge top.

The utility of the Redbird Reef sidescan imagery is not limited to near-nadir regions with low sounding density, as the imagery includes bright spots or shadows near the range limit which indicate potential hazards just beyond the outer swath. Whereas the outer swath is prone to depth artifacts, acrosstrack resolution of sidescan imagery is finest in this region; anomalies may strongly suggest the presence of other objects not well represented in depth estimates at such low angles of incidence. For example, Fig. 7 includes sidescan imagery of the corner of a sunken subway car and adjacent scour (upper right and lower panels, red arrows) very close to the outer range limit. These features are poorly represented in the depth data for a single survey line (Fig. 7, top left, red arrow), but readily confirmed in adjacent survey line (Fig. 7, lower left). Together with Fig. 6, these examples demonstrate the utility of the sidescan data for providing detail and indicating the presence of hazards, especially near nadir and in the outer swath regions. PMBS surveys intended primarily for detection of navigational hazards could feasibly treat the extent of sidescan imagery as the 'effective' swath width for these purposes.

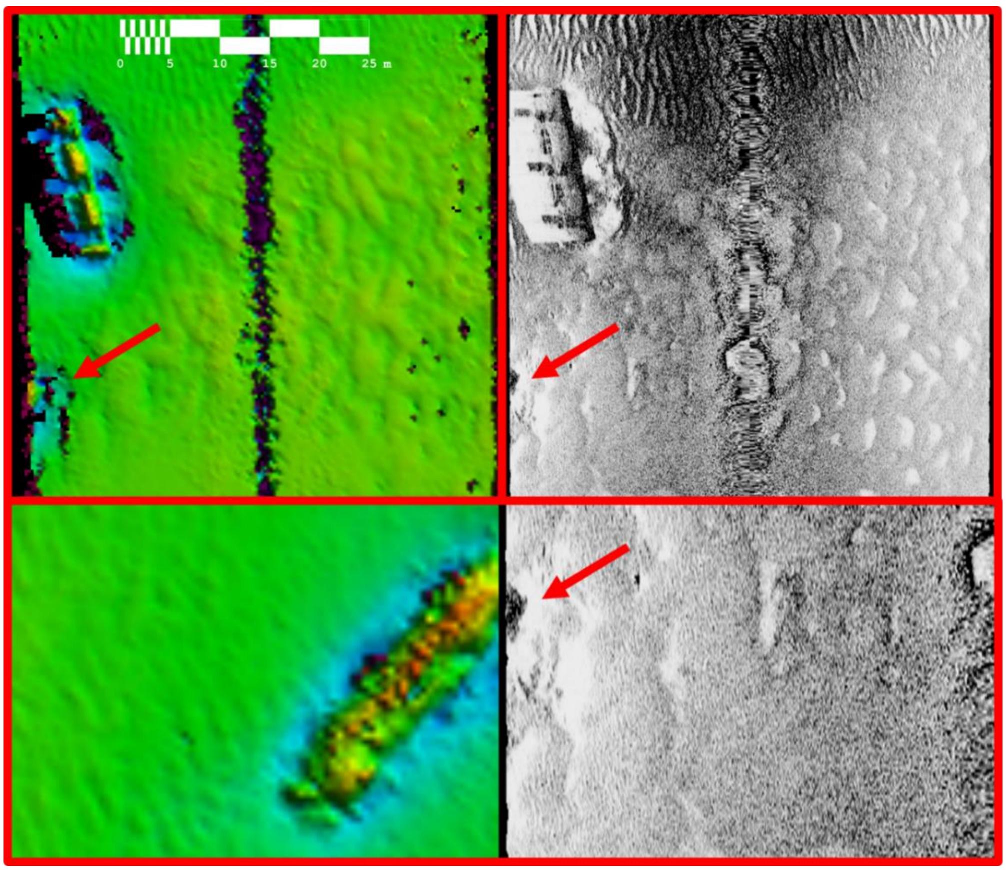


Figure 7. Two sunken subway cars and adjacent bedforms at Redbird Reef, offshore Delaware, are revealed in this composite image of PMBS data products from a survey conducted with an autonomous underwater vehicle (AUV) shortly after Super Storm Sandy. The seafloor depth is 26 m and the subway cars protrude roughly 2 m; the AUV altitude was 6 m. The upper two images include co-located depth (upper left) and sidescan imagery (upper right) products from both sides of a single survey line. All bathymetry was gridded at 30 cm without manual editing. The presence of a subway car beyond the swath coverage is suggested by the high-amplitude sidescan returns from the object's corner (dark pixels) and adjacent seabed scouring (light pixels) (upper right and lower images, red arrows). This region also appears to include anomalies and gaps in the depth data (upper left, red arrow). Additional survey lines (lower left) subsequently confirm its presence and provide estimates of least depths. These examples suggest a method for increased survey efficiency with minimal swath overlap, real-time analysis of depth and sidescan data, and additional data collection only as necessary for development of potential hazards.

Because the maximum effective swath width is inherently a function of the survey goals, storm response survey planning may also need to consider the NOAA standards for gridded bathymetric products. A CUBE depth surface gridded at 30 cm from non-overlapping survey lines (e.g., Fig. 5, right) was used to examine Redbird Reef PMBS sounding density and standard deviation relative to IHO S-44 Order 1 criteria outlined in the NOAA standards. Total propagated uncertainty (TPU) data for individual soundings and gridded depth estimates were not available in the CARIS HIPS 8.1 implementation due to a pending correction in the software's echosounder uncertainty model. To provide some basis for this evaluation of uncertainty at the 95% confidence level, the standard deviation (2-σ) of soundings contributing to each node was used in lieu of TPU. Figure 8 presents the sounding densities and standard deviations of gridded Redbird Reef PMBS depth estimates as percentages of nodes (within 10-cm depth bins for plotting) meeting the respective criterion set forth by NOAA hydrographic standards. Specifically, these criteria include density of five or more soundings per node (Fig. 8, left, black line) and uncertainty (2-σ, by proxy for TPU) less than the depth-dependent maximum total vertical uncertainty set forth by IHO S-44 Order 1 (TVU, Fig. 8, left, red line). The percentage of nodes with uncertainty (2-σ) less than 1 m are also presented (Fig. 8, left, blue line) for reference to the vertical extent of a standard target cube. Maximum TVU allowed by NOAA in depths of 0-100 m is included in Fig. 3 for reference.

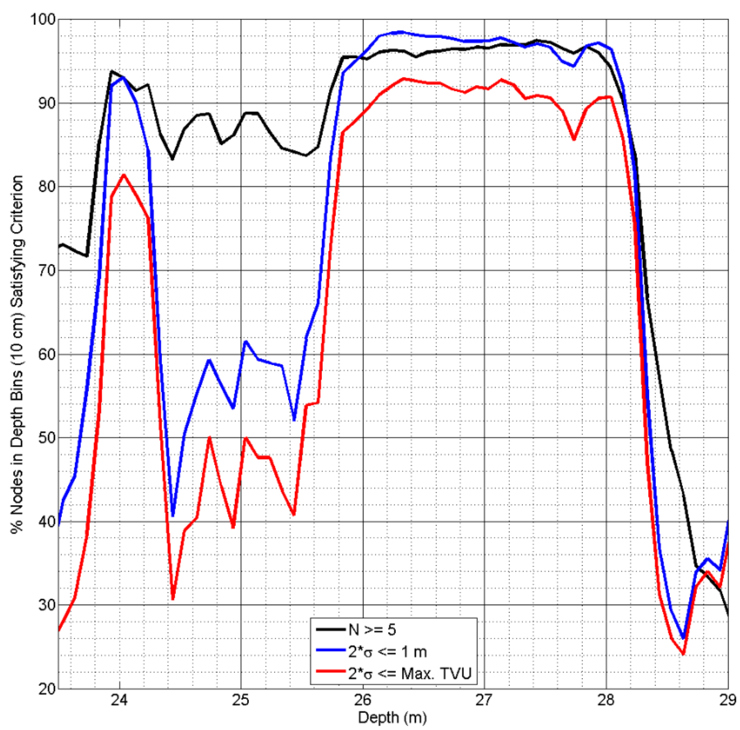


Figure 8. Percentages of nodes (in 10-cm depth bins) meeting NOAA density and uncertainty standards for gridded depth surfaces for non-overlapping PMBS survey lines at Redbird Reef. Data were gridded at 30 cm using the CUBE algorithm in CARIS HIPS 8.1; no manual editing was performed. Standard deviation (2-σ) of soundings is used as a proxy for total propagated uncertainty (TPU), which was not calculated due to a pending correction to the echosounder uncertainty model. In general, 90% or more of nodes in the depth range of the seafloor (25.8-28.0 m) satisfy the individual NOAA standards for density and maximum TVU; this trend could possibly be improved with grid sizing of 50 cm, as specified by NOAA standards in this depth range. The top deck of the barge (23.8-24.2 m) represents another significant flat surface and also corresponds to elevated satisfaction rates for these criteria. Regions with lower percentages likely correspond to edges of objects with high densities and large vertical distributions of soundings (e.g., 24.5-25.5 m) and regions of consistent depth artifacts with low sounding density, such as near nadir (28.5+ m).

Two ranges of depths in Fig. 8 correspond to the highest percentages of nodes with at least five soundings, standard deviation (2-σ) less than maximum allowable TVU, and standard deviation (2-σ) less than 1 m. These depth ranges correspond to the top of the sunken barge (23.8-24.2 m) and the sloping seafloor (25.8-28.0 m). In transitional regions (e.g., edges of structures and scour) and in other regions of depth artifacts (e.g., near nadir), the percentages of nodes meeting uncertainty criteria in each depth bin are severely reduced. These results, in examination with Fig. 5, suggest that a large portion of the PMBS survey area with no swath overlap could still meet NOAA hydrographic standards, and could be further improved if gridded at coarser resolution (NOAA standards allow grid cell sizes as large as 50 cm in this depth range). Depending on survey goals, regions that are determined to be navigationally significant could surveyed in greater detail to achieve higher sounding densities, lower uncertainties, and increased confidence in least depth values. It is important to note, though these examples use non-overlapping survey lines, at least some outer swath overlap must be maintained to ensure ensonification of the entire survey area.

Survey Protocols Using PMBS

In light of the considerations outlined above for PMBS echosounders and examples from Redbird Reef, suggestions for PMBS survey protocols have been developed to attempt to maximize efficiency in response scenarios requiring detection of navigationally significant hazards. These hazards may include large objects (more than 1 m in all dimensions) or significant changes to the seafloor. Intended survey areas include shipping channels and harbors and exclude very shallow regions outside the normal scope of non-response surveys conducted with MBES. These protocols take advantages of increased angular swath widths and co-located bathymetric and sidescan data produced by PMBS systems. The sidescan component does not necessarily provide a bathymetric coverage advantage except that the imagery may be used to detect and identify hazards in swath regions where the depth data are inadequate or equivocal, thereby extending the 'effective' swath width of PMBS for these purposes.

As PMBS sonars may be used alone or in conjunction with MBES, it is important to leverage the existing survey techniques and high-accuracy data products of MBES systems when available. In either configuration, a calibration must be run to ensure that linear and angular offsets for all systems are established. References are available for calibrations of MBES [*Godin*, 1998] and PMBS [*Eisenberg et al.*, 2011] mapping systems. If MBES is available and survey scheduling allows, it may be useful to create an MBES reference surface with very high sounding density from multiple overlapping swaths. MBES and PMBS cross-lines may be run over the reference surface to provide estimates of the accuracies of both systems in the survey environment. If the initial MBES reference surface is not sufficiently wide for potentially increased PMBS swath widths, additional cross-lines may be run with an acrosstrack offset to assess PMBS outer swath accuracy over the MBES reference surface. These steps provide opportunities to optimize echosounder configurations before data collection and preliminarily evaluate the 'effective' swath width in the survey environment.

PMBS survey preparation with MBES

1. Calibrate MBES and PMBS by respective patch test procedures
2. Create a high-density MBES reference surface from multiple overlapping survey passes
3. Run MBES and PMBS cross-lines to estimate accuracies across the swaths for both systems
    a. Ensure outermost PMBS swath is evaluated; run offset cross-lines if PMBS swath exceeds MBES reference surface width

Surveying with PMBS and available MBES

1. Plan initial line spacing of 8-10 WD over relatively flat seafloor, subject to change based on utility of soundings and sidescan imagery for survey goals
2. Complete a primary survey with PMBS range settings to achieve swath coverage of 10-12 WD
    a. If available, collect MBES data simultaneously; ensure coverage of the nadir region
    b. MBES and PMBS should be synced to reduce possible acoustic interference
3. Maintain alongtrack ping spacing less than the desired grid resolution (see Fig. 2)
4. If possible, examine PMBS data in real-time to estimate width of swath useful for survey goals
    a. Evaluate soundings for evidence of hazards and severity of outer swath 'noisiness'
    b. Examine sidescan imagery for evidence of hazards, details of vertical features, and possible identification of objects; this imagery is particularly important near nadir and in the outer swath where soundings tend to be sparse horizontally or scattered vertically
    c. Record locations of hazards or objects and estimate whether soundings sufficiently capture the object based on trends in data density and swath geometry
    d. Record locations of poor data quality or acoustic 'shadows' near objects to ensure adjustment of adjacent survey lines to acquire data in these regions
5. If available, acquire MBES data over objects and/or data gaps identified in the primary survey
    a. MBES survey planning should adhere to NOAA specifications for object development
6. If MBES is not available, acquire additional PMBS data over objects and/or data gaps identified in the primary survey
    a. Additional PMBS survey lines for object development should be planned on opposite sides of each hazard, offset such that the target is located between 1-3 WD athwartship in a swath region with suitable data density and uncertainty

References

Brodet, S., M. Annis, J. Felzenberg, and E. Van Den Ameele (2010), *Test and Evaluation of the L3 Klein HydroChart 5000 Bathymetric Side Scan Sonar*, NOAA Office of Coast Survey.

Dodd, D. (2013), *Uncertainty Evaluation of the EdgeTech 4600 Swath Bathymetry System*.

Eisenberg, J., M. Davidson, J. Beaudoin, and S. Brodet (2011), Rethinking the Patch Test for Phase Measuring Bathymetric Sonars, *Proc. US Hydrogr. Conf.*, (April), 25–28.

Godin, A. (1998), The calibration of shallow water multibeam echo-sounding systems, 1–182 pp., University of New Brunswick.

Gostnell, C., J. Yoos, and S. Brodet (2006), *NOAA test and evaluation of phase differencing bathymetric sonar technology*.

NOAA (2014), *NOS Hydrographic Surveys Specifications and Deliverables*.

Parent, M. (2011), Performance Analysis Using an Uncertainty Model for HydroChart 5000, *Sea Technol.*