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Katrina Wyllie
NOAA

Thomas C. Weber
University of New Hampshire, Durham, thomas.weber@unh.edu

Andy Armstrong
University of New Hampshire, Durham

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USING MULTIBEAM ECHOSOUNDERS FOR HYDROGRAPHIC SURVEYING IN THE WATER COLUMN: ESTIMATING WRECK LEAST DEPTHS

Katrina Wyllie
National Oceanic and Atmospheric Administration, Office of Coast Survey
1315 East West Hwy, Silver Spring, MD 20910
katrina.wyllie@noaa.gov

Thomas C. Weber
University of New Hampshire, Center for Coastal and Ocean Mapping
24 Colovos Road, Durham, NH 03824

Andrew Armstrong
National Oceanic and Atmospheric Administration, Office of Coast Survey
24 Colovos Road, Durham, NH 03824

ABSTRACT

Wreck superstructure can extend into the water column and pose a danger to navigation if the least depth is not accurately portrayed to mariners. National Oceanic and Atmospheric Administration (NOAA) has several methods available to acquire a wreck least depth: lead line, wire drag, diver investigation, side scan shadow length, single beam bathymetry, and multibeam bathymetry. Previous studies have demonstrated that the multibeam bathymetry bottom detection algorithm can fail to detect a wreck mast that is evident in the multibeam water column data.

Modern multibeam sonars can record the complete echo trace from each beam, known as water column data, in addition to bottom detections. NOAA's current Hydrographic Specifications do not require water column collection and the NOAA Field Procedure Manual describes a best practice of collecting additional bathymetry data during wreck developments to determine a wreck least depth. Several multibeam bathymetry and coexisting multibeam water column wreck datasets have been collected by NOAA hydrographic vessels. The least depth of each wreck is determined from the multibeam bathymetry data and compared to the least depth determined from the multibeam water column data. The NOAA wreck least depths results are then compared to previous wreck multibeam field trials done by the United Kingdom Hydrographic Office and the Canadian Hydrographic Office. A workflow to extract filtered and sidelobe suppressed water column point clouds is presented using currently available software packages. This paper explores the challenges encountered with water column data collection and processing and finds that analysis of water column data provides an improvement to finding wreck least depths.

INTRODUCTION

Shipwrecks are important in the field of hydrography because superstructure of sunken wrecks can extend into the water column and pose a danger to navigation. The available methods NOAA hydrographers use to find the shallowest point of the wreck, known as the least depth, include: leadline cast, wire drag, diver investigation, side scan sonar shadow length, single beam bathymetry, and multibeam bathymetry. In the last decade, leadline casts, wire drags, and diver investigations over wrecks have been rare. Side scan sonars are still used regularly to detect wrecks that then require additional acoustic coverage to obtain a least depth and position. Multibeam bathymetry has largely replaced single beam bathymetry and it is currently the most common and preferred method for determining a wreck least depth (NOAA HSSD and NOAA FPM).

Modern multibeam sonars can record the complete trace from each beam, known as water column data, in addition to bottom detections. Recent studies have demonstrated that multibeam bathymetry bottom detection algorithms can fail to detect a wreck mast that is evident in the multibeam water column data and it is because of these studies that some hydrographic offices have started recording multibeam water column during wreck investigations (Hughes Clarke, 2006, Hughes Clarke et al 2006, Mallace et al 2009, Ringholt et al, 2010, Gee et al 2012, Van der Werf, 2012, and Colob et al, 2014). The current NOAA Hydrographic Survey Specifications do not require multibeam water column collection but all NOAA hydrographic vessels now have modern multibeam sonars with this capability.

This paper will explore the value of collecting multibeam water column data for estimates of wreck least depths. The challenges encountered with water column data collection and processing will be explored by presenting NOAA data collected over eight wrecks. First the *Troydon* wreck will be used to describe a water column least depth workflow in FMMidwater and CARIS HIPS. The additional seven wreck datasets will then be presented and, along with the *Troydon*, summarized in a table that compares estimated multibeam bathymetry to multibeam water column least depths. The conditions under which multibeam bathymetry does not detect a wreck least depth and the magnitude of the least depth difference between multibeam bathymetry and multibeam water column will be discussed.

TROYDON

The *Troydon* is a 27m long, intact, steel hydraulic clam dredge. NOAA Ship *Thomas Jefferson*, collected concurrent Reson 7125 multibeam bathymetry and water column data over this wreck with acquisition setting power set to 220 dB and a gain high enough to see sidelobes and water column volume scattering; 57 dB in this case. These high power and high gain settings used for the wreck development are not the normal main-scheme acquisition settings for concurrent multibeam bathymetry and backscatter data. The *Troydon* bathymetry data were processed in CARIS HIPS and an estimated wreck least depth of 28.96m was located on a forward mast.

An estimated multibeam water column least depth of the *Troydon* was obtained by using the same line processed in two available software packages; CARIS HIPS and QPS FMMidwater. The line chosen had the wreck least depth and passed closest to the bow/stern axis of the wreck, within the minimum slant range of the beam pattern where water column data is less contaminated with sidelobes.

FMMidwater Workflow

A multibeam water column least depth of the *Troydon* was estimated using QPS FMMidwater software version 7.4.1. The Fledermaus Reference Manual provides detailed instruction of the FMMidwater software interface and options (Fledermaus, 2014). The specific workflow used to estimate the *Troydon* mast least depth is described:

1. Create a project and import .s7k sonar data
2. Convert the selected line to a generic water column file. Select a down sample factor of 4 to reduce the Reson file, record 7018, size while still preserving the maximum amplitude and location.
3. A MATLAB code created by coauthor Dr. Thomas Weber reads the FMMidwater created generic water column Reson file and suppresses sidelobes for each range ring by finding the maximum amplitude for each range ring and suppressing anything on that ring that is less than 20dB from the maximum value. The product of the MATLAB code is a new, sidelobe suppressed, generic water column file that is imported back into FMMidwater.
4. FMMidwater provides the user options to view and filter water column data by beams, range and depth. First the stacked view, where all beams are stacked on top of each other with the maximum signal displayed, is used to visually identify the wreck least depth timestamp. For this file, the data is viewed in the signal option of "power" (a computed dB value) and the power histogram is clipped by dB to reduce volume scattering and sidelobe signatures.
5. The fan view is used to determine the least depth of the wreck. The multibeam bathymetry raw bottom detections for each beam are represented in the fan view with black dots. The time series tab allows the user to view the power versus range plot of a selected beam where raw bottom detections are red circles and correlate to black dot bottom detections in the fan view.

   Making use of the power histogram and threshold filtering, the least depth of the wreck was located. For that beam, 234, the time series plot was filtered by manually selecting the maximum amplitude of the interpreted mast detection. Using the geo-pick tool, the uncorrected water column least depth was picked at the middle of the beam within the filtered time. The closest mast bottom detection geo-pick was also determined; in this case, the mast detection on beam 235. Selecting the closest bottom detection minimizes the correction that is then applied to the water column detection that was not selected as a bottom detection (Figure 1).

   The fan view calculates depths with an assumed sound speed of 1500m/s and no waterline or vessel offsets are applied to either raw bottom detects or water column data. The FMMidwater uncorrected mast bottom detection on beam 235 is 24.89m. The CARIS HIPS estimated bathymetry depth for the same line, beam, and timestamp is 28.96m. The difference of 4.07m is due to sound speed, tides, and *Thomas Jefferson* vessel offset corrections not applied in FMMidwater. The uncorrected mast least depth from beam 234 is 24.67m and with the 4.07m correction, the *Thomas Jefferson*'s multibeam water column least depth estimate for the *Troydon* using FMMidwater is 28.74m.

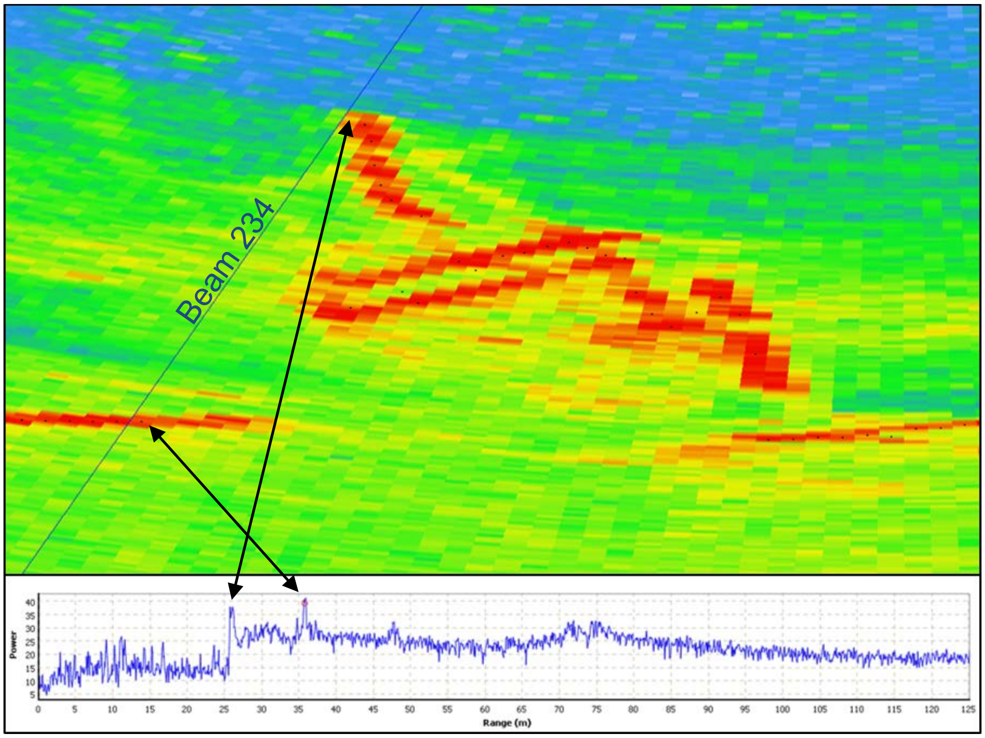


Figure 1: Beam 234 on the forward mast of *Troydon* is highlighted in fan view. For this beam, the black raw bottom detect dot is on the seafloor and is displayed as a red circle in the beam time series power vs range plot. As the bottom detection for this beam has a higher dB, the shoaler mast detection is not selected, although evident in the power vs range plot.

6. FMMidwater has many options for exporting water column data. For this workflow, an ASCII and fan view time series export is used. These products are opened concurrently in Fledermaus with the gridded bathymetry to asses if and where the multibeam bathymetry solution failed to capture the wreck least depth. Viewing the time series fan view concurrently with the exported water column point cloud is also a quality control step to ensure the filtering used in FMMidwater did not remove wreck structure.

CARIS HIPS Workflow

A multibeam water column least depth of the *Troydon* was estimated using CARIS HIPS version 8.1.8 software. The CARIS HIPS 8.1 User Guide provides detailed instruction of the water column interface and options (CARIS, 2014). The specific workflow used to estimate the *Troydon* mast least depth is described:

1. Create a project and convert raw Reson .s7k data
2. Load final zoned tides, sound speed correct, compute total propagated uncertainty and then merge to apply these corrections to the selected line.
3. Swath editor is a line display of the water column data with the option to display raw bottom detections and a stacked view option. This editor is used to identify features that have a least depth not represented in the bathymetry bottom detection solution and infer the targeted intensity range to use in the subset editor tool. In the case of the *Troydon*, the allowed intensity slide range of -64 to 0 dB did not capture the highest intensities on the wreck or the seafloor. The option to select additional bathymetry was not used in this editor.
4. Subset editor can display more than one line of water column and bathymetry data in a user-selected area. The data can be filtered by a min/max depth range and a dB intensity slider.

The individual points can be displayed as a fixed size or by larger points indicating stronger returns and the points can be colored by intensity, depth, project, vessel, day, line, or bottom detection. The water column display assumes a sound speed correction of 1500m/s.

Individual data points can be selected and added to an additional bathymetry layer, which is corrected for everything bathymetry was corrected for; vessel offsets, tide, and sound speed. If data points are added in error, they can be removed from the additional bathymetry layer manually. The additional bathymetry layer can be regenerated if there are any changes to the sound speed profile, tide file, or vessel offsets and it can be included in the creation of a gridded surface (Collins, 2012 and Collins and Eng, 2012). The subset editor tool was used to select the *Troydon* wreck area and lower intensities were filtered out using the intensity slider until the interpreted mast least depth was selected and added to the additional bathymetry layer.

The *Thomas Jefferson*'s multibeam water column least depth estimate for the *Troydon* using CARIS HIPS workflow is 28.73m on the forward mast. Figure 2 illustrates the difference between the *Thomas Jefferson*'s CARIS HIPS bathymetry and water column solution for the forward mast of *Troydon* as shown in Subset Editor 3D view.

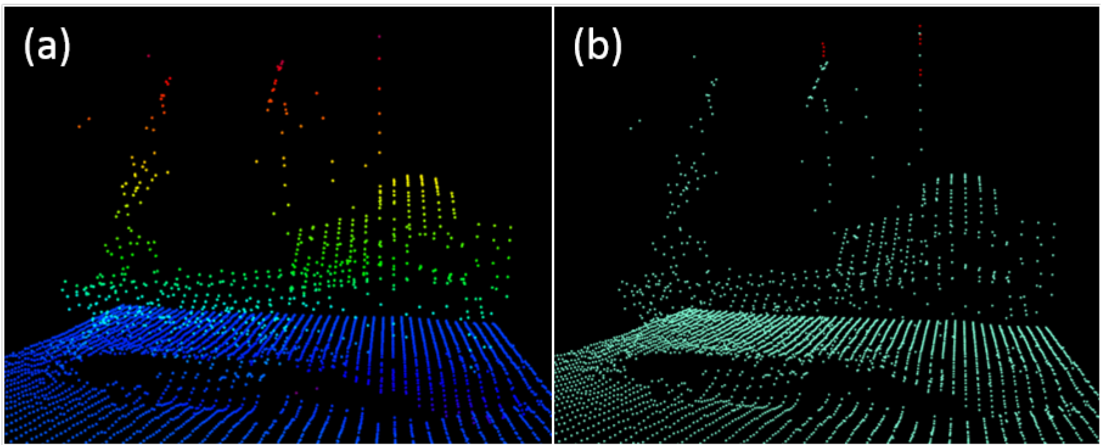


Figure 2a: Bathymetry over *Troydon* colored by depth. Figure 2b: Bathymetry in teal and additional water column data of forward and middle *Troydon* mast in red

Troydon Diver Investigation

A scuba diver investigation of the *Troydon* took place on October 30, 2014 by NOAA divers Sam Greenaway and John Kidd. The divers obtained a least depth of the forward and middle masts using the procedure described in Appendix A. The forward mast is shown in Figure 3a and is described as about 5 inches in diameter and covered in soft growth. The diver least depth of the forward mast is 28.75m. All depths are referenced to the nautical chart datum of Mean Lower Low Water. The middle mast is shown in Figure 3b. This mast has about a 2-foot vertical pinnacle on the port side of the main horizontal beam. This pinnacle was captured in the *Thomas Jefferson*'s water column data but not the bathymetry data. The dive confirmed that the outriggers typical of clam dredgers are not in the upright stored position. The dive also confirmed that the forward mast is the least depth of the *Troydon*. Due to poor water clarity and limited dive time at that depth, the stern mast was not visible and was not investigated by the divers.

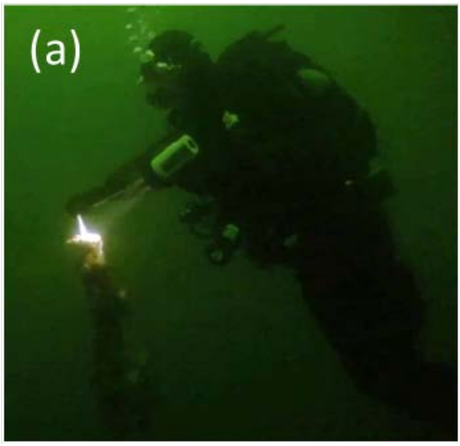


Figure 3a: Forward mast of *Troydon*. Figure 3b: Middle mast of *Troydon*

Table 1 summarizes the bathymetry, water column, and diver least depth results of the *Troydon*'s forward and middle masts. The water column derived least depths agree within 0.01m between software packages, for both masts. The water column derived least depths are shoaler than the bathymetry derived least depths although the difference of the least depth of the wreck, the forward mast, is within the IHO Order 1 depth uncertainty constraints of 0.62m (IHO, 2008). There is a larger difference, not within IHO Order 1 depth uncertainty constraints, between the bathymetry least depth and water column least depth on the middle mast because the multibeam echosounder bottom detection algorithm did not, and was not expected to, pick the pinnacle on that mast that was observed in both the water column data and by the divers. The diver least depth measurements are within 0.02m of the estimated water column least depths. The *Thomas Jefferson*'s bathymetry solution captured the structure of the *Troydon*, including the forward mast, but the water column data provided more information and a shoaler least depth that closely matched the direct diver measurement.

***Troydon* Mast**	**Bathymetry Least depth (m)**	**FMMidwater Water Column Least Depth (m)**	**CARIS HIPS Water Column Least Depth (m)**	**Diver Least Depth (m)**
Forward	28.96	28.74	28.73	28.75
Middle	29.53	28.85	28.86	28.85

Table 1: NOAA Ship *Thomas Jefferson*'s bathymetry and water column least depth estimates compared to diver least depth estimates of *Troydon*'s forward and middle masts

NOAA CASE STUDIES

NOAA hydrographic vessels are not required to collect multibeam water column data but they all have modern multibeam sonars with that capability. Curious hydrographers aboard these vessels have experimented with the collection of water column data using both Reson and Kongsberg multibeam sonars. A compilation of seven wrecks with both bathymetry and water column data collected by NOAA vessels are presented in this section. The bathymetry least depths are compared to the water column least depths using two methods, described below, and the results of all the wreck datasets are summarized in Table 2. The FMMidwater tools are used to estimate the multibeam water column least depths and CARIS HIPS is used to provide the corrected bathymetric solution for the raw bottom detections.

Methods

Method One: In FMMidwater, locate and geo-pick the uncorrected least depth of the wreck and the closest bottom detection. In CARIS HIPS, find the same line, beam, and timestamp of the corrected bottom detection and calculate the depth difference that results from sound speed, tide, and vessel offset corrections. Correct the FMMidwater geo-pick least depth and record the estimated water column least depth. This method was used for the *Thomas Jefferson* and *Ferdinand Hassler* estimated water column least depth of the *Troydon*. The first four NOAA case studies also use Method One.

Method Two: In FMMidwater, locate and geo-pick the uncorrected least depth of the wreck and a bottom detection on the seafloor nearby. Transform the location of the seafloor bottom detect from WGS84 to the projection of the source bathymetry, usually NAD 83 Zone #N. Find the corresponding corrected bottom depth from the bathymetry surface and calculate the correction value at that location. Correct the FMMidwater geo-pick least depth and record the estimated water column least depth. This method has more uncertainty than Method One but can be used if the verified bathymetry source is different than the water column data collection source. This method was used for the *Henry Bigelow* estimated water column least depth of the *Troydon*. The last three NOAA case studies also use Method Two.

Womens Bay Wreck

NOAA Ship *Fairweather* collected Reson 7125 multibeam data over a wreck located in Womens Bay, Alaska in September of 2012 (Figure 4). The bathymetry data of this wreck indicates the wreck is lying on its side but otherwise intact with ample rigging. The FMMidwater uncorrected bottom detection captured the least depth and was geo-picked at 7.97m. The corresponding line, beam, and timestamp of that least depth bottom detection in CARIS HIPS is 7.60m. Because the least depth of the wreck is a bottom detection, the final estimated water column least depth is 7.60m. The field submitted least depth of this wreck is 7.62m, but on a structure of the wreck 3 meters closer to the bow. The 0.02m difference between the submitted least depth and the estimated water column least depth is within the allowed IHO Order 1 depth and position uncertainty constraints (IHO, 2008).

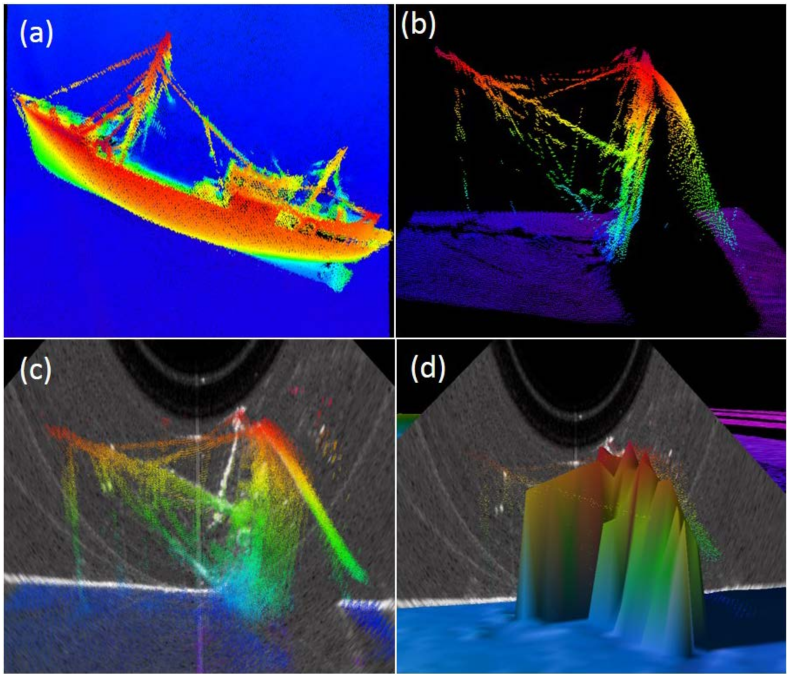


Figure 4a: All bathymetry lines collected over Womens Bay wreck. Figure 4b: Point cloud of single analyzed bathymetry line that includes wreck least depth. Figure 4c: Exported water column point cloud of same line displayed in Figure 4b with the fan at the timestamp of the least depth. Figure 4d: NOAA verified 1m BAG bathymetry surface displayed with water column point cloud and fan indicating 3m distance between designated and estimated position of wreck least depth

San Pedro Feature

NOAA Ship *Fairweather* collected concurrent multibeam bathymetry and water column data using a Reson 7125 multibeam sonar over a submerged feature in San Pedro, California in November of 2013 (Figure 5). This feature is not a shipwreck but resembles a type of drill platform obstruction with vertical structure. Method One was used to determine an estimated water column least depth. The bottom detection geo-picked in FMMidwater, 22.01m, corresponds to a corrected bottom detect in CARIS HIPS of 20.97m. The correction difference of 1.04m was subtracted from the FMMidwater geo-picked least depth of 21.87m for a final estimated water column least depth of 20.83m. The water column least depth was located on the same beam of the bathymetry bottom detection but at a different timestamp.

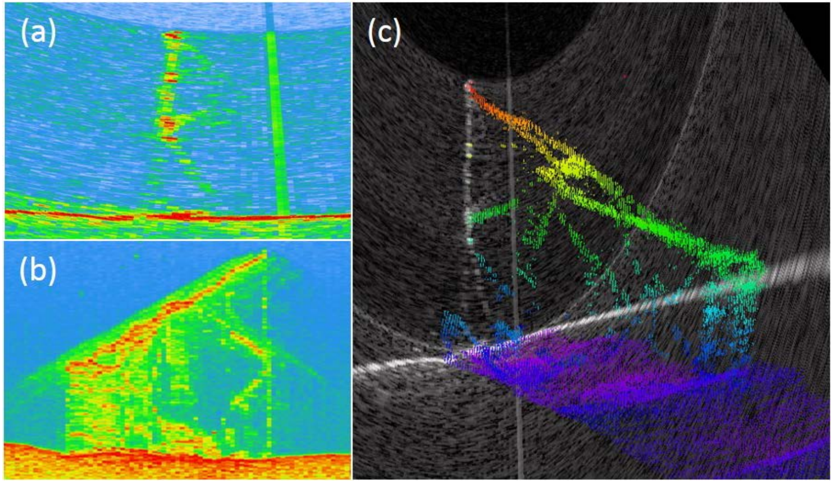


Figure 5a: Fan view of obstruction. Figure 5b: Stacked view of obstruction. Figure 5c: Exported water column point cloud of obstruction with water column fan view at the timestamp of the estimated least depth

Long Branch Wreck

NOAA Ship *Ferdinand Hassler* collected concurrent multibeam bathymetry and water column data using their two Reson 7125 multibeam sonars over a wreck off Long Branch, New Jersey while on a mission to update the nautical charts in the area (Figure 6). The bottom detection of the bow mast geo-picked in FMMidwater, 21.70m, correlated to a corrected bottom detection of 24.95m in CARIS HIPS. The difference of 3.25m was added to the FMMidwater uncorrected mast geo-pick of 21.52m for a final estimated water column least depth of 24.77m. There are large schools of fish visible in the water column data that make it hard to distinguish wreck structure from fish.

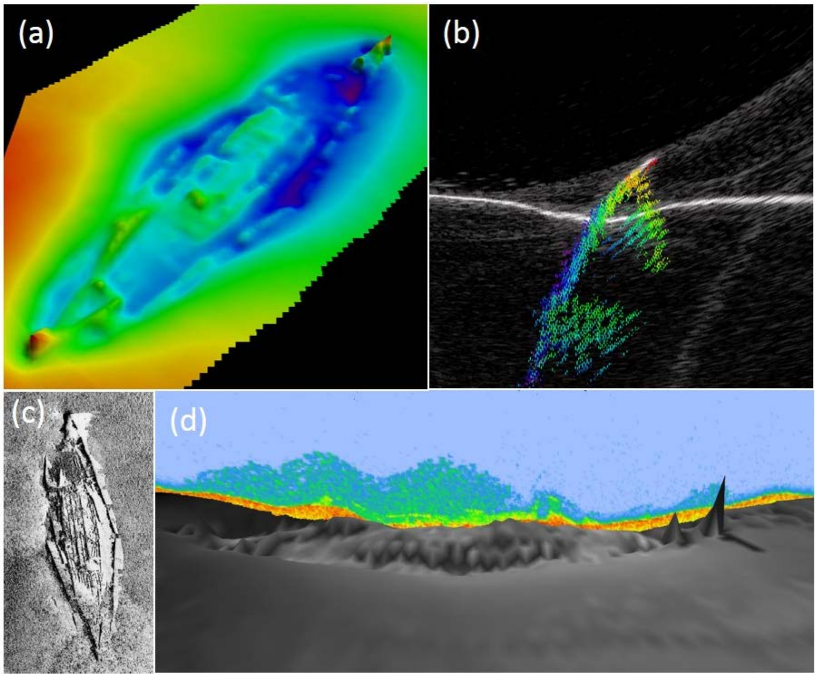


Figure 6a: Bathymetry of New York wreck. Figure 6b: Exported water column point cloud with fan timestamp indicating least depth on bow mast. Figure 6c: Side scan sonar trace of New York wreck, shadows are white with largest relief at bow. Figure 6d: Stacked view of wreck water column with schools of fish masking wreck structure shown in color and submitted bathymetry surface in greyscale

Long Beach Wreck

NOAA Ship *Fairweather* collected concurrent multibeam bathymetry and water column data using a Reson 7125 multibeam sonar over a wreck in Long Beach, California in November of 2013. The FMMidwater uncorrected bottom detection geo-pick of 12.64m correlates to a CARIS HIPS corrected bottom detection of 13.20m. The correction difference of 0.56m was added to the FMMidwater geo-pick least depth on the bow rail of 12.62m for a final estimated water column least depth of 13.18m. The four bathymetry detections on the vessel’s bow were rejected by the hydrographer in the context of the bathymetry point cloud and a bathymetry least depth of 13.40m was submitted on the middle of the wreck. Figure 7 shows the water column fan view of the bow of this wreck with raw bottom detections in red. The bathymetry bottom detection algorithm picks many solutions on the sidelobe generated from the very flat wreck deck even with low power and gain acquisition settings. The actual least depth of the wreck selected from water column is on the bow railing about 5m from the submitted bathymetric least depth.

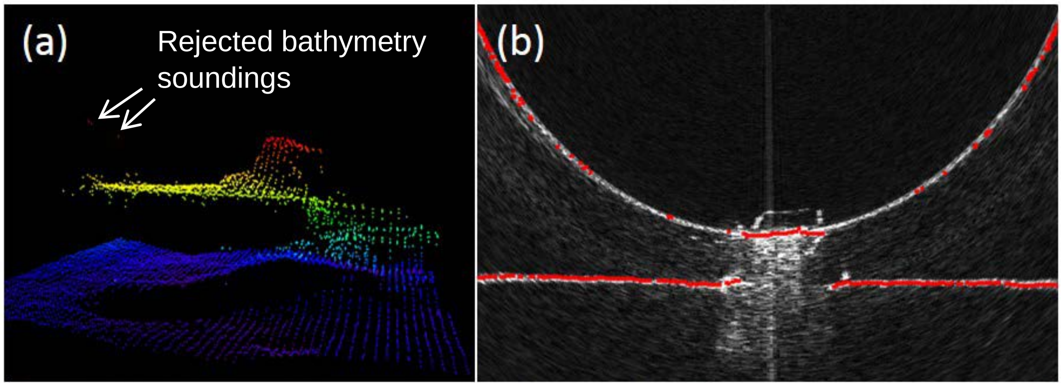


Figure 7a: Bathymetry point cloud of wreck. Four bathymetry soundings on the bow of the wreck were rejected by the hydrographer with the context of the bathymetry point cloud Figure 7b: Fan view of wreck in greyscale with raw bottom detections in red and bow structure in white

Lady Cecelia

NOAA Ship *Rainier* collected concurrent multibeam water column and bathymetry data using a Kongsberg EM710 multibeam sonar over a sunken fishing vessel off the coast of Washington state in May of 2012 (Figure 8). A conservative bathymetric least depth of 110.6m was submitted. The water column fan view indicates a vertical structure of the wreck with what could be an ROV-reported existence of crab pots extending from the vessel. The assumed crab pots and crab pot line introduce ambiguity in the least depth selection. The FMMidwater seafloor bottom detection of 119.35m correlates to the CARIS HIPS corrected least depth of 119.10m. The correction difference of 0.25m was applied to the FMMidwater mast geo-pick least depth of 105.17m for a final estimated water column least depth of 104.92m.

At this depth of ~110m, the mast width is significantly smaller than the beam footprint and so the bottom detection algorithm located the body of the vessel but not the mast structure. Because the *Rainier* was applying sound speed and vessel offsets in SIS during acquisition, the refracted point cloud of this vessel was exported from FMMidwater to obtain a corrected least depth of 104.47m. The difference between the refraction corrected point cloud least depth and the estimated least depth from Method Two is 0.45m, within depth uncertainty constraints, and can be explained by Method Two applying a correction from the seafloor where the sound speed correction varies from that of the depth and position of the mast.

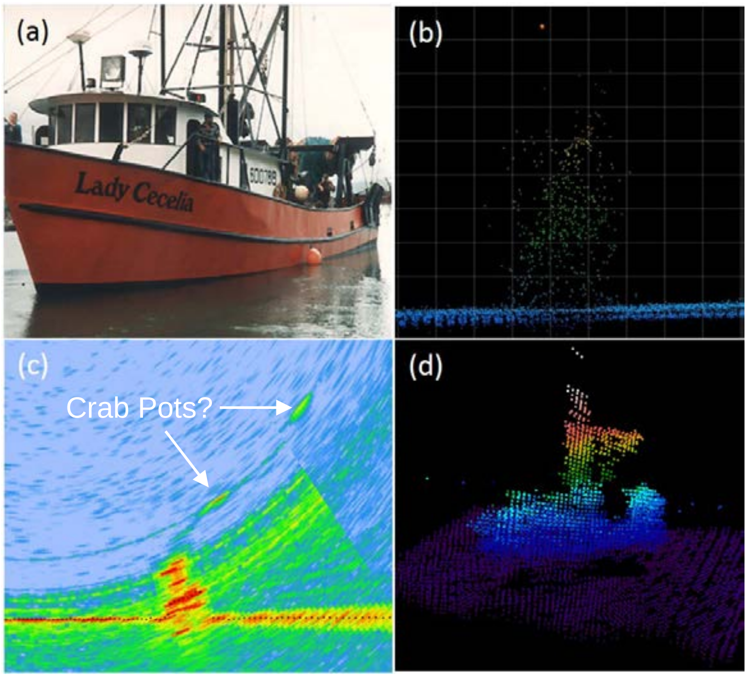


Figure 8a: Fishing vessel *Lady Cecelia*. Figure 8b: Bathymetry point cloud of wreck structure with orange dot indicating hydrographer selected designated sounding of 110.6m. Figure 8c: Fan view of *Lady Cecelia* with raw bottom detections in black dots, vertical mast structure in red (higher dB), and possible crab pots extending from vessel. Figure 8d: Exported water column point cloud of wreck

Bow Mariner

NOAA Ship *Thomas Jefferson* collected multibeam bathymetry using a Reson 7125 multibeam sonar over the *Bow Mariner* in November of 2009. The *Bow Mariner* sank in 2004 and the *Thomas Jefferson* was instructed to investigate the extent of a possible debris field. The submitted multibeam bathymetry least depth of the charted wreck is 36.6m (20 fathoms). In June of 2012 the NOAA Ship *Ferdinand Hassler* was experimenting with the collection of Reson 7125 multibeam water column data and used the *Bow Mariner* as their target.

The FMMidwater uncorrected *Ferdinand Hassler* bottom detection of the seafloor was geo-picked at 75.92m. The corresponding location of seafloor from the approved *Thomas Jefferson* bathymetry data is 75.52m. The correction difference of 0.40m was applied to the *Ferdinand Hassler*'s FMMidwater geo-pick of the mast least depth of 32.15m for a final estimated water column least depth of 31.75m. The water column least depth is 4.85m (3 fathoms) shoaler than the charted bathymetry least depth. The significant difference between multibeam bathymetry and water column was checked against the *Ferdinand Hassler*'s multibeam water column extent of the mast above the bottom detection in the middle of the mast (similar location of the *Thomas Jefferson* bathymetry solution). The additional vertical extent of the mast not captured in the bathymetry solution as determined by Method Two is 4.85m and the extent of the mast found by geo-picking the extents from the *Ferdinand Hassler*'s water column data is 4.74m.

The *Ferdinand Hassler* multibeam water column data not only detected a least depth much shoaler than the bathymetric reported least depth, it also located several masts that were not completely part of the bottom detection solution (Figure 9). Parts of the mast had bottom detects that were rejected by the hydrographer within the context of the bathymetric point cloud. The multibeam water column data provides the context of those masts to the hydrographer.

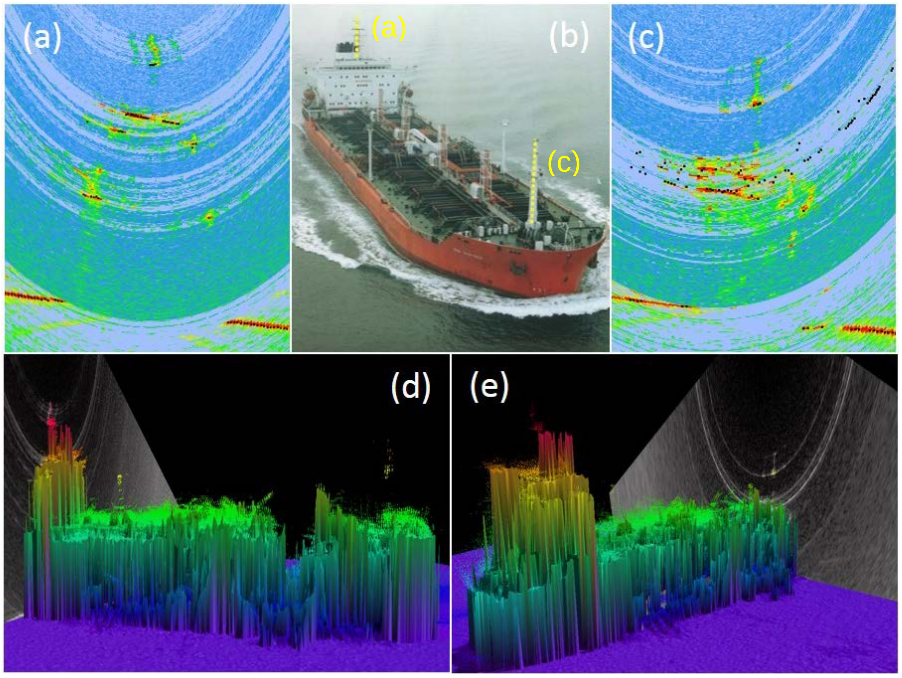


Figure 9a: Sidelobe supporessed fan view of *Ferdinand Hassler*'s water column solution over least depth of wreck. Figure 9b: *Bow Mariner* image with bow and least depth masts highlighted in yellow. Figure 9c: Sidelobe suprresed fan view of *Ferdinand Hassler*'s water column solution over bow mast of wreck. Figure 9d: *Thomas Jefferson* 50cm bathymetry grid with *Ferdinand Hassler*'s filtered exported water column point cloud and water column fan located at timestamp of wreck least depth mast. Figure 9e: *Thomas Jefferson* 50cm bathymetry grid with *Ferdinand Hassler*'s filtered exported water column point cloud and water column fan located at timestamp of bow mast

Montana

The Navigation Response Team (NRT) 4 collected multibeam bathymetry data with a Kongsberg EM3002 multibeam in 2011 over the wreck of the side-wheel steamer *Montana* in Thunder Bay, Michigan. The multibeam bathymetry least depth was determined to be 11.56m on the vertical engine structure. In May of 2014, the National Marine Sanctuary (NMS) vessel R/V *Storm* collected Kongsberg EM2040C multibeam bathymetry and water column over this vessel and the multibeam water column least depth was analyzed. As this is a popular dive site and a well-documented wreck, the NMS diver images in Figure 10 provided additional context to the multibeam data.

A NMS FMMidwater bottom detection on the boiler of 13.89m corresponded to the position of the boiler from the NRT 4 multibeam bathymetry survey of 14.45m. The correction difference of 0.56m was applied to the NMS FMMidwater least depth geo-pick of 10.99m for a final estimated water column least depth of 11.55m. This agrees within 0.01m to the NRT 4's submitted bathymetric least depth. The EM2040C multibeam bathymetry bottom detection least depth was the same as the water column least depth. This success of the multibeam bathymetry data on the least depth of this wreck was expected because the engine structure is larger than the beamwidth; the EM2040C 0.7° beam at a range of 11.5m has a footprint of 14cm. An example of a mast on the same wreck completely missed by the multibeam bathymetry bottom detection algorithm because the mast is smaller than the beam width is shown in Figure 11.

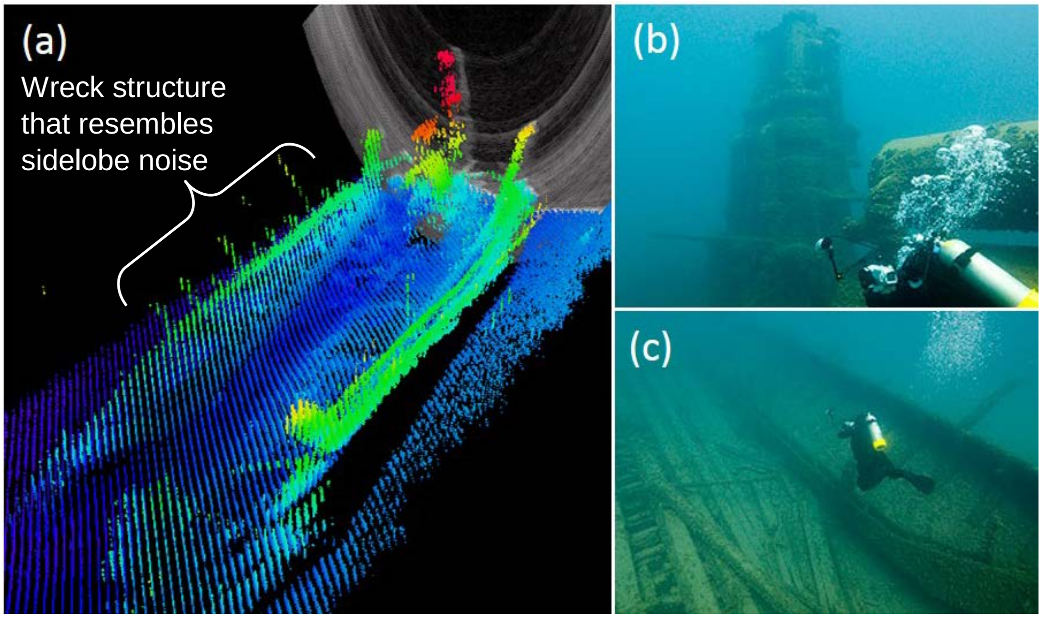


Figure 10a: FMMidwater filtered exported point cloud of *Montana* with water column fan located at timestamp of least depth over engine. Figure 10b: NMS diver image of *Montana* engine (wreck least depth) and boiler (NMS, 2013). Figure 10c: NMS diver image of *Montana* (NMS, 2013). What looks like sidelobe noise in Figure 10a are actually parts of the wreck structure

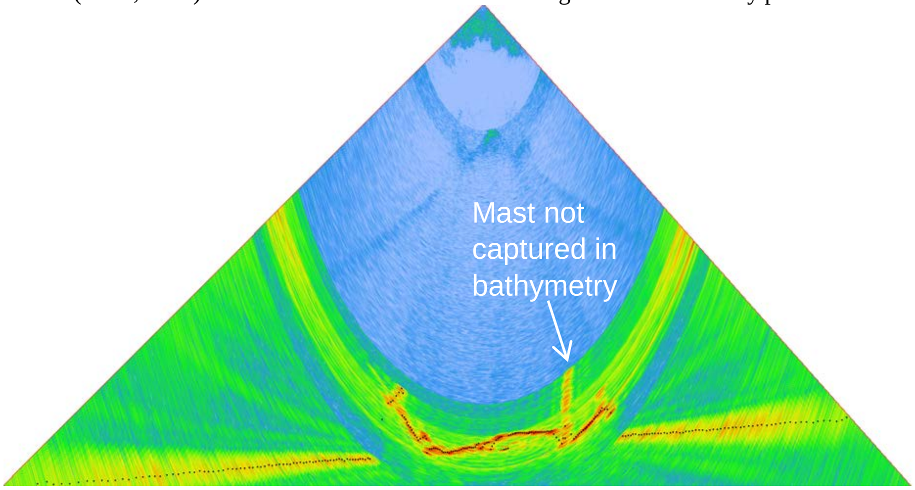
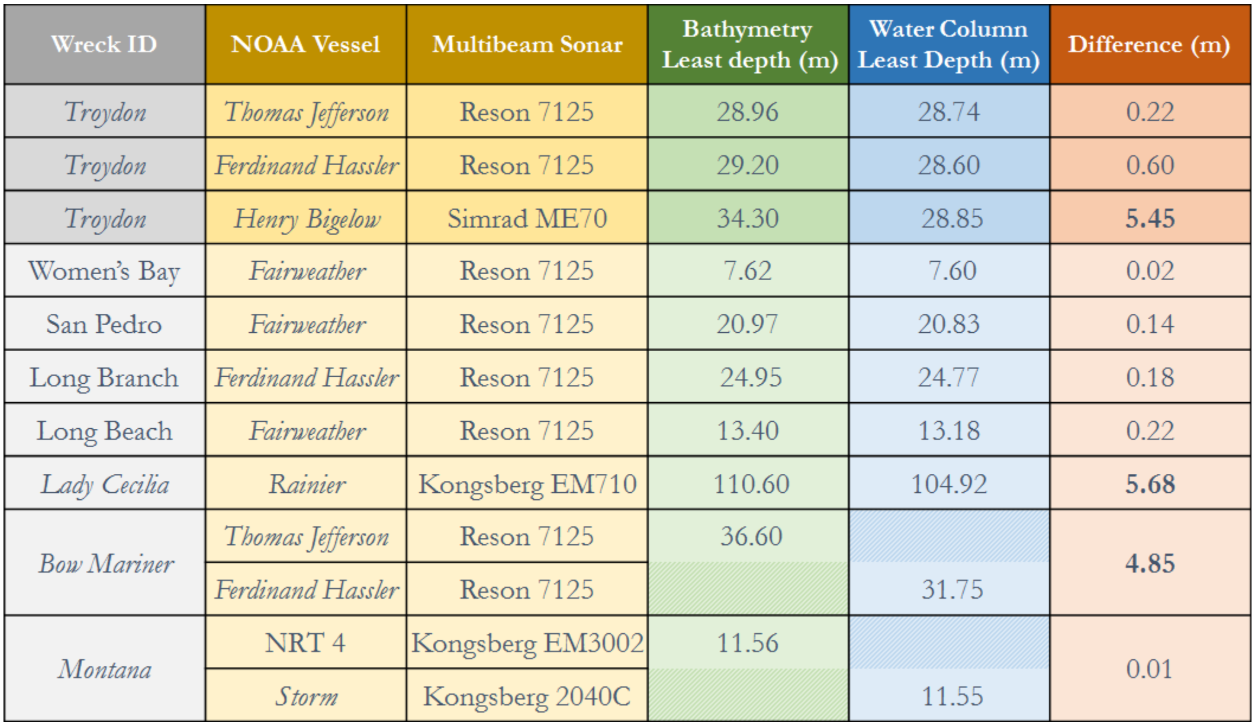


Figure 11: A *Montana* mast not captured in the bottom detection algorithm but visible in the water column fan view. A multiple of the wreck structure can also be seen in the water column.

RESULTS

The comparison between multibeam bathymetry and multibeam water column least depths for the seven NOAA case studies and the three separate datasets of the *Troydon* are summarized in Table 2. The differences between the estimated bathymetry least depth and water column least depth that exceed the allowed IHO Order 1 depth constraints are displayed in bold.



Wreck ID	NOAA Vessel	Multibeam Sonar	Bathymetry Least depth (m)	Water Column Least Depth (m)	Difference (m)
Troydon	*Thomas Jefferson*	Reson 7125	28.96	28.74	0.22
Troydon	*Ferdinand Hassler*	Reson 7125	29.20	28.60	0.60
Troydon	*Henry Bigelow*	Simrad ME70	34.30	28.85	**5.45**
Women's Bay	*Fairweather*	Reson 7125	7.62	7.60	0.02
San Pedro	*Fairweather*	Reson 7125	20.97	20.83	0.14
Long Branch	*Ferdinand Hassler*	Reson 7125	24.95	24.77	0.18
Long Beach	*Fairweather*	Reson 7125	13.40	13.18	0.22
Lady Cecilia	*Rainier*	Kongsberg EM710	110.60	104.92	**5.68**
Bow Mariner	*Thomas Jefferson*	Reson 7125	36.60		**4.85**
	Ferdinand Hassler	Reson 7125		31.75	
Montana	NRT 4	Kongsberg EM3002	11.56		0.01
	Storm	Kongsberg 2040C		11.55	

Table 2: Summary of *Troydon* and seven additional NOAA wreck datasets comparing multibeam bathymetry least depth to multibeam water column least depth. Bold numbers in the Difference column indicate differences that exceed the allowed IHO Order 1a depth uncertainty

DISCUSSION

Every multibeam water column estimated least depth solution is shoaler than the corresponding multibeam bathymetry estimated least depth. The largest bathymetry failures of 5.45m and 5.68m can be explained by a fishery multibeam water column sonar operating in bathymetry mode and a mast that is smaller than the beam footprint and depths of 110m causing the majority of main lobe energy to miss the mast and detect the wreck structure below it. The ME70 water column did successfully locate the least depth of the *Troydon*. The next largest bathymetry failure of 4.85m on the *Bow Mariner*'s mast is the most hydrographically significant because the Reson 7125 multibeam sonar is commonly used in NOAA's hydrographic fleet and the wreck least depth of 31.75m is navigationally significant. This example highlights the failure of multibeam bathymetry over a wreck mast with two NOAA hydrographic vessels, *Thomas Jefferson* and *Ferdinand Hassler*, recording bottom detections almost 5m deeper than the actual mast extent.

Recording the entire water column trace and displaying the filtered and sidelobe-suppressed, exported point cloud together with the time stamped water column fan view provided the context needed to determine that three wrecks; *Troydon* (*Ferdinand Hassler*), Women's Bay, and Long Beach, had bathymetry least depth selections a horizontal 3 to 5 meters distance away from the actual wreck least depth. The multibeam bathymetry bottom detection algorithm performed well when a wreck was on its side with no vertical masts, like the Womens Bay example, or when the vertical mast structure was wider than the beam footprint and detected by the beam main lobe, like the *Montana*'s engine stack. The context provided by multibeam water column is a major benefit to a hydrographer interpreting a wreck and using the methods described, a least depth can be selected from the water column data when the bathymetry fails.

The results in Table 3 are similar to the United Kingdom Hydrographic Office's Civil Hydrography Program (CHP) field study completed in 2010. In their study, seventeen wrecks were surveyed with multibeam bathymetry and multibeam water column and three had significant least depth differences of 1.7m, 2.6m, and 3.6m. Because of this trial, the CHP introduced a requirement in 2012 that all wreck investigations have multibeam water column collected (Parker, 2012). David Parker, the CHP manager, remarked that several hundred wrecks have been investigated with multibeam water column since the new CHP requirement and about 10% of those wrecks have shoaler wreck features evident in multibeam water column that are not detected in the bathymetry solution. He also remarked that what is wreck structure, and hence the least depth result, can be ambiguous and difficult to validate (D. Parker, personal communication, August 15, 2014).

CHALLENGES

Sidelobes

Knowledge of sidelobe behavior in both transmit and receive lobes is important when collecting multibeam water column data. One way a hydrographer can limit the interference of sidelobe noise on a least depth is to record water column data directly over the top of the wreck, within safety constraints (Hughes Clarke, 2006). Even so, if the wreck is located in a transmit sidelobe footprint, there will be a 'ghost' image before and after the actual wreck (Hughes Clarke, 2006 and Van der Werf, 2012). Figure 12 demonstrates the 'ghost' signature as seen in the FMMidwater stacked view of the *Montana*. The actual structure of the wreck is located at the highest amplitude of each 'ghost' arc.

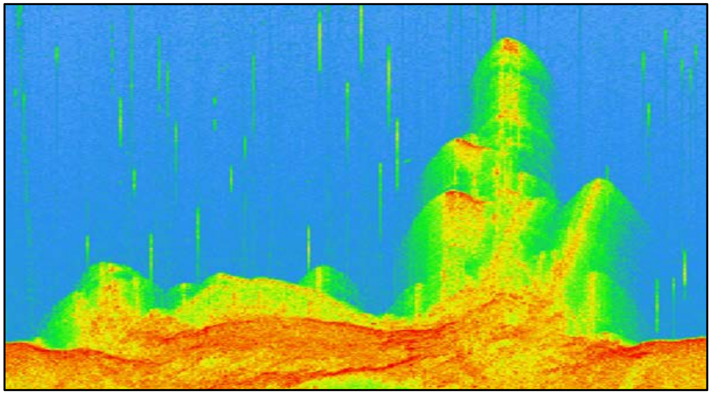


Figure 12: FMMidwater stacked view of *Montana* with transmit sidelobe signature visible

Particularly reflective objects on wrecks detected by all the beams have a sidelobe arc at that range. This is demonstrated in Figure 13a where the Long Beach wreck deck is generating a big sidelobe arc and the bottom detection algorithm is selecting spurious detections on the sidelobe noise. Without the context of the water column data, the bottom detections in the bathymetry point cloud could be mistaken for vertical masts. The result of Dr. Thomas Weber's MATLAB code is a new generic water column file that can be imported back into FMMidwater now with sidelobes suppressed, Figure 13b. The exported point cloud in combination with the water column fan view in Fledermaus helps the user infer if the data has been over-filtered or if the sidelobe suppress value of 20 dB from the maximum value is too severe for a particular dataset.

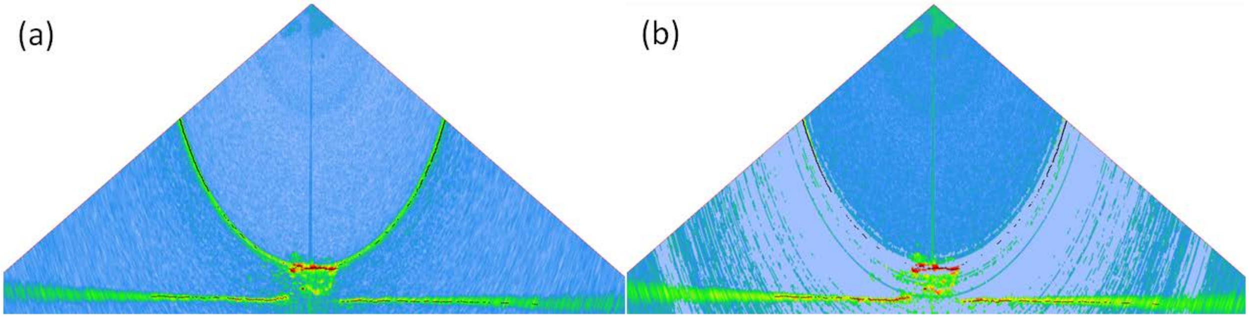


Figure 13a: Receive sidelobe arcs from the deck of the Long Branch wreck with bottom detections displayed as black dots. Figure 13b: Same timestamp as Figure 13a but with the sidelobe-suppressed generic water column file

Ambiguity

The ambiguity of sidelobe noise can be minimized by applying knowledge of sidelobe behavior to suppress sidelobes, but there are additional ambiguities in multibeam water column datasets that cannot be minimized. The ambiguity between wreck structure and fish or other non-wreck things, like crab pots, was highlighted in the datasets of the Long Branch (Figure 6d) wreck and *Lady Cecelia* wreck (Figure 8c), respectively. Especially in relatively flat seabed, wreck structure can provide habitat for various fish species. The amount of fish or the scattering strength of their air bladders can restrict the amount of sound that makes it to the wreck structure. If fish are in line with wreck structure, for example on top of a mast, it can be impossible to differentiate the fish from the wreck without an additional pass at a different time (assuming the fish would move) or a direct measurement of the mast (diver investigation, wire drag, or leadline). This ambiguity is complicated by the variation of wreck construction, from different density woods to steel, all with different target strengths and likelihood that the vessel structure before sinking and the state of wreck structure on the seafloor is unknown.

Acquisition Settings

The challenge of interpreting multibeam water column data is increased if the real time acquisition settings are not optimized for water column data quality. Several of the NOAA hydrographic vessels have developed the practice of turning the Reson 7125 power and gain down during a wreck development to minimize sidelobe contamination in the bottom detection solution without having the context of the water column data. If a wreck is developed with multibeam water column, the power and gain should be tuned until water column scattering and sidelobes are clearly visible.

Data Size

Collecting the entire water column trace of a beam instead of a single detection per beam naturally increases the amount of data that has to be collected, stored, processed, and archived. The multibeam lines for both Kongsberg and Reson sonars that were evaluated in this paper were examined for size of file per length of time. The Reson water column data, record 7018, averages at about 3 gigabytes per minute. None of the Reson datasets were collected using the newly compressed datagram which should decrease that data rate. The Kongsberg 2040C water column data collected over the *Montana* is an order of magnitude smaller than the average Reson water column data rate. And the Kongsberg ME70 and EM710 water column datasets and Reson multibeam bathymetry data are all two orders of magnitude smaller than the Reson water column data.

The collection of water column data in all the examples presented in this paper was done after a wreck had been detected in the bathymetry data and additional data was to be collected over the identified wreck. This *a posteriori* approach limits the amount of additional data that needs to be collected, stored, processed, and archived. A line plan can be oriented directly over the wreck axis using the collected bathymetry data and the appropriate water column acquisition settings can be tuned. The recommendation is not for multibeam water column data to be collected all the time, but for water column data be collected during feature developments of both wrecks and dangers to navigation. As seen in every wreck example presented, the water column estimated least depth is shoaler than the bathymetry estimated least depth, and while the magnitude of that difference is mostly benign and within depth uncertainty constraints, the difference is significant when a vertical structure of several meters is missed. The water column data provides the context needed to see the magnitude of the bathymetry failure and collect a more accurate least depth.

Another way to limit the amount of additional data collected, stored, processed, and archived is the further development of a multiple detection algorithm. The newest Reson 7125 and T20P sonars have a Multi-Detect option that records up to five solutions per beam throughout the water column and includes specular sidelobe suppression (Christoffersen, 2013). Essentially, multiple detection is a heavily filtered version of water column data that does not significantly increase the typical bathymetric data rates. Multiple detections can improve on the bathymetry solution during wreck developments but additional detections per beam, without a full water column fan to provide context, can also introduce ambiguity with detections likely on wreck structure, sidelobes, and fish. The question then is asked, how many detections is enough to ensure a least depth on a mast is selected by a hydrographer; is the Multi-Detect answer of five enough? The safest answer to that question is, for now, to record the entire water column trace. Multi-Detect could be developed further by tracking the number of detections per beam and at a certain threshold, the full water column trace could be recorded until the multiple detections decrease again. Additional water column data may still need to be collected over the wreck depending on the orientation of wreck and acquisition settings, but the chance of missing a feature altogether is reduced.

CONCLUSION

This paper explored the value of collecting multibeam water column data to estimate wreck least depths in the context of providing mariners nautical chart products with the most accurate information obtainable to navigate safely. The estimated least depths from multibeam bathymetry and multibeam water column data over eight different wrecks collected by NOAA vessels were compared. The water column least depth method used to determine the estimated least depth of the *Troydon* wreck was presented in both FMMidwater and CARIS HIPS software. Like previous international studies have found, the multibeam bathymetry bottom detection algorithm in both Kongsberg and Reson multibeam sonars failed to detect some wreck masts. This study demonstrated that present NOAA wreck development practices have the same shortcomings that were identified in other studies. The majority of the multibeam bathymetry wreck least depths were within allowed depth uncertainties of the multibeam water column estimated least depths, but every water column estimated least depth was shoaler. The significant failure of multibeam bathymetry occurred on vertical masts (high aspect ratio features) and the magnitude of those failures were several meters.

Water column is an additional contextual tool to not only locate wreck superstructure like vertical masts, but existing software packages allow for the water column least depth and position to be incorporated into the final survey product. The main workflow presented in this paper used FMMidwater because of the following capabilities: the ability to down sample Reson data, the ability to import sidelobe suppressed generic water column files, visualizing the power vs range plot of an individual beam, the ability to export a temporal fan view used to provide context to the exported water column point cloud, and multiple filtering options. What FMMidwater does not have that CARIS HIPS does have is the ability to apply a sound speed profile, vessel offsets and waterline values to Reson point cloud data and the ability to manually select data points to include or reject from the water column point cloud. CARIS HIPS is currently the software NOAA hydrographers use to process bathymetry data and the Additional Bathymetry Layer, where selected water column point data is stored, easily integrates into the gridded surface deliverable. When using FMMidwater, the exported filtered water column point cloud or geo-picked points can be generically imported into CARIS and then integrated into the gridded surface deliverable.

The water column workflows on their own are not complete but pieces of the workflow exist, and will hopefully be realized soon by both software vendors. In light of this, wreck developments should be done using multibeam water column data as a contextual tool. The sonar acquisition settings of wreck developments are important and a hydrographer should ensure quality water column data is recorded. If multibeam bathymetry fails to capture the wreck least depth by a magnitude greater than the allowed depth uncertainty, the method described in this paper could be used to estimate a least depth and incorporate that depth into the final deliverable. The NOAA hydrographic vessels have shown they can collect multibeam water column data over wrecks. This paper used existing commercial software to analyze and process wreck water column data and found the contextual benefit invaluable as compared to a bathymetry point cloud. Multibeam water column data collection and processing over wrecks is the best method available to support NOAA’s mission to provide accurate navigation products that ensure mariner safety.

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APPENDIX A

NOAA Divers Sam Greenaway and John Kidd dove on *Troydon* October 30, 2014 and Sam Greenaway processed the pressure gauge data combined with a CTD cast to provide an estimated least depth of the forward and middle masts. The following procedure was followed:

1. A Rugged TROLL 100 barometer, serial number 349000, was held by Sam Greenaway 5min before, during, and after the dive. The divers investigated the forward mast first. To indicate where in the record the least depth measurement took place, the diver raised and lowered the barometer before each measurement. The forward mast had a least depth investigation recorded from 12:52:42PM to 12:53:31PM and the middle mast had a least depth investigation from 12:54:33PM to 12:55:16PM. The barometer recorded elapsed time and for each second recorded the pressure (mb) and temperature (C).
2. A Sea-Bird SBE19 CTD cast was taken at the dive site so the density and pressure values could be used to calculate depth values. The formula used to calculate depth (h) is P= r*g*h where P is pressure, r is the density of water, g is gravity acceleration, and h is the height of the fluid above the instrument (depth).
3. The final tide data from Newport, RI tide station 8452660 was downloaded and corrected using NA629 Zone (-6 minutes, 0.86 range). The same tide station and zone correction applied to the dive data was applied to the *Thomas Jefferson* and *Ferdinand Hassler* bathymetry data. The water level correction from MLLW to the surface for both mast timestamps was 1.09m.
4. The depth values calculated from the CTD data in step 2 were calculated by integrating the pressure values following the principle of hydrostatics. This provided a pressure to depth look up table. The pressure recorded by the diver's barometer over the time of each mast investigation was averaged. The forward mast had a recorded pressure of 2909.08mb and the middle mast of 2999.38mb.

   Because P (total) =P (fluid) +P (atmosphere), it is necessary to subtract the pressure of the atmosphere from the diver barometer reading to get the P (fluid). For both masts, the P (atmosphere) recorded 5 minutes before the dive and 5 minutes after the dive was -7.07mb. The corrected pressure for each mast was then located in the pressure vs depth table to find the depth of the mast. Then the MLLW correction of 1.09m was subtracted for the final diver least depth measurement of each mast; 28.75m for the forward mast and 28.85m for the middle mast pinnacle.