VERTICAL ASSESSMENT OF LIDAR BATHYMETRY

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Abstract

Validation of Airborne Light Detection And Ranging (LiDAR) Bathymetry (ALB) is necessary for the production of nautical charts to fill coastal charting gaps and to quickly and accurately measure shallow dynamic seafloors. Previous assessments concentrate on the validation of ALB data within overlapping regions of Multibeam Echo-Sounder (MBES) data. This paper presents new coverage environments to the MBES overlap validation method, and proposes an alternative method for comparison between ALB data and ENC vector information. Analysis of the valida-tion methods favour comparisons using overlapping MBES data; however, the overlap of ALB and ENC information provides an additional assessment method with substantial overlapping regions. The ENC comparison proves to be useful at locations where MBES data is absent and in the assessment of chart adequacy.

Résumé

La validation des données bathymétriques issues de levés LiDAR (Light Detection And Ranging, en français : détection et estimation de la distance par la lumière) aéroporté (ALB) est nécessaire pour la production de cartes marines afin de combler les trous dans la cartographie côtière et de mesurer rapidement et effica-cement l'évolution des planchers océaniques peu profonds. Les évaluations précé-dentes étaient axées sur la validation de données ALB au sein de régions où des données issues de sondages acoustiques multifaisceaux (SMF) se chevauchaient. Le présent article présente les nouvelles conditions de couverture de la méthode de validation par recoupement des données SMF, et propose une méthode alternative de comparaison entre les données ALB et les informations vectorielles des ENC. L'analyse de ces méthodes de validation favorise les comparaisons utilisant le recoupement des données SMF ; toutefois, le recoupement de données ALB et ENC fournit une méthode additionnelle pour les régions comprenant d'importants chevauchements. La comparaison d'ENC s'avère utile à des endroits où il n'existe pas de données SMF et pour l'évaluation de l'exactitude de la carte.

Resumen

La validación de la batimetría mediante la detección y el alcance de la luz aerotransportada (LiDAR – *Light Detection And Ranging*) es necesaria para que la producción de cartas náuticas complete los vacíos de la cartografía costera y mida con rapidez y precisión los fondos marinos dinámicos poco profundos. Las evalua-ciones anteriores se concentran en la validación de los datos ALB en el seno de las regiones de solapamiento de los datos de la Ecosonda Multihaz (MBES). Este documento presenta nuevos entornos de cobertura para el método de validación mediante el solapamiento MBES, y propone un método alternativo para la compa-ración entre los datos del ALB y la información vectorial de las ENCs. El análisis de los métodos de validación favorece las comparaciones utilizando los datos de solapamiento MBES; sin embargo, el solapamiento de la información ALB y ENC proporciona un método de evaluación adicional con importantes regiones de sola-pamiento. La comparación de las ENCs resulta útil en los lugares en que no hay datos MBES y en la evaluación de la idoneidad de las cartas.

1.   Introduction

National hydrographic offices are mandated to guarantee safe navigation across their marine ter-ritories through the production of quality nautical charts (Fisheries and Oceans Canada, 2017). Conventionally, the acoustic-based technologies, such as multibeam echosounder (MBES) sys-tems, have been primarily relied on in nautical chart production. However, these conventional technologies have also displayed a critical limitation in extending bathymetric coverage towards nearshore shallow waters, where ship accessibility has been restricted due to ship draft and com-plexity in seafloor terrain (Scharff, 2007). This inaccessibility during a hydrographic survey has traditionally resulted in uncharted nearshore regions, also widely known as "white ribbon" gaps, persisting on nautical charts (Kotilainen & Kaskela, 2017). Uncharted extents on nautical charts raise a potential risk for the mariner to encounter ship accidents with shoals near these uncharted areas. To address this limitation, Airborne Light Detection And Ranging (LiDAR) Bathymetry (ALB) progressively emerges as a promising alternative to acoustic-based technologies in map-ping coastal regions, considering the capability of ALB to fill in those "white ribbon" gaps. Still, the credibility and reliability of ALB in nautical chart production requires further validation for broad acceptance. It is, therefore, worth investigating the performance of ALB in shallow water bathym-etry for navigational safety (Saylam, Hupp, Averett, Gutelius, & Gelhar, 2018).

In this paper, qualitative and quantitative systematic approaches that include adapting a widely accepted surface differencing method for the assessment of vertical accuracy between ALB and MBES, are adopted for the Atlantic Canada region and additionally adapted for comparisons be-tween ALB and published Electronic Nautical Charts (ENC). An evaluation of ALB datasets using hydrographic survey standards prescribed by the Canadian Hydrographic Service (CHS) and In-ternational Hydrographic Organization (IHO) is presented, along with a method for identifying are-as of ENC inadequacy.

2.   Study Area

Data sources for the comparison were provided by CHS, covering a range of environments including rocky and slopped seafloor regions from Grand Manan (GM), New Brunswick; and Mahone Bay (MB), Nova Scotia to consistent flat seafloor composition seen in Pictou (PI), Nova Scotia. (See *Figure 1*). The datasets for each location included coastal MBES surveys completed by the CHS, overlapping ALB data sets provided to the CHS by contractors, and official CHS ENCs. **Table 1** lists the datasets and each corresponding metadata, including coordinate systems, data types, and data collection methods such as instrument used and data collected.
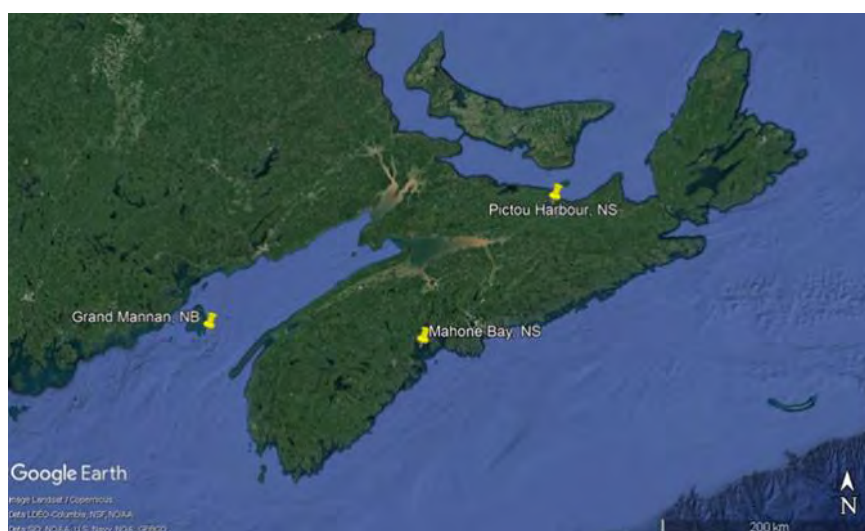

Figure 1 Geographic Location of the Provided Datasets

Table 1 – Study Area Data Sources

Location	Method	Horizontal Coordinate System	Vertical Coordinate System	Data File Type	Date Collected Or Issued Date Year Month	Collection Organization	System or Vessel/ Sonar
GM	ALB	NAD83/ UTM Zone 20N EPSG:26920	CD	Cloud CSAR	2016/ July-August	NSCC-AGRG	Chiroptera II
GM	MBES	WGS 84	CD	5m XYZ	2002-2006	CHS	Unknown
GM	ENC	WGS84	CD	S-57 .000	2018 January	CHS	NA
MB	ALB	UTM 20N WGS84 EPSG 32620	CD	Multiple Raster CSAR 5m	2017 May	IIC Technologies	Optech CZMIL
MB	MBES	UTM 20N NAD83 & UTM 20N WGS84	CD	Multiple Raster 0.5m	2013 July	CHS	Pipit/ EM3002D Tern/ EM3002D
MB	ENC	WGS84	CD	S-57 .000	2017 August	CHS	NA
PI	ALB	UTM 20N NAD83	CD	Cloud CSAR	2016 June-July	IIC Technologies	Optech CZMIL
PI	MBES	UTM 20N WGS84	CD	Multiple Raster CSAR 0.5m	2015 August-September	CHS	Pelican/ EM2040
PI	ENC	WGS84	CD	S-57 .000	2018 July	CHS	NA

3.   Background

Previous research has been completed on developing processes to validate, examine accuracies and
investigate applications and weaknesses of ALB for integration into nautical charting products and
limitations of ALB, such as Pastol (2011), Imahori et al. (2013), and Costa, Battista, & Pittman (2009). Scharff, 2007, specified and highlighted the advantages of ALB for providing depth information at locations difficult for multibeam sonar to access, lists environmental factors as a limitation to ALB technology, and indicates plans to perform comparative analysis for establishing ALB as a useful survey tool

Many techniques for comparative analysis between ALB and multibeam echosounder (MBES) data are described in Imahori et al. (2013) and Pastol (2011). Both references contain many similar comparisons and validation methods of the depth component between ALB and MBES reference surfaces. Imahori et al. (2013) focuses on four coastal areas of the United States that have different seafloor compositions. Surface difference comparisons conclude that three of the four study areas have a comparable agreement to one another. The fourth study area "Pensacola" contains a significantly larger standard deviation much greater than the 0.4 metres consistency reported between the other three areas. Imahori et al. (2013) suggest that this area contains more turbidity, which may have been a factor resulting in this larger standard deviation. Pastol (2011) contains a similar analysis along two coastal regions of France. Study areas include an area fa-

vorable for conducting surveys with clear water properties and another area encompassing a turbid and rugged coastline. Surface differencing results between the ALB and MBES surfaces are at a comparable level of 0.3 metre at standard deviation to the result of 0.4 metres reported by Imahori et al. (2013) at the 2 sigma level.

Costa, Battista, & Pittman (2009) offered a comprehensive combination of methods for comparing between the ALB and MBES datasets, despite the focus on benthic habitat mapping, rather than nautical charting. Bathymetrically, to check their discrepancy in depth against International Hydrographic Organization (IHO) allowable vertical uncertainty, a pixel-to-pixel subtraction was performed between the ALB and MBES derived raster surfaces, with both being preprocessed to be at identical spatial resolutions.

Pastol (2011) compares ALB laser measurements directly to MBES measurements. Similar magnitude values for the standard deviation is observed with a value of 0.3 metres. There are however some discrepancies greater than reported 0.3 metres at specific locations, such as close to piers. These depth discrepancies are suggested to be caused due to properties of an ALB laser that returns values from a spot at the top of a pier as opposed to the actual seafloor value that a MBES would return.

A shoal detection method described in Masetti, Faulkes, & Kastrisios (2018) investigates discrepancies between ENCs derived depths, and a MBES survey derived depths, through interpolation of S-57 ENC hydrographic feature layers. S-57 layers are standard data formats established by IHO, and abided by hydrographic offices across the globe for the transferring and sharing of data sources, such as an ENC, to mariners, and other hydrographic offices. An ENC is an electronic form of a chart composed of several of these S-57 layers (UK Hydrographic Office, 2019). Masetti et al., (2018) utilized a selection of the ENC S-57 layers including the depth soundings (SOUNDG), depth contours (DEPCNT), and coastline (COALNE) layers to create a triangulated irregular network (TIN). A TIN in general, "consists of a network of irregular triangles generated by connecting the nodes of a dataset in a way that guarantees the absence of intersecting triangle edges and superposed triangle faces, but also ensuring that the union of all the triangles fills up the convex hull of the triangulation…" (Masetti, Faulkes, & Kastrisios, 2018). The TIN is then compared with MBES depths through several algorithms to detect potential discrepancies between the data sources as areas the MBES soundings report shallower than reported on the ENC. The study did not consider ALB depths.

The results from the previous comparisons of ALB and MBES show consistency in the magnitude of the vertical differences. However, these studies have been limited to a handful of study areas using only a few ALB sensors and comparative methods. To improve and establish ALB as an effective survey tool, analysis is required over a range of sensors, locations, and exploring alternative methods (Imahori, et al., 2013).

4.   Methods

ALB vertical accuracy is quantitatively assessed by estimating the difference in depth between ALB datasets and a dataset assumed to be the baseline, and then comparing the estimated depth difference with respect to the maximum allowable vertical uncertainty, as prescribed by IHO's and CHS' allowable vertical accuracy for hydrographical surveys (*Figure 2*). Considering data availability at a specific location, the baseline dataset is MBES depth rasters, as investigated in other studies, or depth rasters interpolated from ENC layers, as an extension of the MBES to ENC shoal detection method described in Masetti, Faulkes, & Kastrisios (2018). Therefore, the assessment is realized through surface-to-surface comparison with MBES dataset and ENC surfaces.
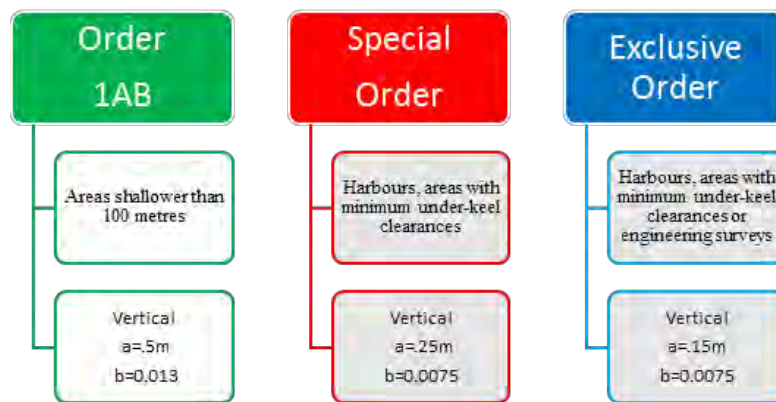
Figure 2– *Survey order levels*

The depth raster datasets for ALB and MBES were imported into Caris Base Editor. Datasets that were provided in Caris Spatial ARchive format (CSAR) were directly imported; however, those not provided in this CSAR format were imported to Caris Base Editor through the Import Wizard as XYZ files. Difference statistics between MBES with respect to ALB surfaces were calculated for each area using the Surface Differencing tool in Caris Base Editor. For consistency in comparisons, ALB was always subtracted from MBES or ENC derived surfaces, and all depths were positive down. Difference CSARs were exported to GeoTiff raster for processing with ArcMap to analyze depth differences at each node with respect to First Order, Special Order, and Exclusive Order from *Figure 2*. By using the Total Vertical Uncertainty (TVU) equation (International Hydrographic Organization (IHO), 2008) and the MBES depth, a surface containing the allowable uncertainty for each node was computed at each survey order and was compared with difference surfaces referred to as "pass and fail" surfaces. A pass-fail surface determines areas that are inside and outside of the allowable uncertainties associated at each survey order based on the depth at the node. These surfaces were created for comparisons of MBES and ENC with respect to ALB. *Figure 3* shows the model used to compare the depth difference values with survey order uncertainties. First the "a" and "b" values (see *Figure 2*), and depth value from the MBES or ENC surface were used as input into the calculation that used the TVU equation to determine the allowable uncertainty at each node. The calculation result created an allowable uncertainty raster created by replacing the depth value at each node with an absolute allowable uncertainty for that specific depth. This raster was then used to compare each node of the depth difference surface to evaluate whether the corresponding node from the depth difference surface was within the value from the allowable uncertainty raster. If the value was within the allowable uncertainty, the node was assigned a value of 1, and if it was not within the allowable uncertainty, a value of 0 was assigned to create a new surface to represent regions where depth differences meet the allowable uncertainties. Statistical analysis was conducted through Matlab to compare difference values of MBES and ENC datasets with respect to ALB. Statistics for each dataset, including the mean, median, and standard deviation at the one and two sigma levels were computed and compared with survey orders uncertainties.
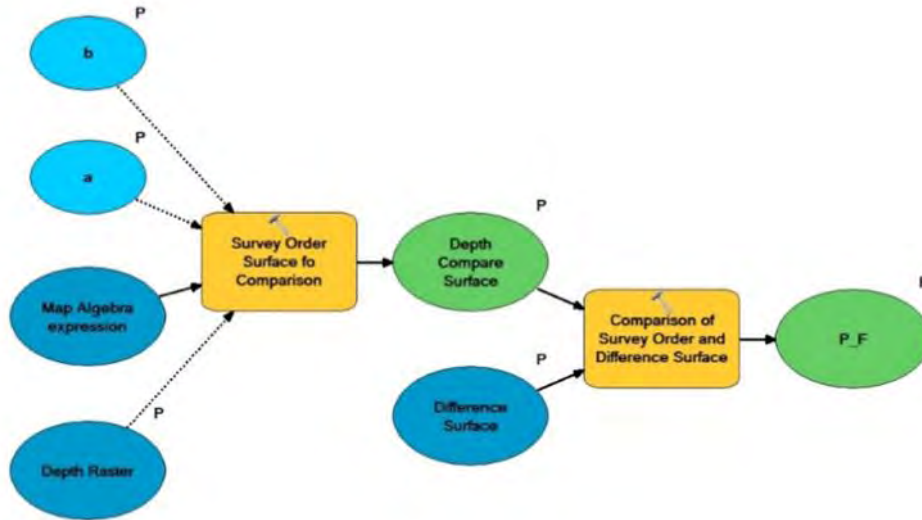
Figure 3- Depth comparison model

Adopting the methodology for creating a TIN provided by Masetti, Faulkes, & Kastrisios (2018), an ENC derived depth surface was created for comparison to ALB. The TIN was generated in Caris Base Editor through selection and creation of a HOB file containing the ENC depth contours (DEPCNT) and ENC soundings (SOUNDG) layers. This HOB file was created through a *Select by Feature Acronym* and by exporting the selection to a HOB file. TINs for each ENC from **Table 1** were created using this HOB file (see ***Figure 4***). TINs included Delaunay triangles which passed through land features that required removal, as these provide false depth values. Using the Arc Map Model Builder process that uses a land feature polygon to cut out overlapping regions from the interpolated surface, all falsely interpolated values that appear over land were removed. This process is illustrated through a flow chart and images in ***Figure 4***.
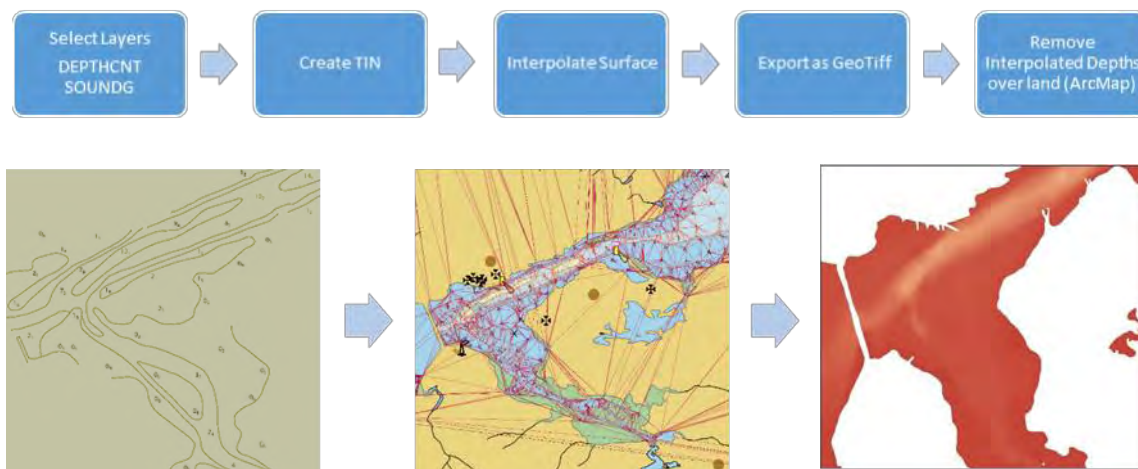

Figure 4 - ENC layers to depth raster

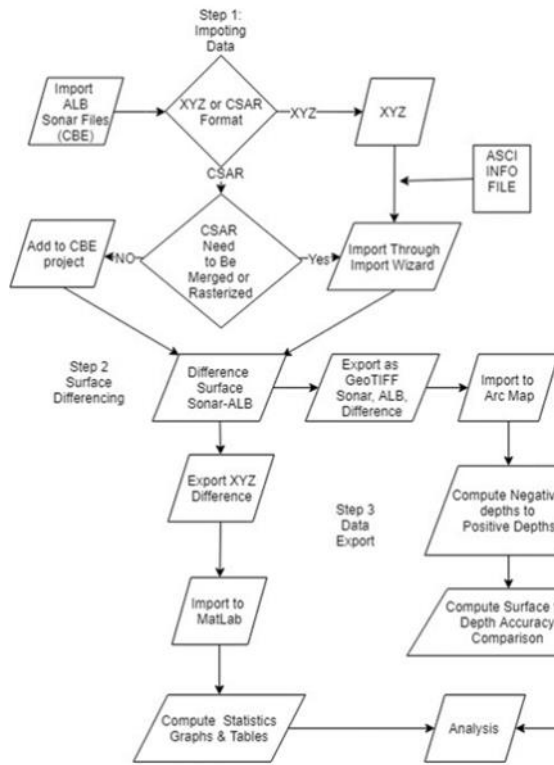**Figures 5 and 6** illustrate the process followed for comparisons and analysis of MBES and ENC with ALB, respectively.

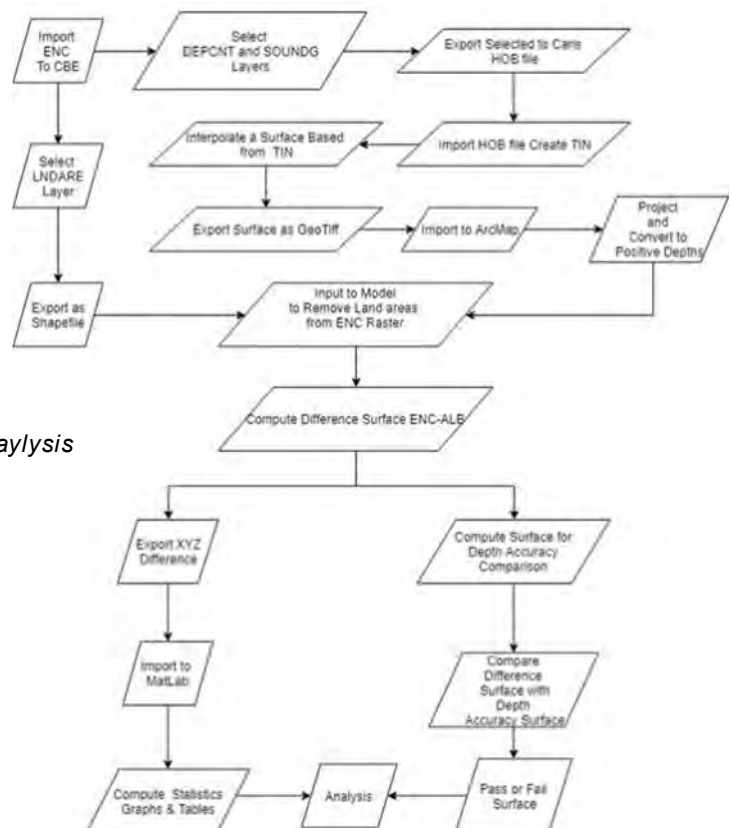Figure 5 MBES processing and anaylysis with respect to ALB

Figure 6 ENC processing and anaylysis with respect to ALB

5.   Results

MBES vs ALB Comparison

Depth Differencing using MBES as a baseline in Pictou, and Mahone Bay NS show that over 90% of depth differences fall within the allowable uncertainty at each node for First Order survey (see **Table 2**). A pass and fail map shown in **Figure 9** describes areas that are within First Order survey standards. Blue areas represent regions in Pictou that do not conform to the survey stand-ard requirements, in this case, the First Order level. Closer investigation of satellite images in these areas suggests that dense under-water vegetation may have been an affecting factor for the ALB to penetrate through to the seafloor in Pictou (Kuus, Hughes Clark, & Brucker, 2008). **Figures 11 and 12** profile graphs illustrate this possibility by ALB (red) depth values reporting much shallower than the MBES (blue) derived depths. In Mahone Bay difference values that are not within survey First Order uncertainties correspond to the blue areas in **Figure 10**. Local inspection through profile analysis show ALB (red) reporting depths with magnitudes of up-wards to 2 metres deeper than the MBES (blue) reported depths (see **Figure 11 and 12**). The red box over the left tail of the difference histogram in **Figure 8** shows that ALB is reporting depths that are statistically deeper than MBES approximately 8% of the time. This is of concern for safe navigation as if the ALB depths were to be incorporated directly into navigational products; this deep bias could lead to vessel accidents where published depths on navigational product are incorrect.

Table 2 - Percentages of Depth Difference within each Survey Order

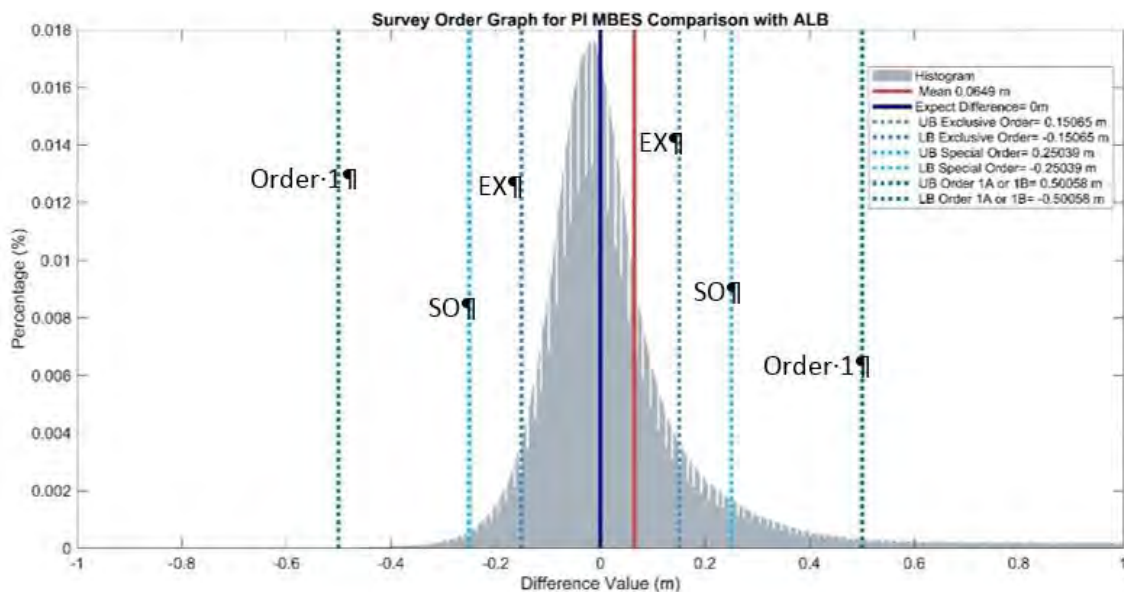| Location Technol-ogy	PASS Percentage Order 1	PASS Percent-age SO	PASS Percent-age EX
GM ENC	17	8	5
MB ENC	31	16	10
MB MBES	91	52	27
PI ENC	61	32	19
PI MBES	95	89	79

Figure 7-Pictou, NS MBES Histogram of Depth Differences compared with Survey Orders
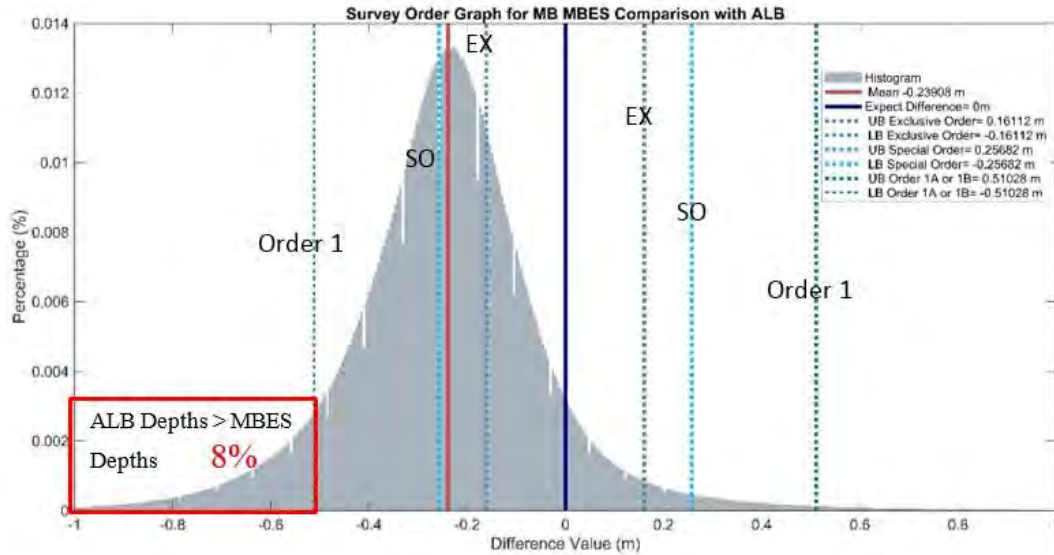
Figure 8-Mahone Bay, NS MBES Histogram of Depth Differences compared with Survey Orders
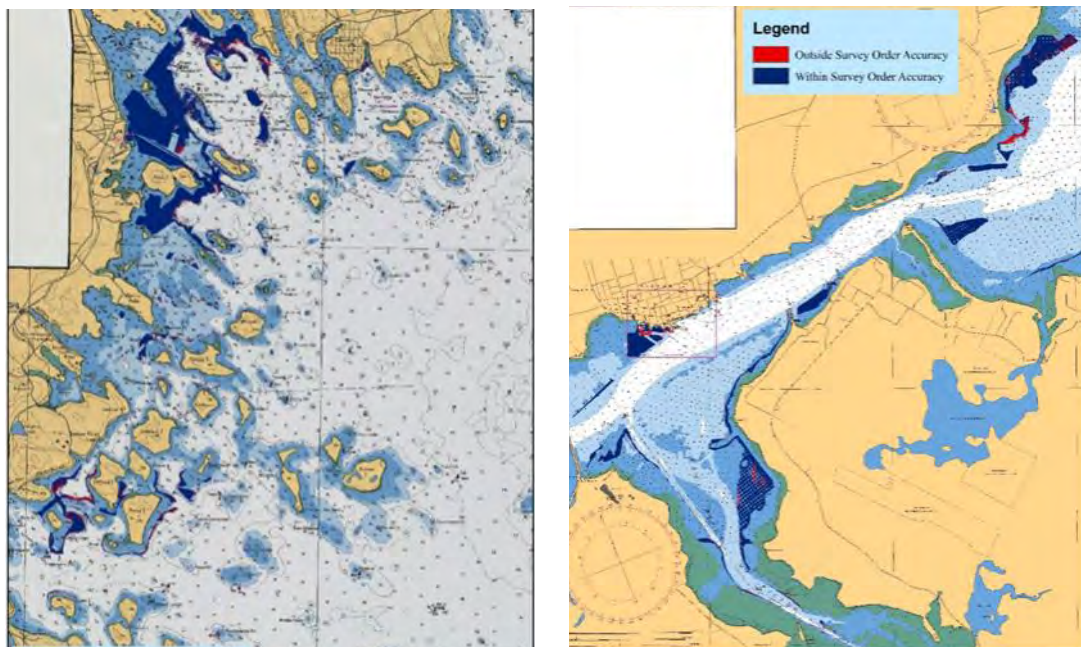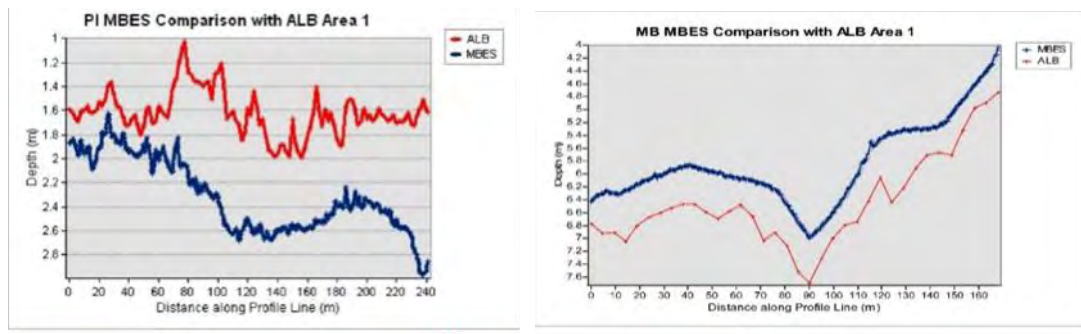

Figure 9 and 10-MBES Pass/Fail Map at First Order (left Mahone Bay, NS, right Pictou, NS)

Figures 11 and 12-profile analysis (Depth is positive down, MBES shown in Blue, and ALB shown in red left Pictou, NS, Right Mahone Bay, NS

An additional finding with the Mahone Bay dataset was visible systematic flight-line patterns in the ALB dataset. *Figure 13* illustrates a systematic bias in each flight line that can be correlated to the skew noticed by the histogram in *Figure 8.*
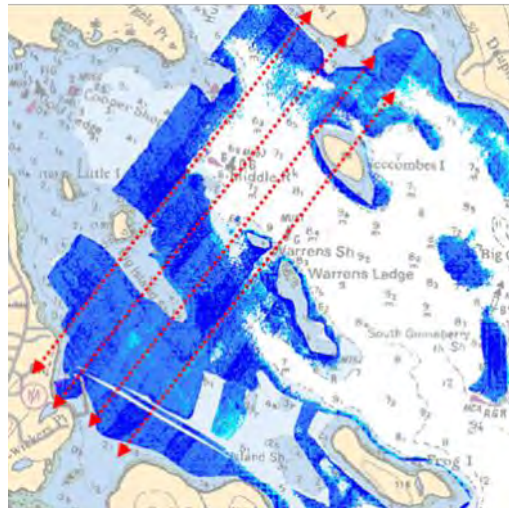

Figure 13- ALB Flight lines at Mahone Bay, NS

ENC vs ALB Comparison

The ENC surface contained a significantly larger amount of overlap with ALB than compared to the MBES surface, as expected (see *Figures 14 and 15*). Although a larger amount of coverage was provided, the depth differences reported only 61% to be within the First Order for Pictou, 31% for Mahone Bay, and 17% for Grand Manan (see **Table 2**). *Figures 16* illustrate the percentages for each location in blue that were within First Order uncertainties. Simplified cartography data were interpolated to a surface for comparison with high-density ALB surface leading to a conclusion that the TIN interpolation using depth contour, and depth sounding layers, does not represent the detailed seafloor between the depth values. While this result is expected, the power of the comparison methodology is in shoal detection. The region outlined by the red boxes in of the histograms of *Figure 17, 18 and 19* show that 23%, 25% and 43% for the locations Pictou, Mahone Bay, and Grand Manan respectively have depth differences between ALB and ENC larger than the allowable First Order survey level with ALB reporting depths shallower than the ENCs . These regions signify where chart updates and further investigations are required to ensure safe and accurate depths are shown on navigational products.
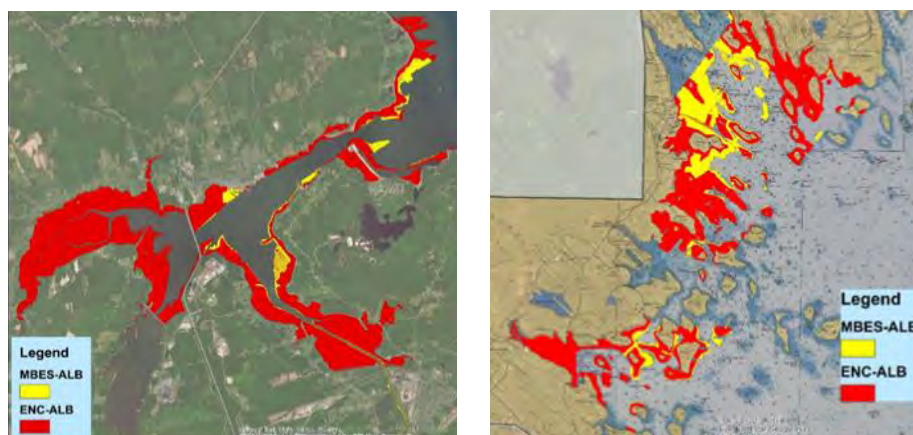

Figure 14 and 15-ENC overlap with ALB compared with MBES and ALB overlap
(left Pictou, NS, right Mahone Bay, NS)

Areas Not Within Accuracy
Areas Within Accuracy

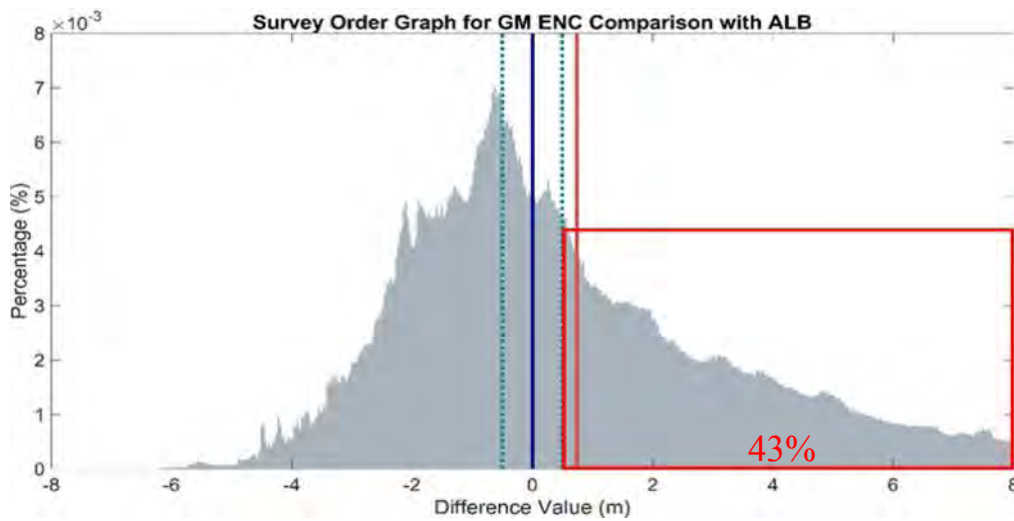*Figure 16- Area within first order accuracies from ENC*

Figure 17- ENC Grand Manan, NB Histogram of Depth Difference between ENC and ALB Surfaces
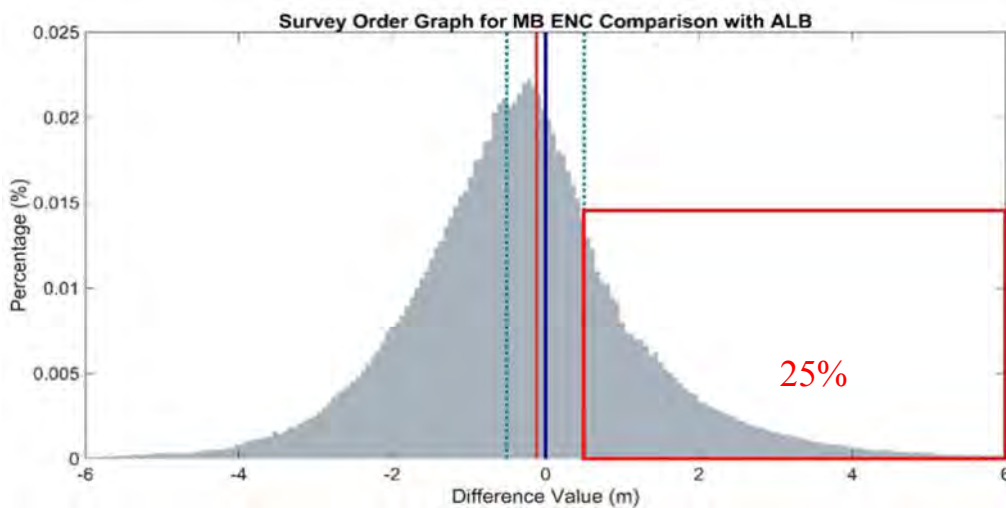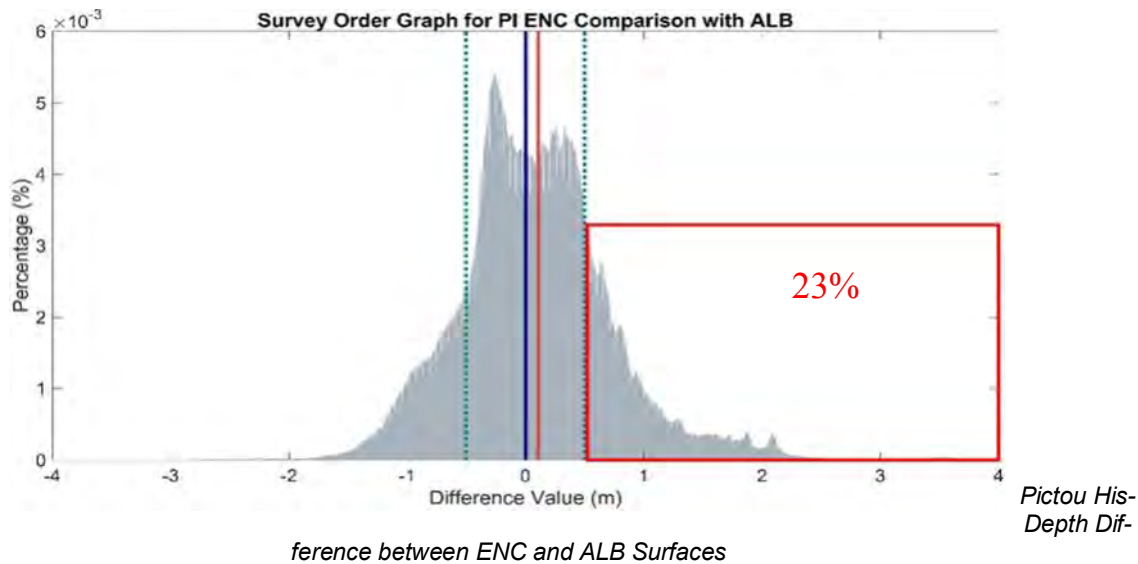

Figure 18- *Mahone Bay, NS Histogram of Depth Difference between ENC and ALB Surfaces*

Figure 19- *Pictou His-*
togram of *Depth Dif-*

ference between ENC and ALB Surfaces

6.   Conclusions

Vertical depth differencing comparisons between ALB and MBES datasets provided a good agreement for Pictou and Mahone Bay locations, with over 90% of depth differences within the allowable uncertainties of the First Order Survey Level. Results in areas with pronounced natural seafloor attributes, such as vegetation in Pictou and slopped areas from Mahone Bay, deviated from this high percentage of agreement with most differences in these areas well outside of the allowable uncertainty ranges.

The use of ENCs was explored to interpolate a surface for comparison and assessment of ALB datasets. This comparison produced the poorest statistical results of all the vertical comparison methods, mainly due to how the surface was interpolated for the ENC layers. The ENC depth difference and assessment with ALB did, however, highlight areas to consider for ENC chart updates, providing an efficient means of focusing ALB data assessment and processing.

In summary, the most effective method for vertical assessment of ALB datasets is depth differencing with MBES datasets, but the comparison results vary greatly by region. The technological limitations of ALB are highlighted in areas of dense seafloor vegetation (Pictou) and steep slopes (Mahone Bay), but the efficiency gains are clear, especially in relatively flat, shallow areas (Pictou). Comparisons with ENCs provides an additional method for assessment, which may prove especially useful in locations where MBES datasets are not available or where focused data processing areas need to be identified for chart updates.

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