From Crowd to Chart: Methods and Applications of Crowdsourced Bathymetry in Support of Safe Navigation

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Author Note

The python programming script referenced in this paper can be found on the author's GitHub repository:

https://github.com/anthonyklemm/Crowdsourced_Bathy_Processing

Abstract

The available holdings of crowdsourced bathymetry (CSB) data carry significant seafloor mapping potential. Some potential benefits of CSB include chart updates, reconnaissance for hydrographic surveys in remote or unsurveyed areas, Notice to Mariner hazard to navigation alerts, and temporal monitoring of the quality (i.e. channel health) of existing bathymetry in addition to contributing towards SEABED 2030's goals of increasing global knowledge of our ocean floor. This article describes Coast Survey's initial automation techniques for reducing raw CSB observations to chart tidal datum and applying data-derived best estimates of vertical transducer offsets of the contributing vessels. In addition, this article discusses results and techniques used to verify the outcome and estimated quality of CSB against existing qualified bathymetry.

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Introduction

The National Oceanic and Atmospheric Administration's (NOAA) Office of Coast Survey (OCS) plays a critical role in ensuring the safety and efficiency of maritime transportation and commerce within United States coastal waters and exclusive economic zone (EEZ). Their mission to chart the seafloor, produce maintain critical navigation products, and respond to maritime emergencies supports and protects the lives of mariners and the fragile marine environment while providing a foundation that is crucial for the health of the US economy. This responsibility is compounded by the sheer amount of seafloor OCS is charged to map; the US EEZ is the largest in the world. While major ports and harbors are well surveyed, significant portions of the US EEZ do not have adequate bathymetric data to support safe navigation or our understanding of our oceans. As of January 2020, NOAA estimated that only 46% of the US EEZ (including the Great Lakes) has been considered minimally mapped. (Office of Coast Survey, 2020) As such, and in coordination with the GEBCO/Nippon Foundation SEABED 2030 initiative, OCS has been considering many non-traditional bathymetric data sources to augment the efforts of traditional hydrographic survey field units, such as airborne lidar bathymetry, structure from motion, fisheries science acoustic data archives, and passive and active satellite-derived bathymetry, especially for near-shore locations that are typically more dangerous and time consuming areas to survey with traditional acoustic means.

In recent years, crowdsourced bathymetry (CSB) has emerged as a valuable source of data for mapping the seafloor. CSB is defined in publication B-12 from the International Hydrography Organization as "the collection and sharing of depth measurements from vessels, using standard navigation instruments, while engaged in routine maritime operations." (IHO, 2023) As a result of advances in technology and a concerted international effort from a coalition of governmental, academic, non-profit, and business organizations to grow awareness in the maritime community, it has become increasingly feasible to collect and process data from a large number of sources, including private vessels, conscientious citizen scientists, and willing contributors in the work boat and marine research communities. Until recently, the majority of effort invested by the CSB community was concentrated on building the infrastructure and technical pipelines to collect and distribute CSB, as well as growing a sufficient and enthusiastic crowd willing to share and supply their data with the wider community. However, CSB data has yet be used by any meaningful measure to update NOAA's nautical chart suite, nor has it been used as reconnaissance data for planning systematic hydrographic survey projects. Reasons for this include a variety of factors, such as general lack of awareness of the data that is available, skepticism from individuals regarding the actual value CSB could provide. These reasons highlight the importance of developing tools, such as this methodology, that could be used to aggregate, process, and assess the quality of CSB data and thus alleviate some of the skepticism or lack of awareness of the value of CSB.

This paper describes a methodology for processing and preparing crowdsourced bathymetry data to improve nautical charts. We present a workflow that involves collecting and aggregating data from multiple vessels, cleaning and validating the data, and incorporating it into a bathymetric model. We also describe methods for quality control and assessing the accuracy of the resulting data. Finally, we demonstrate the potential benefits of crowdsourced bathymetry for updating nautical charts through case studies that illustrate the use of the data in real-world scenarios.

The contributions of this paper are twofold. First, we provide a practical guide for processing and applying crowdsourced bathymetry data with open-source and semi-automated tools, which can serve as a useful resource for hydrographic offices, government agencies, and other organizations involved in charting and mapping the seafloor. Second, we highlight the potential benefits of using CSB data for updating nautical charts, especially in areas where there is either no or very low-quality bathymetric data available on current NOAA nautical charts. Overall, we believe that this paper will contribute to the growing body of knowledge surrounding the use of CSB data and will help to advance the understanding and impact CSB can provide to support safe navigation.

Analysis

Data Information and Preprocessing

The dataset used in this analysis was from the IHO's Data Centre for Digital Bathymetry (DCDB), hosted at NOAA's National Centers for Environmental Information (NCEI). (DCDB, 2023) The DCDB's CSB holdings contain data from multiple trusted nodes, each with their own subset of the collective "crowd." Figure 1 shows a generalized view of publicly available CSB data on the DCDB website in Galveston, TX, and Seattle, WA.

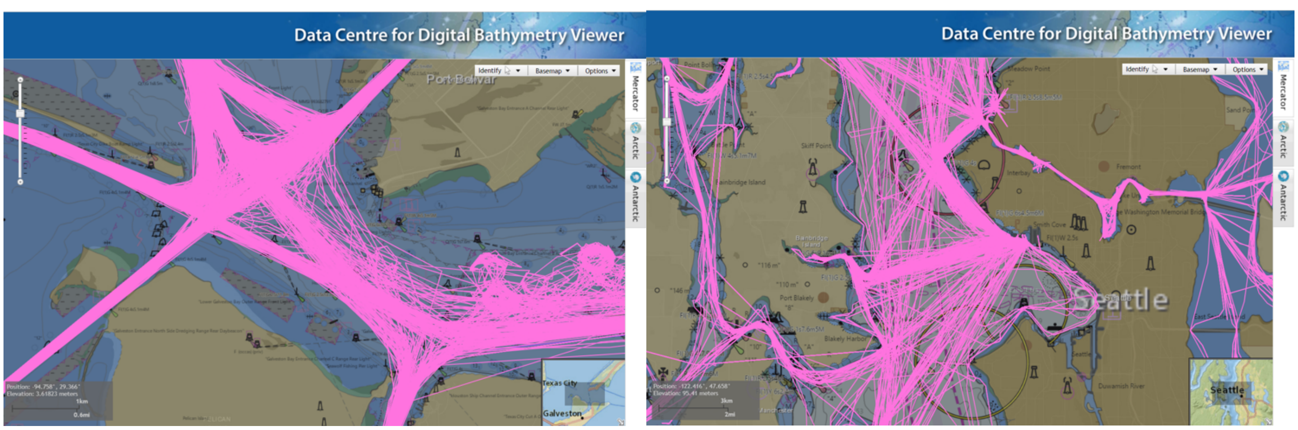

Figure 1: Overview of publicly available CSB data from the DCDB website

As of March 2023, the DCDB estimated that more than 930 million individual depth observations have been collected and are publicly available (Zelenak, 2023). The number of unique contributing vessels is approximately 300, and over 85% of data by volume was provided by Rose Point Navigation Systems contributors. It should be noted that this dataset is but a mere drop in the bucket of potential CSB data. In the US alone, some estimate the number of registered boats is upwards of 12 million (Statista, 2022), and while not all operate in waters charted by either NOAA or the United States Army Corps of Engineers or have the necessary hardware required to collect CSB, there is certainly a lot of room for growth.

The DCDB distributes CSB data in two different general formats. The primary form of CSB data downloaded from the DCDB is housed in JSON files aggregated by the voyage of a vessel. The DCDB also provides an option for a simplified CSV file of individual depth observations extracted from a user-defined spatial query from an experimental cloud-based point store. This analysis used data from the cloud-based point store. The point data file contains the location and depth values, as well as some basic metadata of each vessel, which is pared down considerably compared to the full datasets housed in the JSON files. Table 1 shows the data structure of the CSV files used:

Attribute Number	Name	Description
1	lon	Numeric; Longitude in decimal degrees. CRS: WGS84 (ex. -165.43086)
2	lat	Numeric; Latitude in decimal degrees. CRS: WGS84 (ex. 60.64586)
3	depth	Numeric; raw depth in meters with two-decimal precision (ex. 11.45m)
4	time	Date/time; given in UTC (ex. 2021-10-11 07:52:23.000)
5	platform	String; name of contributing vessel (ex. ALULAQ)
6	provider	String; name of Trusted Node (ex. 'Rose Point')

Table 1: Attribute information in CSB data from experimental cloud-hosted point store

Multiple test areas were identified to illustrate the efficacy of this processing approach with a wide range of "crowd" demographics (i.e. the mix of types of vessels contributing), seafloor characteristics, and data density. The areas chosen include a portion of the Chesapeake and Delaware Bays; Kivalina, AK; Ninglick River, AK; San Juan Islands, WA; and Houston, TX.

Multiple steps were taken to prepare the data for processing. CSB data is inherently noisy, with erroneous depth values stemming from multiple reasons. While this study does not investigate all reasons for erroneous depth values in CSB, many are due to the loss of bottom tracking due to user error (e.g., the vessel was navigating in depths outside the user defined depth range) or transiting in depths beyond the physical limits of the equipment. Additionally, debris, suspended sediment, fish, and cavitation in the water are all sources of noise in the dataset. For the sake of simplicity, all raw depth values less than 0.5m or greater than 1000m were removed from the dataset at the start of the process.

Additional steps to clean data include restricting the data to only those with timestamps between the year 2015 and the present, as erroneously timestamped data has been observed. Due to a temporary limitation with the cloud-based data, the unique vessel id field, a hexadecimal UUID assigned by the DCDB for each unique vessel, was missing from the dataset. As such, all vessels where platform == 'Anonymous' were removed from the dataset, as it is a requirement in this processing workflow to have a way to uniquely identify contributing vessels. The assumption going forward in this analysis is that the 'platform' field provides a type of primary key unique identifier for the dataset, although it is acknowledged that more than one vessel could have the same name. As soon as the DCDB adds in the unique vessel id field to the cloud-based dataset, this extra cleaning step will be removed from the process, allowing for the vessels to retain anonymity, yet still provide a unique id for data processing.

Methodology for Processing CSB

Ultimately, the purpose of this workflow is to provide automated tools to transform raw CSB data into a product at chart datum that could be evaluated for quality and considered for application to a nautical chart with the goal to support safe navigation. This workflow is broken into simple stages. First, raw CSB data is downloaded from the DCDB's website using the spatial query and extraction tool from their experimental cloud-based point store, in CSV format. Once the CSV is local to the processing computer, our code performs some initial data cleaning (as described earlier). Next, the raw depths are referenced to a common water level at chart datum, using discrete zoned tide models. After that, transducer draft estimations are derived from comparing the tide-referenced CSB to high-quality bathymetry. Once the data-derived transducer draft estimates are complete, those values for each vessel are applied to the tide-referenced data. Finally, the data is exported as a simple shapefile point dataset, as well as gridded as a raster dataset. The script itself employs a simple averaging gridding method, although the point data could be used for more sophisticated interpolation algorithms, such as inverse distance weighted, or IDW interpolation, typically with better results. Figure 2 illustrates the general workflow that the script follows. Each step is described in more detail below:

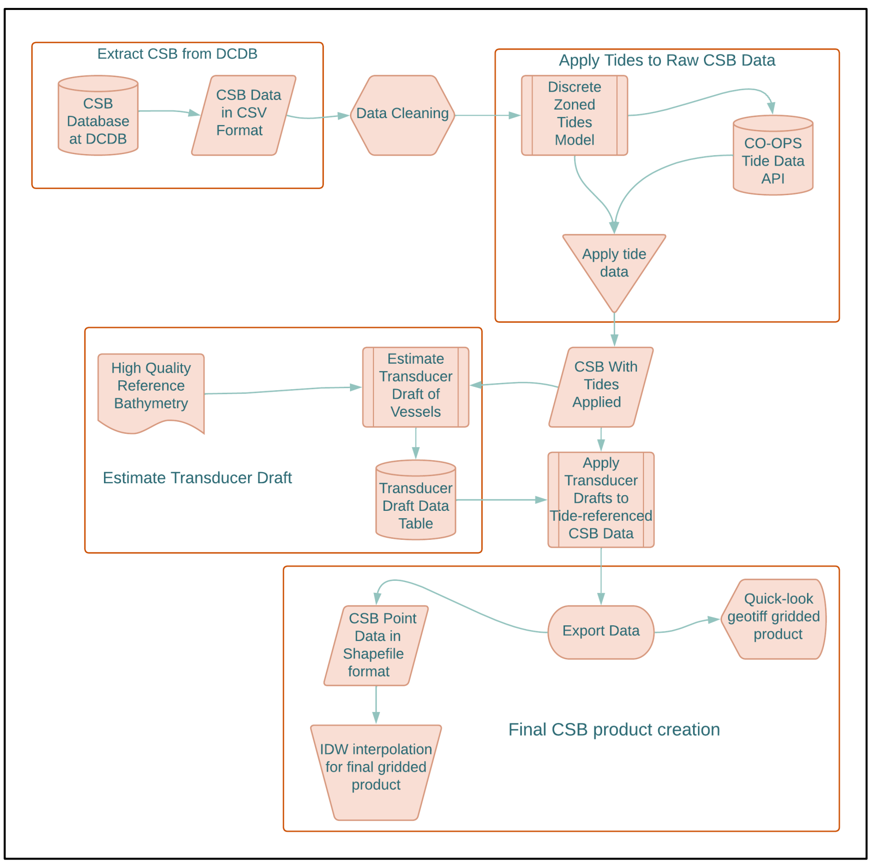

Figure 2: General workflow diagram for CSB processing script

Water Level Adjustments to Chart Datum: The first main step after data cleaning and preprocessing is referencing the raw CSB depths to a common water level at chart datum, usually Mean Lower Low Water (MLLW) in the US. The CSB point data is converted into a geographically referenced vector point dataframe using the Geopandas python library. (Jordahl, 2020) Then, a spatial join with the CSB point data is performed against the discrete zoned tide model polygons provided by NOAA's Center for Oceanographic Observations and Products, or CO-OPS, to query tide reference stations required, as well as the time span of the tidal data needed. Next, the CO-OPS tide data API is called to systematically request and download all 6-minute tidal data prediction values (tide observations are preferred but not available for every control station) from all relevant control stations. Then, the tide data is temporally joined to the CSB point dataset, and the CSB depths are adjusted in reference to the time and magnitude coefficients defined in each tide zone polygon.

While the CO-OPS discrete zoned tide model works well in this initial workflow, the most significant limitation is the lack of coverage in many coastal and inland areas, especially in places such as Alaska, as seen in Figure 3.

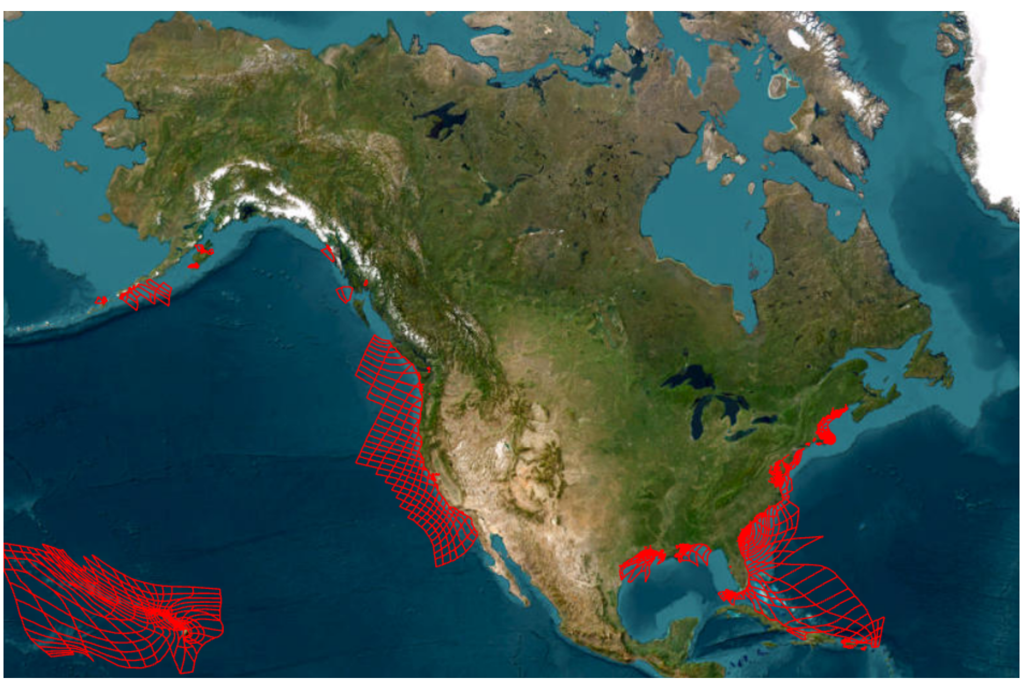

Figure 3: Coverage of CO-OPS discrete zoned tide model. Many gaps exist, especially in Alaska and inland/intracoastal waterways (not seen due to scale).

Another limitation comes from the nature of the data, which requires tidal data from multiple tide control stations over a large period of time. A more efficient method would be to utilize the AVISO+ FES2014 global tide model, as demonstrated in the EK60 processing workflow published by NOAA in 2020. (Burkhalter-Castro, 2021) This method was tested with CSB, but the model infrastructure only existed in the US Northeast waters, and not enough analysis regarding the model's accuracy in inland waters have been published as of the time of this paper.

To validate the efficacy of the discrete zoned tide model implementation, a vessel that collected CSB while moored was identified near a NOAA tide sensor at Friday Harbor, WA. The CSB data spanned a local high and low tide cycle. Tides were applied and the results were compared to the actual tide data from the gauge, as well as the latest hydrographic survey of the area as seen in Figure 4.

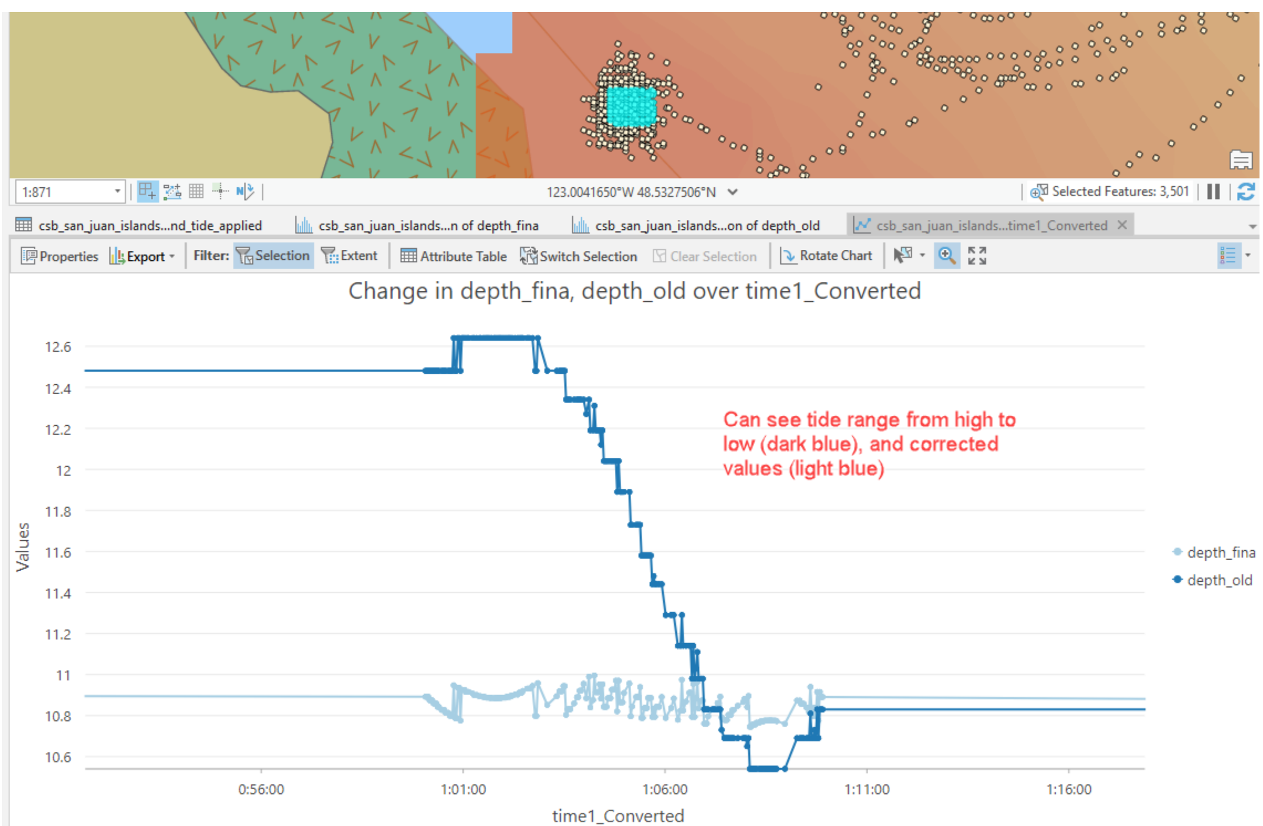

Figure 4: CSB depths from same moored vessel before and after applying tides to reference data to MLLW, with the dark blue line representing the raw CSB depths spanning a high and low tide, and the light blue line representing the CSB depths after tides were applied.

Data-derived Transducer Draft Estimation: The other large hurdle to overcome in preparing CSB data for application to a nautical chart is to correct any static vertical offset, or bias, found in the data. The guidance provided to trusted nodes from the DCDB outlines the importance of correcting for transducer draft before data transmission to the DCDB, but does not make it a requirement. The depth data typically comes from the NMEA DBT (depth below transducer) or DPT (depth) strings output from the vessel's transducer. Additionally, transducer draft is optional metadata field. However, the cloud-based bathy point data from the DCDB does not provide that more granular metadata at this time. Further, many mistakes are present in the metadata itself, whether from erroneous draft values, or the recording of the DPT string without any applied transducer draft (a user-induced error).

In an attempt to circumvent these issues, a strategy to estimate each contributing vessel's transducer draft was scripted into the processing methodology. To do this, the analyst processing the CSB identifies a common navigational bottleneck, such as an entrance channel to a harbor, where most (ideally all) vessels transit across. Then a high-resolution bathymetry dataset (BAG file) in the bottleneck area is downloaded from the NCEI website. The script converts and aggregates the elevation data band in the BAG file, and then extracts the known bathymetry value from the BAG to each tide-referenced CSB depth data point. Those values are compared against each other, and summary statistics for each vessel are populated in a separate datafile. The mean vertical offset value of each vessel between the known bathymetry and the tide-referenced CSB is used as the data-derived transducer draft estimation if the standard deviation (1-sigma) is less than 2m. Those transducer draft values are then applied to the tide-referenced CSB data. This table of data-derived transducer drafts is retained and appended as more data is processed. In remote areas where quality reference bathymetry is not available, correcting for transducer draft offsets is still possible if the draft of those vessels was estimated in earlier analyses. Table 2 highlights a sample of the derived draft measurements from the Chesapeake Bay test area, with drafts ranging from 0 to 6m.

platform	mean	std	count
ATB GENESIS PATRIOT			0
Blue Note	-0.23	0.89	1434
Gray Eagle	-0.48	0.19	475
Hank The Tank			0
JOE PYNE			0
Joe Pyne			0
Kairos	-1.64	0.12	222
Lay Time			0
Magnolia	-0.15	0.18	872
Maverick			0
NOAA Ship Thomas Jefferson	-0.87	0.31	772
Okeanos Explorer	-5.78	0.42	1440
One With The Wibd			0
Paragon			0
R/V Bay Hydro II	-0.86	0.43	1006
Ren Chai	-1.88	0.43	6426
Rockhopper			0
SAILS	-0.04	0.45	7162
SERENITY	-1.51	0.32	423
Sea Dweller	-0.41	0.25	1331
Sea Saga			0
Sempre Avanti	-0.14	0.33	2129
Silence Rising	-0.08	0.45	1776
Tapestry	-0.41	0.35	1551
Tootega	0.07	0.40	4561

Table 2: Sample of data-derived transducer draft estimations. Notice the wide range of drafts (mean).

This data could be used in the future to inform a type of contributor confidence or reputation score. This confidence score could be incorporated into future uncertainty models, or even customized weighting parameters in interpolation algorithms.

Data Gridding and Interpolation: The final step in the processing methodology is to export the tide-referenced and draft-corrected data to usable and more accessible geographically-referenced dataset. The script exports the Geopandas vector point dataframe to an ESRI shapefile for use in external GIS software. Additionally, the script performs a basic gridding of the data to a resolution of 10m using an averaging algorithm. This step is done mostly to facilitate rapid visualization of the data, but is not recommended as a final product. Instead, the exported point data was interpolated using ESRI ArcGIS Pro's IDW interpolation algorithm. The IDW parameters used in this analysis include an output grid of

5m, with a 12m fixed search radius, and a power coefficient (exponent of distance) of 0.5, allowing more influence from distant points, a feature that helps mitigate the influence of noise or fliers present in the dataset.

Results

Once the methods described earlier were tested and integrated into an automated, open-source process, the results of the processed CSB was analyzed for reliability and accuracy. The first study area was Houston, TX. Houston harbor has some of highest CSB data density available from the DCDB. The vast majority of contributors are workboats that spend a lot of time in the harbor. The dataset only consisted of about 2km of the harbor, but over three-million individual observations. A very recent high-resolution hydrographic survey (H13387) was used to compare the processed CSB grid for accuracy. The mean difference between H13387 and the CSB data was 0.19m, with a standard deviation of 0.60m at 1-sigma, as seen in Figure 5.

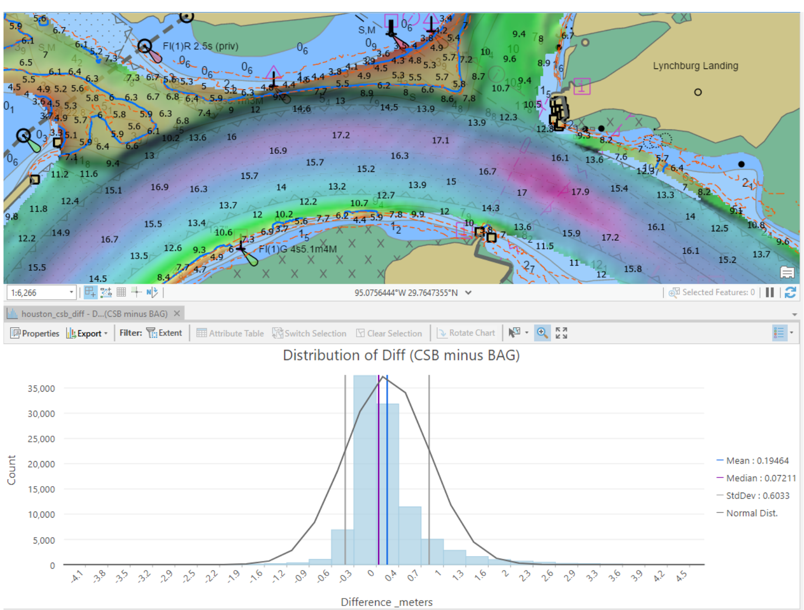

Figure 5: Results of processed CSB data in Houston, TX compared to survey H13387

These comparative results against a high quality (CATZOC A1) survey show that CSB data, when processed correctly, easily fits within IHO CATZOC C quality metrics, and thus a cursory uncertainty layer could be calculated based on the maximum allowable vertical uncertainty threshold for CATZOC C for application to the nautical chart. For reference CATZOC C defines a vertical accuracy threshold value of 2m + 5% of depth.

Another test area was near Friday Harbor in the San Juan Islands of Washington. Compared to the Houston TX test area, this area had lower CSB data density and most of the data was contributed by pleasure craft instead of commercial workboats. The seafloor topography is much more dynamic than the Houston area, with large rocky areas and steep slopes between the islands. Compared to the latest NOAA hydrographic survey in the area from 2014 (survey F00638), the mean difference was 0.03m, with a standard deviation of 1.50m. A higher standard deviation was anticipated due to the dynamic nature of the seabed. See Figure 6 for comparison results in Friday Harbor, WA.

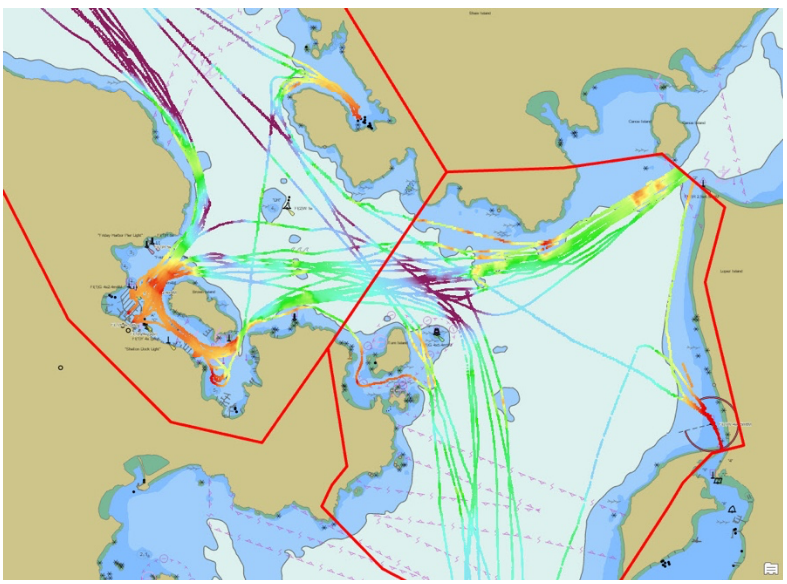

Figure 6: Resulting processed CSB near Friday Harbor, San Juan Islands, Washington

Some latency artifacts (presumably horizontal positioning latency) were clear in the CSB data when overlaid at the same color scale as F00638, as seen in Figure 7. The data with latency artifacts came from a single provider and could be a problem with how their electronics are integrated on their vessel, but the problem did not seem consistent enough to correct using a timing shift. This information could be an input into a future vessel "reputation" metric, as mentioned earlier.

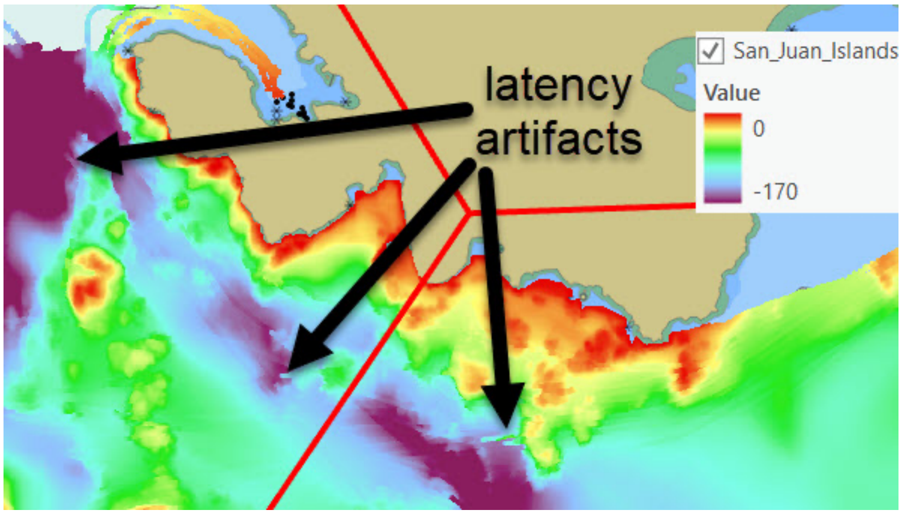

Figure 7: Latency artifacts seen in the CSB data when overlaid on NOAA survey F00638.

In the Chesapeake and Delaware Bays, the processed data provided some convenient comparison areas, since one contributor, the NOAA R/V Bay Hydro II, collected CSB data in tandem with hydrographic surveys in the Patuxent River and in Delaware Bay (see Figure 8).

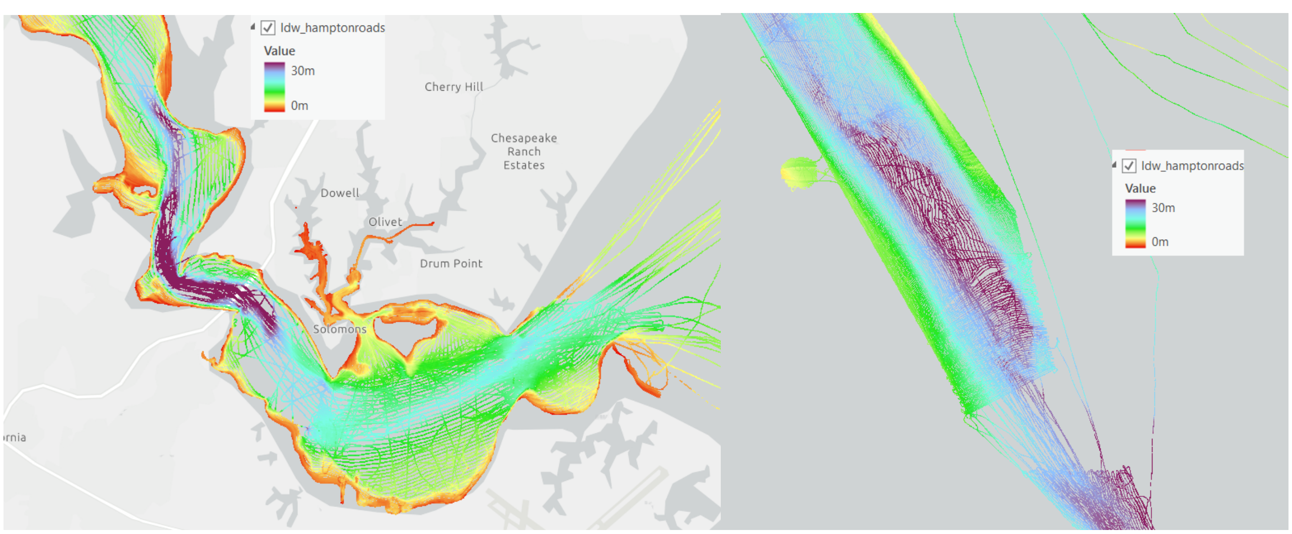

Figure 8: Processed CSB Data from the R/V Bay Hydro II

A subset of the CSB data was compared to the survey F00747, with a mean difference of 0.32m, and a std dev of 0.47m (see Figure 9). These areas illustrate the internal consistency when processed with this methodology, including the data-derived transducer draft estimation and using predicted tides, weather-related tide residuals notwithstanding. The estimated draft of the R/V Bay Hydro II was 0.86m with a 40cm std dev, and their published draft from their Data Acquisition and Processing Report was 1.03m. It is unclear if the vessel used the nadir depth from their multibeam echosounder for the CSB, or was logged from their navigation echosounder simultaneously.

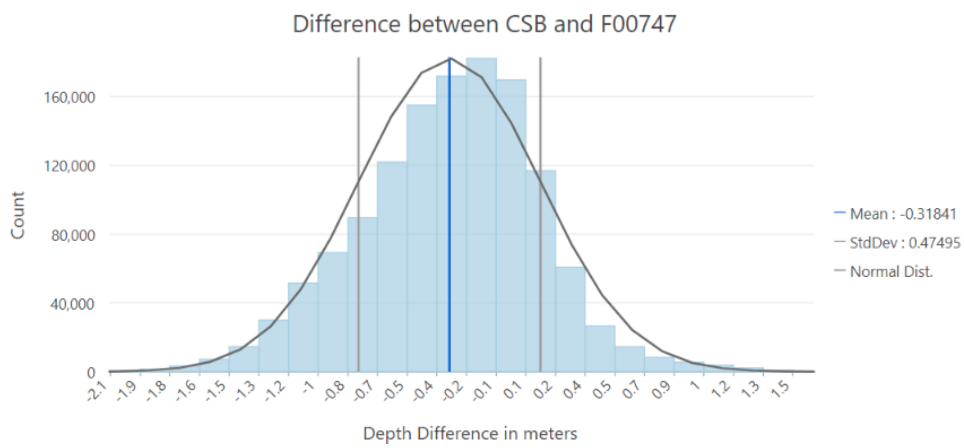

Figure 9: Histogram of difference between survey F00747 and CSB from R/V Bay Hydro II

Additional results from the Chesapeake and Delaware Bay test area were the detection of shifted shoals. Nautilus Shoal is south of Cape Charles in the mouth of Chesapeake Bay. Two CSB tracklines from two different vessels at different times were observed transiting south of the charted shoal with charted depths of around 8m but observed depths near 3m. To corroborate this finding, pseudodepth satellite-derived bathymetry (SDB) from Sentinel 2 was processed using NOAA's SatBathy tool developed by NOAA National Geodetic Survey's Remote Sensing Division in conjunction with NOAA's National Centers for Ocean and Coastal Science. This product helped to quickly corroborate the CSB detection of the shifted shoal (see Figure 10).

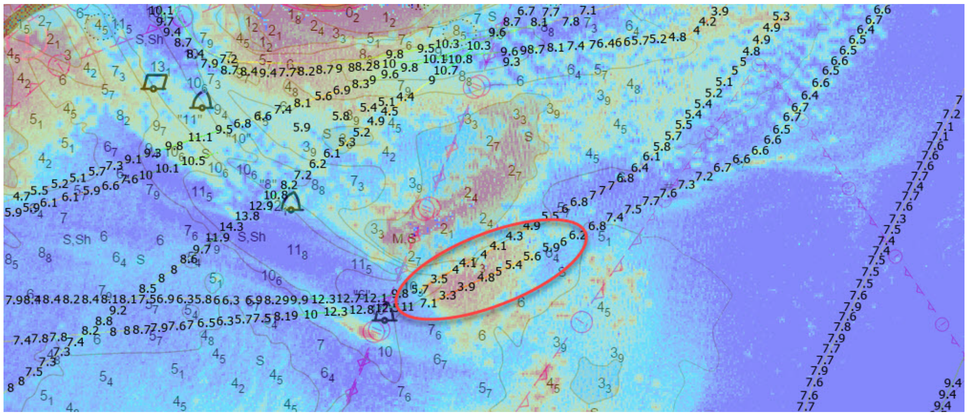

Figure 10: Uncharted shifted shoal detected by CSB, and corroborated with pseudo SDB

Similarly, in Delaware Bay near the approach to Lewes Harbor at Cape Henlopen, shifted shoals were detected in the CSB data compared to the nautical chart (see Figure 11).

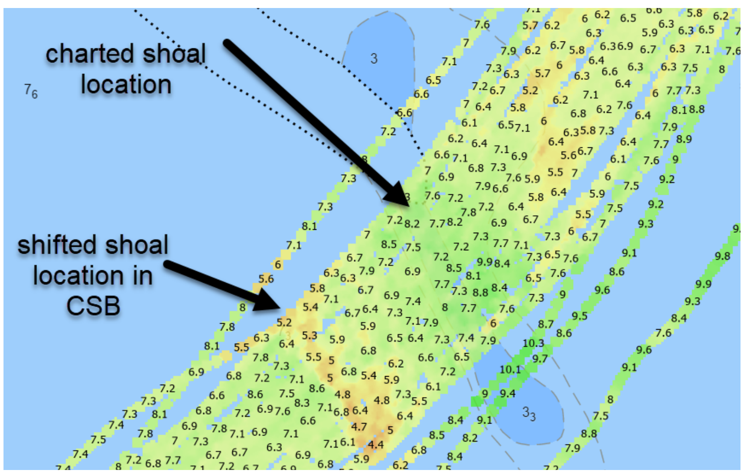

Figure 11: Shifted shoal detected in CSB compared to charted location

The test cases in Alaska highlighted the value and beneficial impact CSB could have on the nautical charts, especially to uncharted or under-charted navigable waters. For example, the last hydrographic survey in the approach to Toksook Bay south of Cape Vancouver stopped short of the harbor. Using CSB, bathymetry could be charted all the way to the docks, supporting safe navigation in places where there is no bathymetry currently charted (see Figure 12).

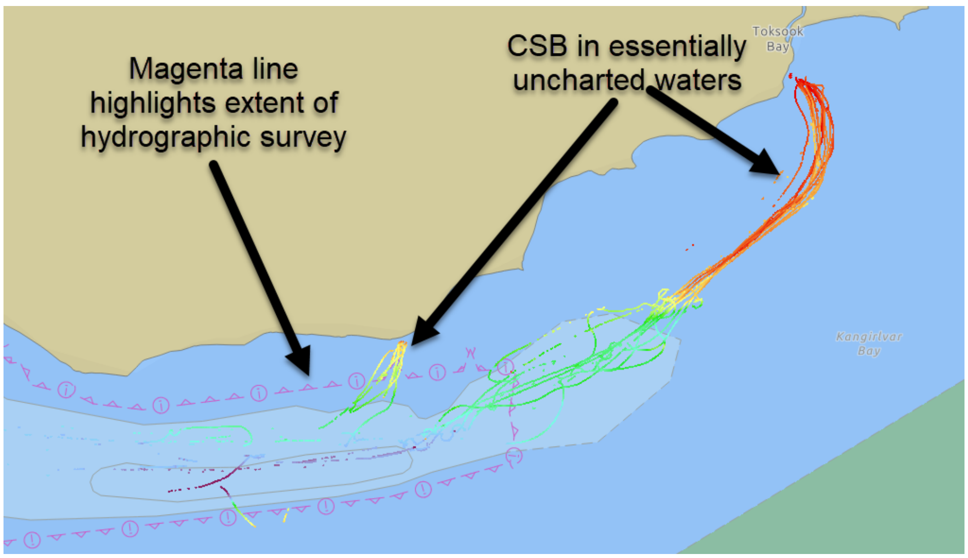

Figure 12: CSB in Toksook Bay, Alaska in areas without charted bathymetry

CSB data was compared to the survey H12869, with similar results from other test areas, with a mean difference of 0.02m, and a standard deviation of 0.60m (see Figure 13).

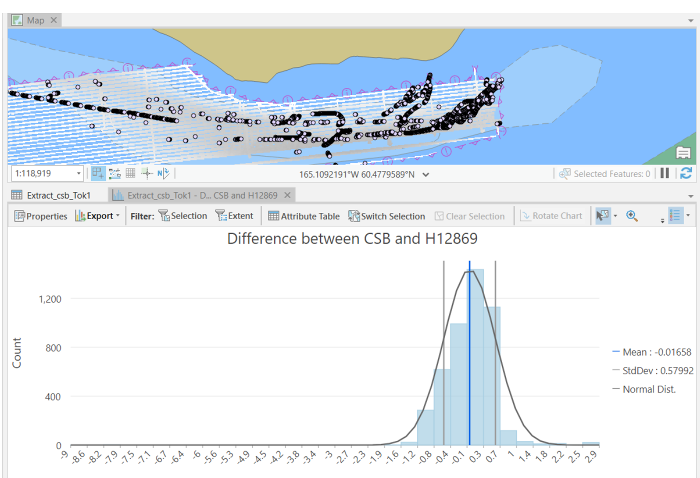

Figure 13: Comparison CSB and survey H12869 (mean difference 0.02m, std dev 60cm)

Similarly, the Ninglick River in Alaska is also extremely under-charted, with the largest scale chart US2AK95M at 1:1,534,076 (see Figure 14). CSB data could be used in conjunction with updated shoreline and shoals detected by SBD to create charts similar to what was done in the Yukon River. (Kampia, 2016) These are areas with small communities that rely on maritime-based transportation of goods.

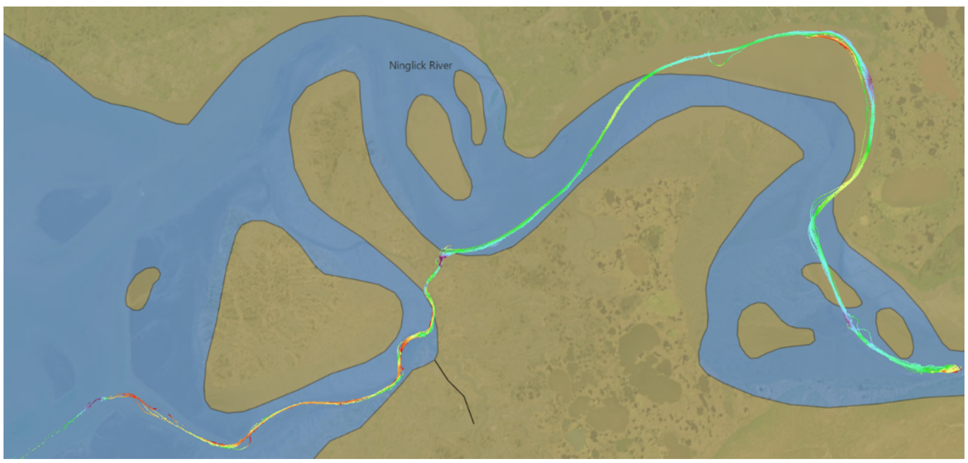

Figure 14: CSB Data overlaid on the best available NOAA nautical chart in Ninglick River, Alaska

The last test area was in a remote area of Alaska north of the Bearing Strait called Kivalina. The best available NOAA nautical chart has the approach to Kivalina charted as an unsurveyed area (see Figure 15). The CSB in this area could provide the best bathymetry available for this chart, and in conjunction with SBD, could help support navigation in the area where currently, no bathymetry exists on the nautical charts.

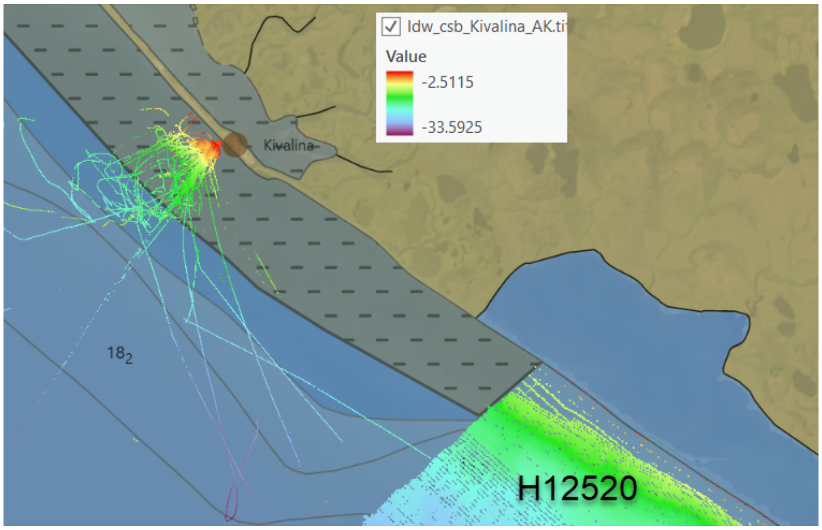

Figure 15: CSB in 'unsurvey area' at the approach to Kivalina, Alaska

Conclusion

In conclusion, this processing methodology for publicly available CSB data from the DCDB has emphasized the fact that CSB data continues to be an underutilized and extremely valuable source of bathymetry that could be judged suitable for application to the nautical chart to support safe navigation at a quality level of at least CATZOC C. Table 3 summarizes the key findings regarding quality and/or key take-aways from the test areas.

Test Area	CSB quality as compared to hydrographic survey (mean difference and std dev)	Summary insights
Houston, TX	0.19m ± 0.60m	CSB could monitor channel health
Chesapeake and Delaware Bays	0.32m ± 0.47m	CSB detected mischarted shoals
San Juan Islands, WA	0.03m ± 1.50m	CSB latency artifacts present
Approach to Toksook Bay, AK	0.02m ± 0.60m	CSB is best available bathymetry
Ninglick River, AK	No comparison bathymetry available	CSB is best available bathymetry – may be combined with SDB
Kivalina, AK	No comparison bathymetry available	CSB is best available bathymetry – may be combined with SDB

Table 3: Summary of findings from CSB test areas

The results outlined in this paper illuminate the potential return on investment for Hydrographic Offices that dedicate resources to using CSB. As Hydrographic Offices demonstrate and communicate the value of CSB, this will in turn fuel engagement and participation in crowdsourced bathymetry from the public, as the current holdings are but a small portion of what could potentially be collected. Additionally, CSB data has great value for those planning hydrographic surveys or maritime operations in remote unsurveyed or under-surveyed areas, as well as automated near-real-time change detection when compared against best known bathymetry. It also has great potential for augmenting the calibration process for SDB products.

Much research is needed in the area of CSB, particularly in studying alternative tide models for referencing CSB to a common water level datum (such as AVISO+ FES2014), as well as building a CSB contributor 'reputation' database that can aid with uncertainty modeling and interpolation algorithm weighting. Additionally, other steps to further process CSB are yet to be employed, such as a low-pass filter for smoothing heave artifacts in the data, correcting for horizontal transducer offsets, and modeling dynamic draft curves for contributing vessels. As an open-source tool written in the python programming language ecosystem, this methodology makes processing CSB accessible without the need for expensive software licenses and allows for further development and refining of the software from throughout the hydrographic community. The authors hope that by building more awareness of the value and potential of CSB, more individuals and organizations will be interested in supporting safe navigation through the application of this underutilized source of bathymetric information.

References

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