Evaluating Outside Source Interferometric Data for Chart Updates

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ABSTRACT

Incorporation of "outside source" bathymetric data is advantageous to maintaining accurate and current NOAA nautical charts. Whether from governmental, academic, or commercial sources, many surveys are conducted annually around the country for purposes other than hydrography. While many of these surveys adhere only to some degree to the NOAA and International Hydrographic Office requirements, when properly vetted they provide useful information for survey reconnaissance and chart updates. Most outside source data comes from beam-forming sonars similar to those used by NOAA. However, a small portion comes from interferometric (non beam-forming, phase measuring) systems, which until recently NOAA did not accept for internal or contract survey work. This exclusion results from the volume of data and noisy nature of first generation systems, whose data proved difficult for NOAA's standard processing methods and software to accommodate. Here we investigate a USGS survey within Buzzards Bay, MA, collected with a first generation SEA SwathPlus interferometric sonar. Methods are shown for assessing the data for hydrographic purposes. In addition, methods are proposed for assessing survey uncertainty allowing the data to be used for charting. Guidelines are given for collection and processing of data that may aid in their future use for hydrography.

INTRODUCTION

Outside Source Data

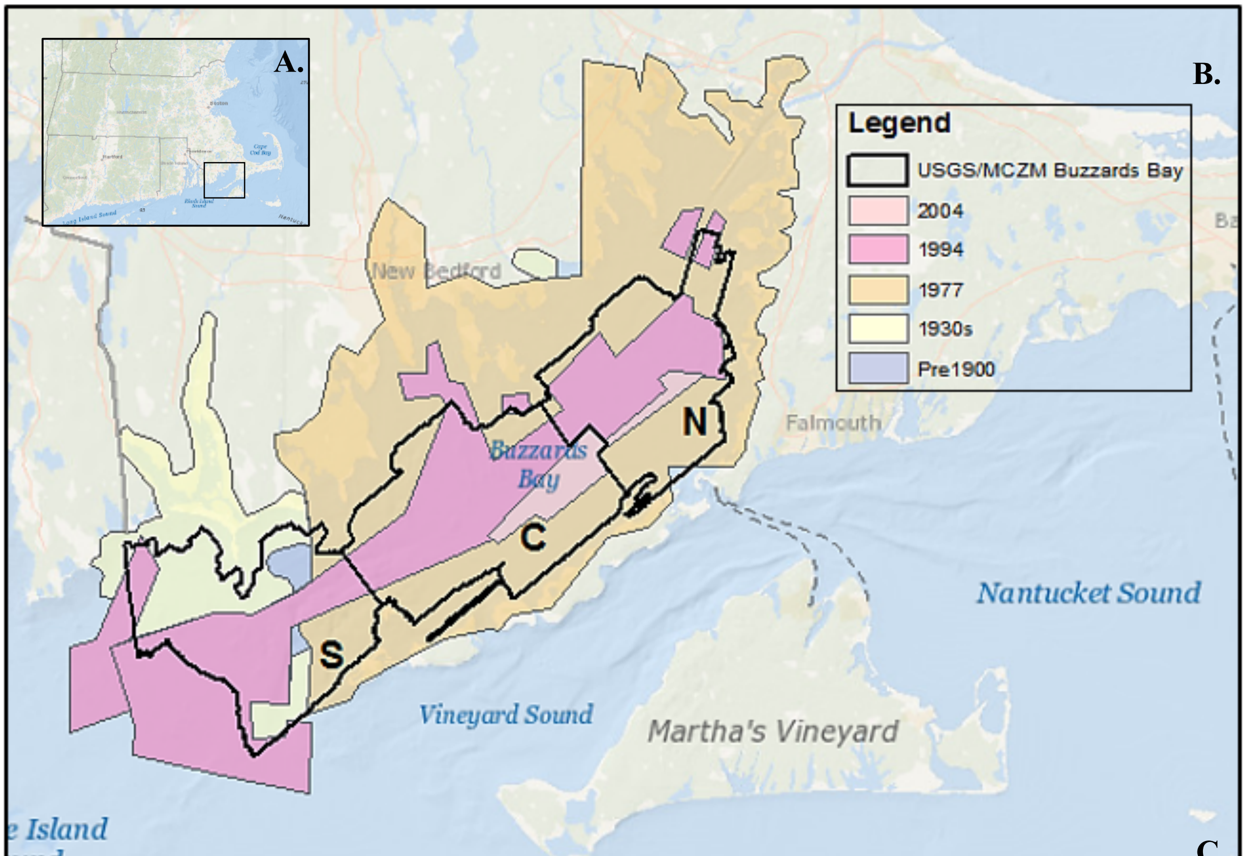
In recent years, government sectors have increased efforts at interagency collaboration and coordination. NOAA's Integrated Ocean and Coastal Mapping (IOCM) group works to achieve this goal through coordination of mapping efforts and identification and analysis of outside source data (data not collected by NOAA) for use in nautical charting. The acceptance of outside source data has allowed for increased frequency of chart updates and overall bathymetric coverage of the United States coastal regions.

Through this effort, a United States Geologic Survey (USGS) dataset was identified in a high-priority survey area for NOAA and found to have been collected more recently than currently charted data. The application of this bathymetric data set would eliminate the need for NOAA to resurvey these areas in their entirety. The cost associated with NOAA completely resurveying these areas far outweighs the cost of a thorough analysis.

The USGS/MCZM data

The USGS, in collaboration with the Massachusetts Office of Coastal Zone Management (MCZM) collected geophysical data over a large portion of southern Massachusetts' waters including Buzzards Bay and Martha's Vineyard from 2009-2011. The USGS and MCZM survey priorities focus on seafloor characterization for sediment and subsurface geologic mapping [1], by collecting seismic profiles, backscatter, sediment samples, imagery, and bathymetry [2]. Here we focus on their bathymetric and sidescan data collected in Buzzards Bay, Massachusetts (Figure 1).

Data procured from the USGS/MCZM Buzzards Bay surveys were collected with a pole-mounted first-generation interferometric SEA SwathPlus sonar for bathymetry with concurrent sidescan, and a towed Klein 3000 for supplementary sidescan [2]. The survey was RTK navigated, with ellipsoidal referencing to a single average tidal offset applied to approximate Mean Lower Low Water (MLLW) over the entire survey area [2]. While the surveys were professionally conducted, bathymetric data was not generally the highest priority and were not collected with NOAA or IHO specifications in mind.



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Source Data	South (m²)	%	Central (m²)	%	North (m²)	%
Pre 1900 SOURCE DATA	7,298,055	5.6	0	0	0	0
1930s SOURCE DATA	44,542,070	34.2	0	0	0	0
1970s SOURCE DATA	24,981,198	19.2	66,529,688	49.5	63,594,599	51
1990s SOURCE DATA	53,424,760	41	68,000,530	50.5	53,305,786	43
2004 SOURCE DATA	0	0	0	0	6,844,618	6
TOTAL	130,322,416	100	134,530,218	100	124,539,410	100

Figure 1: **A.** This images shows the location of Buzzards Bay, Ma. **B.** The coverage outline of the USGS Buzzards Bay, MA data is shown in black separated by the north region (N), central region (C), and south region (S). This outline is placed over the NOAA charted source data colored according to collection year. NOAA source data can be found on the National Centers for Environmental Information (NCEI) and the United States Interagency Elevation Inventory (USIEI). **C.** This table explains the breakdown of the charted source data for the area of each USGS/MCZM region and the corresponding percentage it makes up.

The processing path used by USGS was to acquire and create "sxr" and "sxp" files containing raw measurements and processed x,y,z soundings, respectively. The "sxp" files are generated during acquisition, after filtering, application of patch test calibration parameters and correction for refraction, all conducted by the acquisition software in real-time. In post processing the "sxp" files were then ingested into CARIS™ HIPS and SIPS (hereafter CARIS) where tidal corrections were applied and surfaces were created. It is important to note that because "sxp" files do not contain launch angles and travel times, any subsequent patch test or refraction correction is impossible within post-processing tools such as CARIS. These corrections must be made by "replaying" the data through the acquisition software and re-ingesting the data into CARIS.

The data package sent by the USGS included the raw "sxr" files, CARIS projects from the processed "sxp" files, and raw Klein sidescan .XTFs. Detailed daily survey logs with records of ship speed, navigation failures, and sidescan feature identifications were kept and included in the data received. CARIS projects were separated regionally – north, central, and south Buzzards Bay.

Buzzards Bay, Ma

Buzzards Bay, Massachusetts is located to the west of Cape Cod and north of Martha's Vineyard (Figure 1A). This area was identified by NOAA as a priority survey area for the 2015 field season due to the lack of recent source data. Currently charted source data for the Buzzards Bay is shown in Figure 1B-C. Over 53% of the charted data was conducted in surveys prior to 1978, and nearly 6% predates 1900.

PROCESSING

Initial CUBE Surfaces (HVF: "Unknown" Sonar)

The USGS/MCZM CARIS projects included all imported .sxp files with their associated HIPS Vessel Files (HVF) and offsets already applied, but no surfaces suitable for evaluation purposes. To generate CUBE surfaces one must first calculate Total Propagated Uncertainty (TPU), which combines estimates of uncertainty in positioning with a model (when available) of sonar measurement uncertainty to estimate the total uncertainty in each sounding. When TPU is properly calculated, the resulting CUBE surface provides uncertainty estimates for the surface and multiple depth hypotheses are generated where measurements are not statistically consistent. However, proper calculation of TPU is not straight forward for PMBS systems within CARIS and the potential for confusion warrants comment.

The TPU calculation involves a root-mean-square sum of depth uncertainty due to many components involved in determining each fully corrected sounding. These include vessel navigation, attitude, sonar lever-arms, vessel draft and the sonar's depth measurement itself. When the sonar does not provide real-time uncertainty of its measurements, a model (when available) is used to estimate that uncertainty. Parameters to the sonar uncertainty model are provided by a table indexed by the user's sonar type selection in the CARIS vessel configuration file. What is not immediately clear is that the TPU model implemented as part of the CUBE algorithm is only applicable to multibeam echosounders.

Confusingly, in the CARIS vessel configuration file's list of possible sonars, there is a SEA SwathPlus option, which is what was previously selected by USGS in the provided project. By selecting SEA SwathPlus, TPU will be calculated with meaningless inputs to an inappropriate multibeam algorithm and will produce an incorrect "Uncertainty" layer upon surface creation. To prevent confusion and produce a more meaningful surface one may instead choose "Unknown" as the sonar type in the vessel file to omit sounder uncertainty from the TPU calculation altogether. Although no sounder uncertainty will be included in the TPU calculation, CUBE will still produce reasonable surfaces in most instances. Note however that the "Uncertainty" layer produced by CUBE will also not include the sounder uncertainty component and cannot be used to meaningfully assess the quality of the data.

Filtering

Unlike beam-formed systems whose bottom detection is confined to one of many individual beams, interferometric sonars measure the angle to each return in a single wide beam to either side. Therefore measurements are typically filtered spatially during acquisition to remove outliers generated from water column targets, the surface and low-amplitude measurements. The filtering is primarily achieved by a collection of static, slant range, along-track, across-track and depth windows, combined with dynamic along-track and across-track filters.

The filter settings for the USGS/MCZM Buzzards Bay data typically included several filters: low amplitude (100%), range (0-4m), box (3-50m depth, 1.5-75m horizontal), median (window size 5), along-track 1 (depth difference of 5-m, window size 5-m, and learn rate of 0.7), along-track 2 (depth difference of 1.5-m, window size 1m, and learn rate of 0.9), and mean filters (0.25m) [2].

The phase-difference measurement process from which soundings are generated is a noisy one by nature. When individual soundings are generated from individual measurements with no binning and averaging to mitigate noise, as is the case with the SwathPlus, the resulting soundings can be noisier than systems commonly used for hydrographic purposes. In addition, the data was collected with swath widths approaching 10 times the nadir water depth, resulting in a vertical distribution of soundings on a flat seafloor spanning more than a meter (Figure 2A). This level of noise was deemed unable to meet IHO uncertainty specifications for Order 1a surveys and generally unsuitable for object quantification. A CARIS "across-track" filter of 1.7 times water depth was applied to limit the data to that whose stochastic uncertainty would likely meet IHO requirements. The application of this filter removes soundings that fall outside of 1.7 times water depth on either side of nadir to have a total swath of 3.4 times water depth – similar to that of a typical multibeam. Note that, unlike an angular filter, the across-track filter preserves all soundings within the specified across-track distance. This method prevents objects near the outer edge of the acceptable swath from being truncated and erroneously biasing the resulting data deep at the outer edge of the swath.

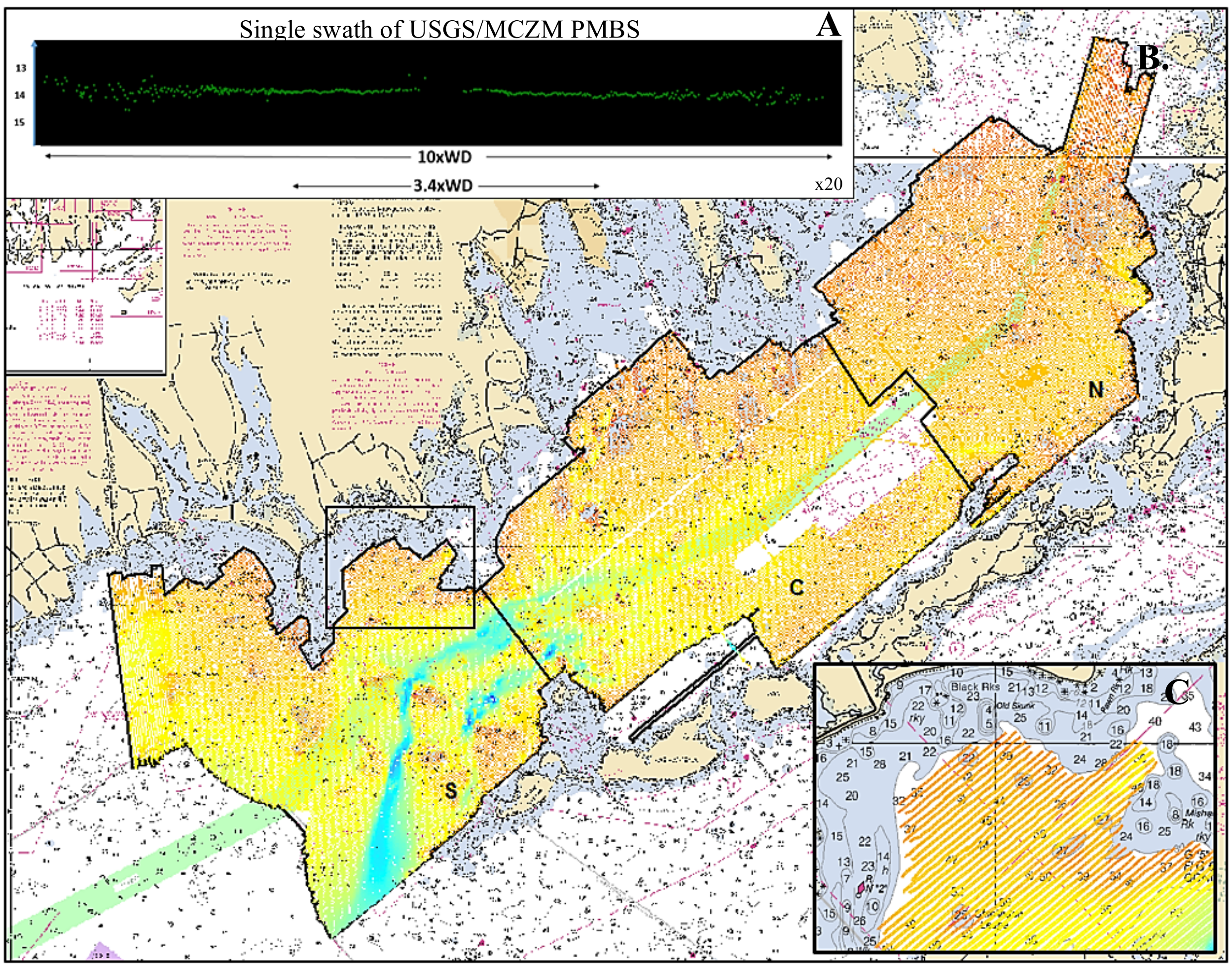

Figure 2: **A.** Shown is a single full swath of data at 20x vertical exaggeration and a depth of 14m. While there is data up to 10x water depth, only the data up to 3.4x water depth was kept as it had less noise and less uncertainty. **B.** Shown is the trimmed USGS/MCZM data with across-track filter applied. **C.** A close-up of the black box indicated in Southern region on the trimmed

surfaces is shown to highlight the data gaps between each swath. The large space in the middle of the central region is due to the 2004 NOAA Ship *Rude* survey and was not resurveyed by the USGS/MCZM surveys.

The application of the across-track filter trimmed the swath width to ~100m in most areas and created surfaces similar to those of a single beam skunk-stripe survey with ~50m data gaps between each line (Figure 2C). Any mentioned of trimmed surfaces from here forward refers to these surfaces.

NOAA's 2015 Hydrographic Survey Specifications and Deliverables document states that "complete coverage" can be met with 100% sidescan and concurrent single beam or multibeam as well as feature developments when necessary [3]. As the Buzzards Bay surveys were not acquired with these specifications in mind, any identified features were not developed for accurate least depths. Thus, to be considered a complete-coverage survey, additional developments would be required.

NOAA Validation Effort

Prior to the NOAA Ship *Thomas Jefferson*'s 2015 field season, an initial analysis was performed of the Buzzards Bay data. This analysis included trimming the data as described above, identifying significant features from both the bathymetric surfaces and the sidescan waterfall, as well as identifying areas of shoaling or significant holidays in the data. The results and recommendations of this analysis were presented to NOAA project managers and included in the final project instructions for the *Thomas Jefferson*'s 2015 survey effort.

Plans were made to investigate several features identified in the USGS/MCZM data set, including 5 uncharted wrecks and 17 potential DTONs (dangers to navigation). In collecting data over these identified features with a hydrographic survey launch and in accordance to their specifications, updating the chart with these data is guaranteed regardless of the outcome of the overall data evaluation. In addition to feature investigations, 54 nautical miles of crosslines were strategically placed through the USGS/MCZM Buzzards Bay data. These crosslines were designed to cover both deep and shallow areas of the bay as well as cross through the 2009 and 2010 surveys to determine the agreement between the two years of acquisition.

RESULTS

Sidescan Analysis

An evaluation of the raw KLEIN sidescan data was performed and was found to meet NOAA's object detection requirement having a ping rate and survey speed sufficient to ensonify a 1m target 3 times. Contacts were identified during this analysis in accordance to NOAA contact specifications and included all features with a shadow height of 1m or greater in areas shoaler than 20m. The preliminary results indicated well over 9,000 contacts (boulders deposited during the last glaciation are common in this area) and provide suitable evidence for updating "rocky" designations on the chart.

Crossline Comparison

Crosslines measured by NOAA launches in the summer of 2015 were used to further evaluate the USGS/MCZM data set. To accurately compare the two datasets, the mean tidal correction used by USGS was replaced with the NOAA TCARI tidal model. CUBE surfaces were generated for both the crosslines and Buzzards Bay surveys and differenced against each other in CARIS. The average difference between the north, central, and southern region and the NOAA crosslines were 41cm, 42cm, and 54cm respectively. The distribution curves for each difference surface highlighted the presence of uncorrected biases in the USGS/MCZM data in addition to other stochastic errors (Figure 3).

The difference surface and the distribution curve for the north region revealed an uncorrected 30cm bias between data collected by USGS/MCZM in 2009 and 2010 surveys. This offset was evident in a bimodal difference distribution curve.

In addition, the difference surface in the southern region revealed an uncorrected roll bias whose effect becomes evident in waters deeper than 15m. Based on depth differences between NOAA crossline and USGS/MCZM starboard side data, an approximately 0.7 degree roll bias is estimated and the effect constitutes nearly half of the observed differences. Detection of this roll bias by USGS with normal patch test procedures was likely complicated by an inadequate internal calibration of the SwathPlus system that masked the effect. Crosslines run by NOAA made clear a near 1m bias in the outer portions of overlapping starboard survey swaths (Figure 3) in these deeper water depths.

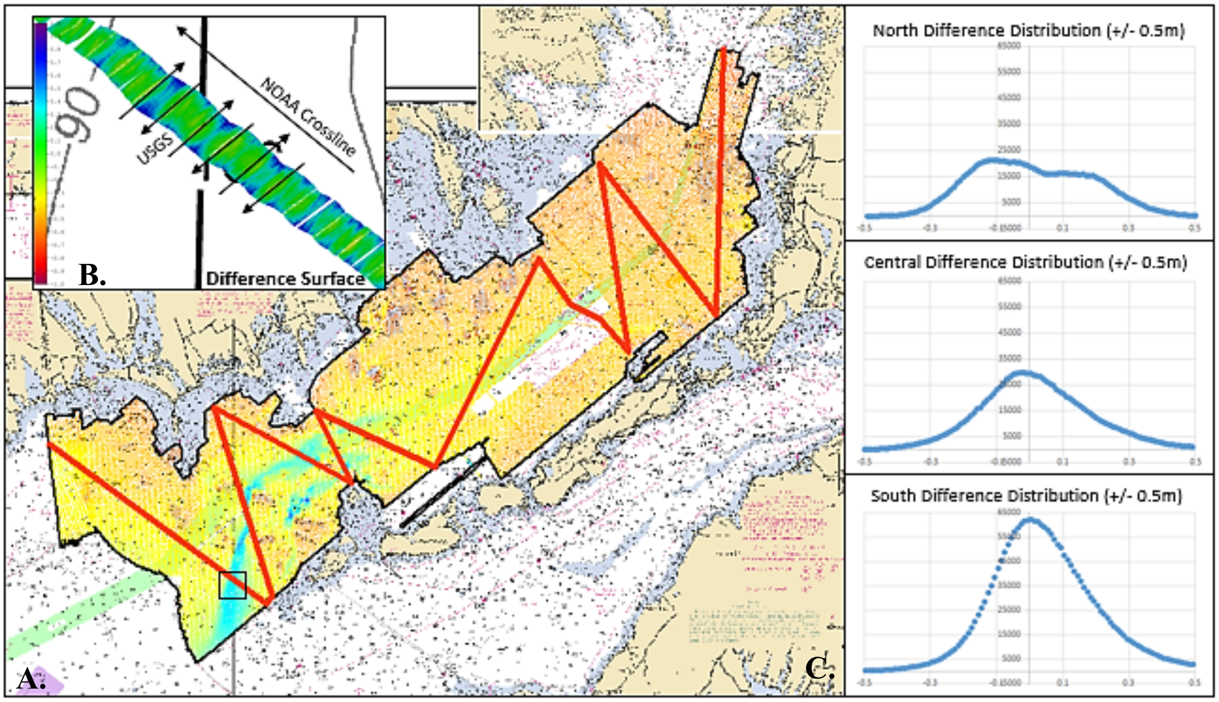

Figure 3: A. The main image shows the 1m CUBE trimmed USGS/MCZM surfaces with the NOAA crosslines in red. **B.** A portion of the southern difference surface, the location is indicated on the main surface by the black box. The difference surface has a color bar ranging from 1m to -1m (purple to dark red); green indicating near 0m differences and the dark blue indicating ~0.8m difference between the NOAA crossline and the USGS/MCZM data. **C.** The graphs on the right are the distribution curves for the differences surfaces of each region. Each graph shows the number of soundings (0-65,000) per average difference value (+/- 0.5m) between the USGS/MCZM Buzzards Bay data and the NOAA crossline surfaces.

Unfortunately, the roll bias error could not be resolved in CARIS. Because data was ingested as x,y,z triplets in the form of “sxp” files without raw receive angles, CARIS could not appropriately apply the necessary correction (which would also require a subsequent refraction correction). A proper correction would require “replaying” the raw “sxr” files through the SwathPlus acquisition software to regenerate the “sxp” files; a process that was deemed too arduous to be practical.

No other survey wide systemic biases were identified in the comparison; however mean differences between the NOAA crosslines and USGS/MCZM data sets exceed 0.3 m. The majority of the remaining differences are thought to be attributed to general seafloor change over the six year difference in acquisition.

Uncertainty Calculation

As discussed previously, specifying “*unknown*” as the sonar model in CARIS results in an incomplete computation of the uncertainty layer that is generated upon CUBE surface creation. Instead, the standard deviation layer of each surface was used to empirically estimate the uncertainty of these data. Empirical estimates of this type can then be added to other sources of error that are not generally captured in the estimate such as that from draft, heave and tides. In addition, uncorrectable biases require a more comprehensive uncertainty calculation to include them.

To conservatively estimate the uncertainty in the SwathPlus data the standard deviation of measurements in each 1m grid cell was combined with other non-stochastic uncertainty sources (tide, heave and draft) and a separate component to accommodate the residual roll bias in a root-mean-square sum (Equation 1) [4]. Note that a roll bias is not, strictly speaking a stochastic error, however uncorrected biases may be accounted for in this way in total uncertainty calculations [5]. Although the depth error due to a fixed roll bias increases with across-track distance, calculation of this error was conservatively estimated with a fixed value calculated at a 60 degree angle from nadir. The roll bias itself was estimated to be 0.7^{o} due to the ~1m depth difference on the starboard side (seen in Figure 3B).

EQUATION 1:

$$\sigma_{Sonar} = Standard\ Deviation$$

$$\sigma_{Tide} = TCARI\ error\ estimate = 0.15$$

$$\sigma_{Heave} = 0.05$$

$$\sigma_{Draft} = 0.05$$

$$\sigma_{Roll} = \frac{0.7}{180}\pi$$

$$\sigma_{Depth} = Depth \times \tan(60^{o}) \times \sigma_{Roll}$$

$$\sigma_{estimated} = \sqrt{{\sigma_{Sonar}}^2 + {\sigma_{Tide}}^2 + {\sigma_{Heave}}^2 + {\sigma_{Draft}}^2 + {\sigma_{Depth}}^2}$$

Equation 1: The equation used to estimate the uncertainty of the USGS/MCZM Buzzards Bay data. The uncertainty for the sonar is the CARIS generated CUBE surface standard deviation layer, the uncertainty for tides is 0.15 –worst-case scenario from the estimated error of the TCARI tidal model for all of Buzzards Bay, the uncertainty for heave and draft are estimated to be 0.05 each, and the estimated uncertainty for depth is dependent on both the roll bias and depth of the sounding.

The IHO, order 1a, 2σ total vertical uncertainty (TVU) requirement is 0.5m plus a small depth dependent component in areas shoaler than 100m. The 2σ average uncertainty calculated for the northern region is 0.6m, 0.7m for the central region, and 0.9m for the southern region. The USGS/MCZM Buzzards Bay data did not meet IHO order 1a based on these conservative uncertainty calculations that include the uncorrectable roll bias.

DISCUSSION

Trimmed Surfaces

The across-track CARIS filter applied to the USGS/MCZM Buzzards Bay data results in an approximately 50m gap between each line. While the removal of the outer swath of each line was justified, it is possible that DTONs large enough to be seen in spite of the poorer data quality were removed. However, the 100% sidescan coverage from both the SEA SwathPlus interferometric system and the Klein 3000 allows for identification of these objects and, in line with current NOAA practices, would require further investigation should they be of a large enough size. The outer edges of the swath did not prove sufficiently reliable for least depth identifications and would warrant further investigation of any identified objects regardless.

Nonetheless, the creation of the full-swath surfaces (i.e. without the reduced swath) were beneficial for object detection during surface evaluation. Complete bathymetric coverage helped achieve a more comprehensive understanding of the geologic processes in the bay, providing context for identification of potential navigation hazards. It is recommended that full-swath surfaces be used to only guide identification of objects and to rely on sidescan and additional bathymetric development for depth measurement.

NOAA's Crossline Validation Effort

NOAA's validation effort was useful in that it revealed biases in the USGS/MCZM data that were not otherwise evident. The analysis also highlighted an approximately 40cm difference in each of the three regions between the shoaler NOAA crosslines and the USGS/MCZM data. However, the differences between the two were not uniform throughout each surface, which might have been indicative of a remaining correctable static bias. Instead the differences are variable, sometimes clearly resulting from navigation errors on small objects or slopes, sometimes due to regional changes in seafloor morphology, and sometimes the cause of the differences are not clear. It is possible that a portion of the ~40cm difference can be attributed to sedimentation in the bay over the 5-6 year duration between the surveys and validation effort.

Uncertainty

The conservative uncertainty calculations predict that the USGS/MCZM Buzzards Bay data exceeded the IHO TVU requirements for order 1a by at least 15cm. Increased uncertainty was primarily due to the inclusion of the uncorrectable roll bias. Had the roll bias been correctable, 98% of the trimmed data would meet IHO order 1a – well within the requirements.

The uncertainty calculation remains an estimation. The stochastic uncertainty estimated from raw soundings cannot capture unaccounted for biases in the system's setup. When possible crosslines can aid in determining these biases, both when run by operators and when performed by an independent survey near the time of the original data collection effort. Unknown biases are very difficult to estimate, as in this case, by crosslines run 5-6 years later.

In addition, uncertainty can be particularly difficult to estimate from interferometric bathy systems when real-time sounding uncertainty estimates are not provided by the sonar itself. Empirical estimates of sounder uncertainty can be biased by over-aggressive filtering of outliers.

The effect is shown in Figure 4, in which the uncertainty in the outer portion of the swath is markedly lower during several days of survey. The change in uncertainty does not correspond to changes in water depth or backscatter level or any recorded change in sonar operation. Although no indication of a change to sonar settings is made in the logs, there is evidence that the outlier rejection filters were adjusted. When these filters are set too conservatively, the tails of the seafloor measurement distribution are clipped, and while it is likely that the seafloor falls within the retained data window on average, the standard deviation of that data is artificially reduced in the outer swath. Uncertainty empirically estimated from this data will be biased low.

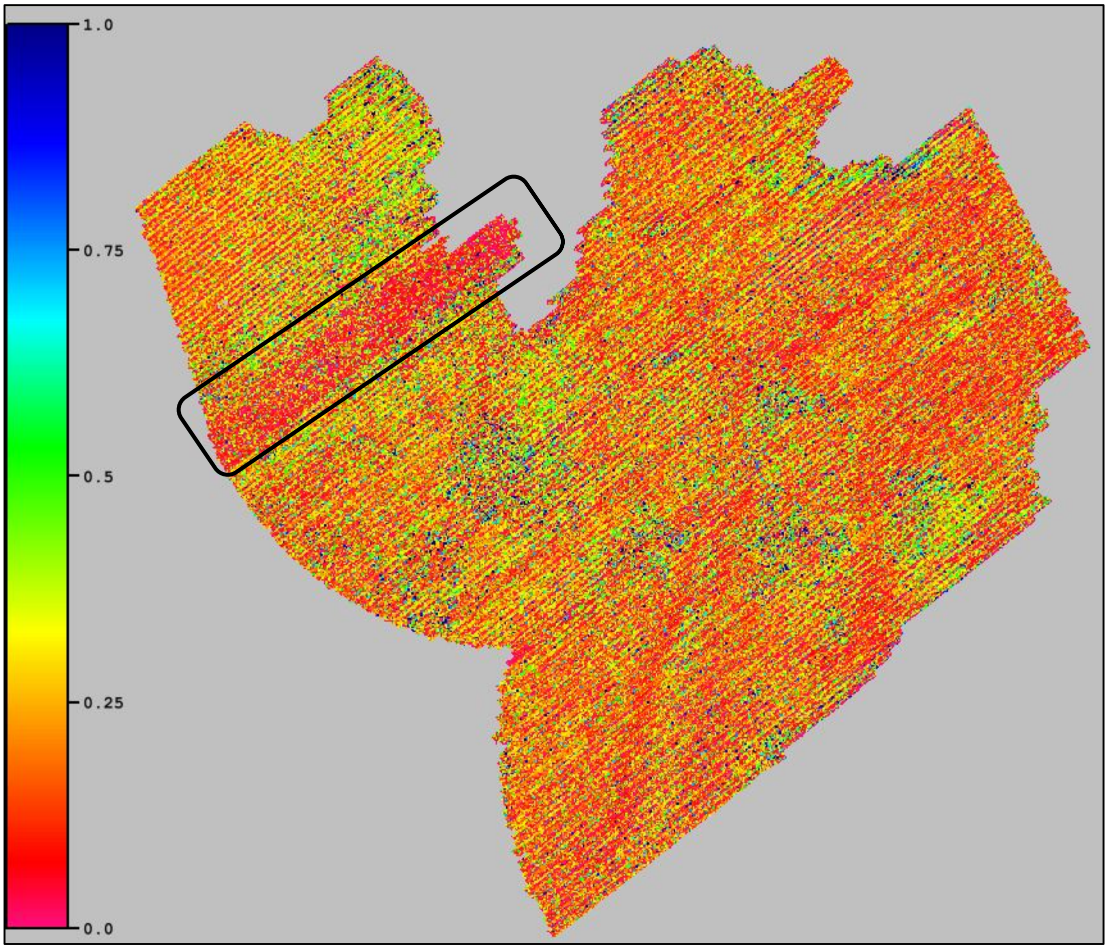

Figure 4: The southern region's standard deviation layer scaled to a range. The black box highlights an area where the standard deviation is markedly lower than the surrounding survey lines, unexplained by bathymetry, backscatter or logged changes in sonar operation. The effect is likely a result of a change in acquisitional filtering parameters. The density and uncertainty of this section is similarly altered as a result.

Chartability

The analyses performed on the survey were conducted to determine its ability to meet NOAA and IHO's strict requirements. Had the identified post-processing errors previously discussed been correctable, the data could have met NOAA requirements for "complete coverage" with a trimmed swath (i.e. the requirements for single-beam and concurrent sidescan). Unfortunately, the data could not be corrected without heroic effort and the question still remains are these data able to update the chart?

The current practice for NOAA branch offices is to grade incoming hydrographic surveys using a modified version of the S-57 "Categorical Zone of Confidence" attribute or CATZOC (Table 1). Surveys are assigned a "ZOC" level according to the following categories: the quality of navigation used in the survey, the accuracy of the acquired data, completeness of bathymetric data coverage in an area, the likelihood that significant objects were detected and the quality of the sounding system. NOAA appends an additional column to the standard CATZOC categories, to more closely align the ZOC levels with the coverage requirements ("object detection," "complete coverage," etc.) provided to their own survey teams and contractors. The additional column provides guidance regarding sidescan coverage for object detection, source data type and age of surveys. A survey is ultimately assigned the highest ZOC level in which all requirements are met.

Using Table 1, it is possible for one to estimate how NOAA's branch offices might evaluate the USGS/MCZM data set. Positional accuracy of the data is high enough to meet all ZOC levels. Vertical uncertainty of the data, including the roll bias error, is likely sufficient to meet ZOC Level A2. At this level the final 2σ uncertainty is 1m plus 2 percent of the water depth and while uncertainty in this table refers to both contributions from the data itself and that which results from the chart production process, additional significant uncertainty is not expected. Regarding the “seafloor coverage” requirement, the sidescan data meets the object detection acquisition requirements specified by NOAA’s definition of “complete coverage”, including a ping rate and survey speed sufficient to obtain 3 pings on a 1m square cube. When combined with the analysis for uncharted features and subsequent resurvey for depth measurement by NOAA hydrographic launches, all seafloor coverage requirements for ZOC Level A2 are met. Finally, “NOAA’s CATZOC Description” provides additional guidance regarding classification. “Interferometric surveys without beamforming developments” are specified at Level B. As all requirements of a given level must be met for classification purposes, the survey would fall in ZOC Level B, limited by complete beamforming developments. However, the subsequent survey of all charted and uncharted hydrographic features by NOAA launches would provide those developments and result in fulfillment of all higher Level A2 requirements of consistent 100% sidescan coverage.

Although not formally classified as such, given the age of the existing data and technologies used, much of the existing chart would likely be classified as CATZOC Level A1 or A2 (for MBES surveys conducted in 2004), Level B (for single beam + sidescan surveys in the 1990’s) and Level C (for single beam and lead-line surveys predating 1970). Therefore, significant improvement to the chart can be made, if only to newly determined features and areas of lower CATZOC level, with confidence that the USGS/MCZM data set is likely a better representation of the seafloor, in spite of not having met IHO uncertainty requirements.

Standard protocol for bathymetric survey assessments call for comparison of the survey with current charted soundings to establish the overall consistency of the survey with the chart, and to identify localized areas of significant difference that require chart updates. In direct sounding to sounding comparisons with the current nautical charts covering Buzzards Bay, the data were found to be quite comparable overall with differences commensurate of the crossline evaluation. However, some areas had more drastic differences stemming from shoal movement. Rocky areas also showed differences resulting from errors in source data navigation rather than changes in the seafloor. These results are similar to those of typical bathymetric surveys.

ZOC[1]	Position Accuracy[2]	Depth Accuracy[3]	Seafloor Coverage	Typical Survey Characteristics[5]	NOAA CATZOC Description
A1	± 5 m + 5% depth	=0.50 + 1%d Depth (m) / Accuracy (m) 10 / ± 0.6 30 / ± 0.8 100 / ± 1.5 1000 / ± 10.5	Full area search undertaken. Significant seafloor features detected[4] and depths measured.	Controlled, systematic survey[6] high position and depth accuracy achieved using DGPS or a minimum three high quality lines of position (LOP) and a multibeam, channel or mechanical sweep system.	1. Object detection multibeam coverage (HSSD 5.2.2.1 - objects larger than 1x1x1 meter up to 22 meters depth and 5% of depth in depths greater than 22 meters) 2. Complete multibeam coverage (HSSD 5.2.2.2 - objects larger than 2x2 meters by 1 meter height in depths less than 20 meters and greater than 5% of depth vertically in depths greater than 20 meters). 3. 200% side scan with concurrent "skunk stripe" bathymetry, and all significant contacts developed by MBES and/or investigated by divers (HSSD 5.2.2.3 and 6.1 – side scan to be operated so as to detect objects larger than 1x1x1 meter. (Note: 100% side scan may meet this standard under optimal conditions when the full imagery swath consistently meets object detection standards.) 4. 100% side scan with complete multibeam coverage, generally in areas where least depths are required on numerous significant features. **Note: For all survey methods, horizontal and vertical uncertainty estimates must be computed and meet ZOC A1 accuracy standards at 95% confidence interval.**
A2	±20 m	= 1.00 + 2%d Depth (m) / Accuracy (m) 10 / ±1.2 30 / ±1.6 100 / ±3.0 1000 / ±21.0	Full area search undertaken. Significant seafloor features detected[4] and depths measured.	Controlled, systematic survey[6] achieving position and depth accuracy less than ZOC A1 and using a modern survey echosounder[7] and a sonar or mechanical sweep system.	1. Complete multibeam coverage (see Example 1 in row above) where uncertainty does not meet ZOC A1 requirements. 2. 200% side scan sonar surveys with concurrent bathymetry; SBES developments. (Note: 100% side scan may meet this standard under optimal conditions when the full imagery swath consistently meets object detection standards.) **Note: For all survey methods, horizontal and vertical uncertainty estimates must be computed and meet ZOC A2 accuracy standards at 95% confidence interval.**
B	±50 m	= 1.00 + 2%d Depth (m) / Accuracy (m) 10 / ±1.2 30 / ±1.6 100 / ±3.0 1000 / ±21.0	Full area search not achieved; uncharted features, hazardous to surface navigation are not expected but may exist.	Controlled, systematic survey achieving similar depth but lesser position accuracies than ZOCA2, using a modern survey echosounder[5], but no sonar or mechanical sweep system.	1. Bathymetric Lidar surveys 2. Interferometric surveys (without beamforming multibeam developments) 3. Side Scan Sonar survey with <100% acceptable coverage and concurrent "skunk stripe" bathymetry. 4. Single beam or <100% Multibeam nearshore surveys (1:40,000 scale or larger) since 1940.
C	± 500 m	= 2.00 + 5%d Depth (m) / Accuracy (m) 10 / ±2.5 30 / ±3.5 100 / ±7.0 1000 / ±52.0	Full area search not achieved, depth anomalies may be expected.	Low accuracy survey or data collected on an opportunity basis such as soundings on passage.	1. Offshore single beam surveys since 1940 and 1920-1940 surveys on known horizontal and vertical datums
D	Worse than ZOC C	Worse than ZOC C	Full area search not achieved, large depth anomalies may be expected.	Poor quality data or data that cannot be quality assessed due to lack of information.	1. Pre-1920 surveys and surveys with unknown horizontal or vertical datums which are Pre-1940
U	Unassessed - The quality of the bathymetric data has yet to be assessed ***NOTE: Unassessed shall not be used.***				

Table 1. NOAA modified CATZOC Table from S-57 Suppliment No. 3, June 2014, from NOAA Document "Office of Coast Survey HCell Specifications", 10/1/2015. Note numerous notes annotate the original table, but are not reproduced here in their entirty for succinctness. All requirements for a level must be met. Positional and depth accuracy are assessed for the final charted value including all errors accumulated through acquisition, digitization and cartegraphic representation.

CONCLUSIONS

The process of evaluating outside source data for hydrography is not a simple one. For example, without reprocessing data from source measurements it can be difficult to reliably estimate the uncertainty of soundings with empirical statistics (grid cell standard deviation). Over-aggressive filtering alters the statistics, artificially lowering these estimates. Having no spatial filtering capability through beam forming, the real-time filters that must be applied in first generation interferometric systems are particularly prone to clipping the tails of the measurement distribution and artificially reducing the standard deviation of the resulting data. (Note recent systems that provide real-time uncertainty estimates with each sounding can provide an independent measure of uncertainty of their data.)

Nonetheless, interferometric systems are able to quantify the seafloor well, meeting IHO standards within 3.5x water depth or beyond when refraction conditions are favorable [6, 7]. Further, while the increased swath beyond 3.5x water depth provided by the system is not always suitable for measuring least depths of DTONs, the wider swath provides a sufficiently good representation of the seafloor that when combined with careful scrutiny for dangers to navigation in the accompanying sidescan, a wider swath and efficiency increase is possible. In addition, surfaces created from this outer swath data are well suited to providing geologic context for object identification. The complete coverage provided by even inferior data is far preferable when scrutinizing possible navigation hazards than no data at all.

Outside source data containing crosslines that can be used to evaluate the system's uncertainty and repeatability at the time of survey provide great advantage over those that do not. Conducting these checks with the system used in the survey allows one to more easily identify systematic errors. In addition, crosslines conducted by hydrographic launches after the fact can provide an additional independent check. However, their utility is greatly diminished the longer time has passed since the original survey or if there is any question of which system is in error.

The uncertainty assessment of outside source data must capture the effects of uncorrectable errors in processing. A significant roll bias on the starboard side was identified in these data from crossline analysis. Because the data is imported into CARIS as XYZs having all corrections applied during acquisition, correction of the roll bias would have required "replaying" the data through the acquisition software - an expense in time and manpower that was deemed impractical. (In theory, a partial correction could have been made during the "conversion" process in CARIS, but because the XYZ files do not contain launch angles, a proper correction is not possible and the partial approach was not implemented by CARIS.) Accounting for this roll bias in the uncertainty estimation was the primary reason for these data not meeting NOAA and IHO uncertainty requirements.

NOAA's CATZOC table does not explicitly address the age of the survey (unless it predates modern echo-sounders), nor does it address the likelihood that the seafloor has changed since the survey was completed. These factors may ultimately result in a reduction in CATZOC level for this data set.

In an attempt to try to address these issues the IHO S-101 revision to the S-57 ENC standard includes factors to characterize seafloor variability [8, 9]. Specifically, an attribute CategoryOfTemporalVariation will be used to express the expected regular change in the seafloor or to warn mariners when a sudden change is likely to have occurred due to storms or other phenomena. More work will be required to determine the methods by which this attribute should best be assessed.

Finally, the following recommendations are provided from our experience with this project:

- NOAA should encourage known producers of outside source data to conduct crossline analyses with their system at the time of survey and to fix any systematic errors in their own post-processing.
- When crosslines are not being done, NOAA should proactively task hydrographic launches to conduct them within one year of the original survey if at all possible.

- NOAA should encourage potential producers of outside source data to conduct surveys referenced to the ellipsoid allowing more sophisticated transitions to tidal datum by NOAA in post processing than might be necessary for the original purposes.
- NOAA should make the tidal modeling tool TCARI open-source and freely available to the public to facilitate best practices in tidal correction.
- When a data set's IHO uncertainty compliance is marginal, all data should be used to identify DTONs, as complete surveys of even borderline data provide better geologic context than "skunk striped" surveys.
- In general, bathymetric data should be limited to that which meets IHO uncertainty requirements for inclusion on the chart or provides a significantly superior representation of the seafloor than existing charted data.
- If data does not meet requirements for coverage with a suitable combination of single beam, multibeam and sidescan data, it should be used only as a guide for subsequent survey planning to achieve these requirements.

Through the processes we have discussed in this paper, we find that these data are suitable for charting and meet the CATZOC B requirements. Additional coverage over significant features would enhance the overall data quality to meet CATZOC A2. The acceptance of these data to the chart would not only save NOAA valuable time and resources in resurveying, but also serve to update areas of the chart that haven't been resurveyed since before 1900 and minimize the overall risk to the mariner – NOAA's overall purpose.

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