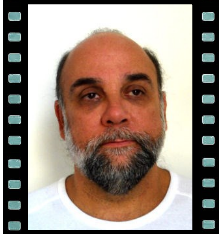

EVALUATION OF THE PRECISION OF PHASE-MEASURING BATHYMETRIC SIDE SCAN SONAR RELATIVE TO MULTIBEAM ECHOSOUNDERS

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Abstract

The International Hydrographic Organization (IHO) and the Directorate of Hydrography and Navigation (DHN) consider that where the under-keel clearance is critical, bathymetric surveys should provide full seafloor coverage. Multibeam Echosounders (MBES) and Phase-Measuring Bathymetric Side Scan (PMBS) are capable sensors to achieve this coverage, however, they have different technologies. The MBES is widely accepted by the international community and considered the standard system in surveys that require the highest IHO accuracy. The aim of this paper is to assess whether the PMBS can achieve comparable results with the MBES, focusing on Nautical Chart production. Despite “noisy” data and some effects, this research suggests that PMBS can be used to meet IHO requirements, under some special conditions.

Résumé

L'Organisation Hydrographique Internationale (OHI) et la Direction de l’hydrographie et de la navigation (DHN) considèrent que les levés bathymétriques devraient fournir une couverture complète du fond marin pour mettre à jour les cartes marines où le dégagement sous la quille est critique. Les capteurs bathymétriques capables d'atteindre une telle marque sont les sondeurs multifaisceaux et le balayage bathymétrique à mesure de phase. Cependant, la technologie d'acquisition est différente dans chaque capteur. L'échosondeur multifaisceaux est déjà largement accepté par la communauté internationale et considéré comme le système standard dans les enquêtes qui nécessitent la plus grande précision de l'OHI. Par conséquent, cet article évalue si le côté bathymétrique à mesure de phase atteint un résultat compatible avec l'échosondeur multifaisceaux, en se concentrant sur la production de cartes marines. Malgré les données bruyantes et certains effets, cette recherche suggère qu'il peut être utilisé dans certaines conditions.

Resumen

La Organización Hidrográfica Internacional (OHI) y la Dirección de Hidrografía y Navegación (DHN) consideran que cuando la sonda bajo quilla es crítica, los levantamientos batimétricos deberían proporcionar una cobertura completa del fondo marino. Las Ecosondas Multihaz (MBES) y el Sonar de Barrido lateral batimétrico de medición de fase (PMBS) son sensores capaces de lograr esta cobertura. Sin embargo, tienen tecnologías diferentes. El MBES es ampliamente aceptado por la comunidad internacional y se considera el sistema estándar en los levantamientos que requieran la mayor precisión de la OHI. El objetivo de este documento es evaluar si el PMBS puede lograr resultados comparables al MBES, centrándose en la producción de Cartas Náuticas. A pesar de los datos «ruidosos» y algunos efectos,

1. Introduction

An important component of a hydrographic survey is the bathymetric measurements. Currently, Multibeam Echosounder (MBES) systems are the most used sensor for morphological investigation and seafloor mapping. It fulfills the International Hydrographic Organization specifications (IHO, 2008) and the Brazilian Hydrographic Service requirements, due to its swath and low uncertainty.

However, the Phase-Measuring Bathymetric Sidescan (PMBS) has been presented as an alternative technology to the MBES. Some studies were presented by Gostnell (2005), Gostnell, Yoos and Brodet (2006), Madricarlo, Foglini and Tonielli (2011), Dodd (2013), Brisson, Wolfe and Staley (2014), Ai, Armstrong and Fleury (2015), Jerram and Schmidt (2015a), Ma, Xu and Xu (2016) and Bongiovanni and Schmidt (2016), where issues regarding data acquisition, processing methodologies and potential uses of this equipment were discussed.

Even after positive results, the PMBS technology remains under discussion. The equipment is applied by some hydrographic services (e.g. USACE – USA) and not fully adhered to by others (NOAA – USA). In Canada, regulations are provided to be followed, but no specific equipment is mentioned to achieve them. In Brazil, the present standard procedures do not define the acceptance of any equipment, but several requirements are usually achieved by MBES (DHN, 2017). The use of PMBS is, therefore, very incipient in the country, owing to both the existing world controversy and the lack of national studies with methodical hydrographic rigor focusing on regional scenarios (oceans, rivers, lakes and seas).

This work adds to previous efforts in the analysis of PMBS performance, seeking to improve consistency to the evaluation of the PMBS suitability for Special Order hydrographic surveys. To accomplish this, the IHO and the Brazilian Hydrographic Service specifications (defined by the Directorate of Hydrography and Navigation) were strictly observed.

2. Theoretical concepts

MBES are sonars capable of providing bathymetric data by crossing the acoustic waves through a transmitting and a receiving sensor, which are arranged orthogonally, in a technique known as mills cross (Bjørnø, 2011; L-3 COMMUNICATIONS SEABEAM INSTRUMENTS, 2000; Simmons et al., 2017). In this arrangement, the beams are formed at the intersections between the transmitting and the receiving wavefronts (L-3 COMMUNICATIONS SEABEAM INSTRUMENTS, 2000). These beams, after the two-way travel time, provide the seafloor signal detection that is used to calculate the depth, which is done by amplitude or phase detection (IHO, 2005).

The PMBS is a sensor capable of simultaneously providing backscatter and bathymetric information (Jerram and Schmidt, 2015a). It consists of a transmitter and more than one receiver spaced at a distance multiple of the signal wavelength “λ” (KONGSBERG MARITIME, 2014; Lurton, 2000; Wilby, 1999). Georeferenced depth information is provided by measuring the echo’s phase difference at the receiver transducers (IHO, 2005).

In a quick comparison, the PMBS has a lower cost (Ai and Parent, 2011); has a greater swath capability in shallow water (Brisson; Wolfe; Staley, 2014; Gostnell, 2005; Jerram and Schmidt, 2015b); provides a faster survey with better visualization at the edges of the swath (Brisson; Wolfe; Staley , 2014); has a higher data density (USACE, 2013), leading to a larger across-track resolution (1-10 mm) (Jerram and Schmidt, 2015a; Jerram and Schmidt, 2015b; Ma; Xu; Xu, 2016); has the same backscatter view of a sidescan sonar (Brisson; Wolfe; Staley, 2014; Jerram and Schmidt, 2015b); and uses the principle of interferometry, which is also used in MBES phase detection of the outer beams.

Despite these characteristics, the PMBS is not yet fully accepted by the international hydrographic community (Brazil included). This is due to a number of factors such as low detection capacity in nadir (Dodd, 2013, Ma, Xu, Xu, 2016); very noisy data (Dodd, 2013; Jerram and Schmidt, 2015b); depth ambiguity (layover); large volume of data, which requires better computing capability (Jerram and Schmidt, 2015b; Ma; Xu; Xu, 2016); and strong vertical uncertainty (Brisson; Wolfe; Staley, 2014; Jerram and Schmidt, 2015b; NOAA, 2017).

3. Methodology

3.1 TESTS AND AREAS

In order to evaluate the acceptance of PMBS by the Brazilian Hydrographic Service, tests were developed to assess certain critical capacities, while comparing the results with a simultaneously acquired MBES survey. To perform this experiment, a vessel-pole-mounted PMBS and vessel-organic hull-mounted MBES were used.

Five test sites were chosen within the Guanabara Bay (***Figure 1***). The Guanabara Bay has an area nearly 384km^2, with a central channel approximately 30 meters deep. The seafloor has an average depth is 5.7 meters and consists of quartz sand at the entrance to the Atlantic Ocean, associated to the effects of waves and tides. The remainder of the seafloor, is mostly mud, resulting from Holocene transgression and river sedimentation (Kjerfve et al., 1997).

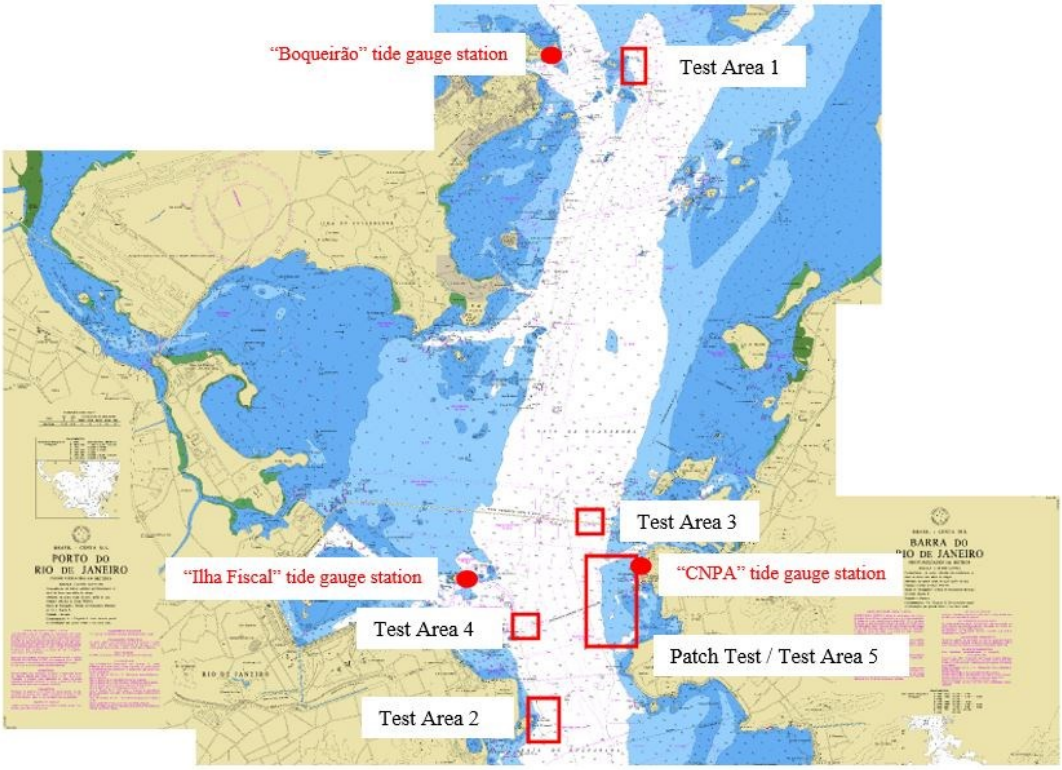


Figure 1 *– Location of the test areas and the tide gauge stations. Source: Adapted by authors.*

Test Area 1 aims to verify the ability of PBMS to precisely detect and delineate bathymetric features. The area is about 13 meters deep and approximately 0.375km^2 wide (750m x 500m), with numerous rock outcrops with varied sizes and shapes.

Test Area 2 is designed to check the ability of PBMS to resolve slopes with shallow to steep gradients. The chosen area covers around 0.350km^2 (550m x 700m) in the vicinity of Villegagnon

Island, with varied gradients and depths ranging from 1.5m to 39m. In this way, several slope gradients (approximately 4 to 10 degrees) were covered, providing data for different analyses.

Test Area 3 aims to observe the maximum distance the PMBS can detect objects that are pronouncedly off the seafloor and estimate their height. The detection of objects with substantial vertical relief is a fundamental factor for safety of navigation. For this purpose, an area of 0.1Km^2 (250m x 400m) and with an average depth of 15 meters was selected. The area comprises 5 pillars of the Presidente Costa e Silva Bridge which rise above the water. This allows simulation of targets that the survey vessels cannot approach due to the risks involved.

Test Area 4 seeks to detect the shoalest depths of pronounced vertical features that do not reach the water surface. Thus, a wreck area of 0.330Km^2 (600m x 550m) was chosen, with an average depth around the object of 30 meters, with a minimum known depth of 20.8 meters.

Test Area 5 aims to verify the efficiency of the PMBS compared to MBES. The survey line spacing was chosen according to interferometric parameters. It is known from the literature that the PMBS has a maximum swath width of approximately 10-12 times the water depth, while the MBES has 5-6 times the water depth (Jerram and Schmidt, 2015b). The purpose was to verify the useful coverage efficiency of the PMBS. For this test, we choose an essentially flat area of approximately 1.4km^2 (1,750m x 800m) with depths varying from 3 to 20 meters.

Test Areas 3 and 4 were also used for the resolution tests; verifying bathymetric resolution and data density.

3.2 EQUIPMENTS

The survey was performed on August 02nd and 03rd of 2017. The equipment used were:

A blister-mounted *Kongsberg EM2040* multibeam echosounder, operating at 400KHz central frequency; INS *Kongsberg Seapath 300* with *MRU5* and 2.582m spaced heading antenna; GPS positioning with *Fugro DGNSS 3710* correction; *AML Micro X* sound velocity sensor; and *Kongsberg SIS* navigation and acquisition software.

A pole-mounted Kongsberg Geoacoustics Geoswath 4R phase-measuring bathymetric sidescan, operating at 250KHz central frequency; INS *Applanix POS MV WAVE MASTER* 2 and 1.9m spaced heading antenna; GPS positioning with *RTK Marinestar Fugro* correction; *Valeport Mini SVS 25mm* sound velocity sensor; and *Geoswath Plus* acquisition software*.*

The Sound Velocity (SV) Profile information was acquired using the *AML Minos X* sensor at 10cm resolution. SV data was processed into the SIS software and uploaded into the data during acquisition in MBES and during the post-processing in PMBS. The profiles were acquired before commencing the survey in each area and in every time the SV varied more than 2 m/s at the face-of-transductor sound velocity sensor.

The tide information was collected at tide gauge stations of Boqueirão, Fiscal Island and the Ponta da Armação Naval Complex (CNPA, in Portuguese) (***Figure 1***).

Throughout the survey, the weather was fine, with low wind speeds (0-3 on the Beaufort scale).

3.3 PROCESSING DATA

MBES data were processed in CARIS HIPS & SIPS 10.2. The PMBS data were processed in the GEOSWATH PLUS software. Both data were then exported to CARIS HIPS & SIPS 10.2 for the CUBE surface generation at different resolutions.

3.4 QUALITY CONTROL

The quality control was performed by measuring the precision and accuracy of each surface node.

3.4.1 Precision

The precision was verified by two methods: 1 - calculating the CUBE hypothesis TPU (Calder and Mayer, 2013); 2 - calculating the sample uncertainty of each node.

In the first method, if 95% of the nodes had a TPU within the recommended range for a given IHO Order, the surface would be accepted for that Order. In the second method, the node sample uncertainty was calculated from the standard deviation multiplied by 1.96 (in order to have 95% confidence, considering a Normal distribution) of all the considered valid depth information that is contained within a node (Pereira, 2016). In practical terms, it represents the dispersion of the data and is equivalent to the first one. If 95% of the nodes show sample uncertainty within the range recommended for a particular IHO Order, the surface will be considered in that Order.

While the first method takes into account the uncertainties that give rise to depth information, the second is based on the coherence of the bathymetric data.

3.4.2 Accuracy

The accuracy of PMBS surfaces was evaluated in three ways: (1) observing the dispersion of the MBES data (here considered as the reference surface) relative to the PMBS depth surface (here called layer $\text{Depth}_{\text{PMBS}}$); (2) by calculating the depth difference surface between the MBES ($\text{Depth}_{\text{MBES}}$) and the PMBS ($\text{Depth}_{\text{PMBS}}$) surfaces; (3) by calculating the surfaces that contain the difference of the shallowest depth information, hereinafter referred to as Shoal layers ($\text{Shoal}_{\text{MBES}}$ and $\text{Shoal}_{\text{PMBS}}$).

The multibeam data dispersion from the $\text{Depth}_{\text{PMBS}}$ layer was done using the "QC Report" tool of the CARIS HIPS & SIPS software (CARIS, 2017). The program checks the statistics of some standard lines (MBES lines) against the surface that will be evaluated ($\text{Depth}_{\text{PMBS}}$). Based on the surface depth values, another two above-and-below parallels surfaces are virtually created, ranging the TVU IHO Orders. If, the percentage of pings of each line that lies within this range is higher than or equal to 95%, the surface can be considered representative of the order it was evaluated against (Pereira, 2016).

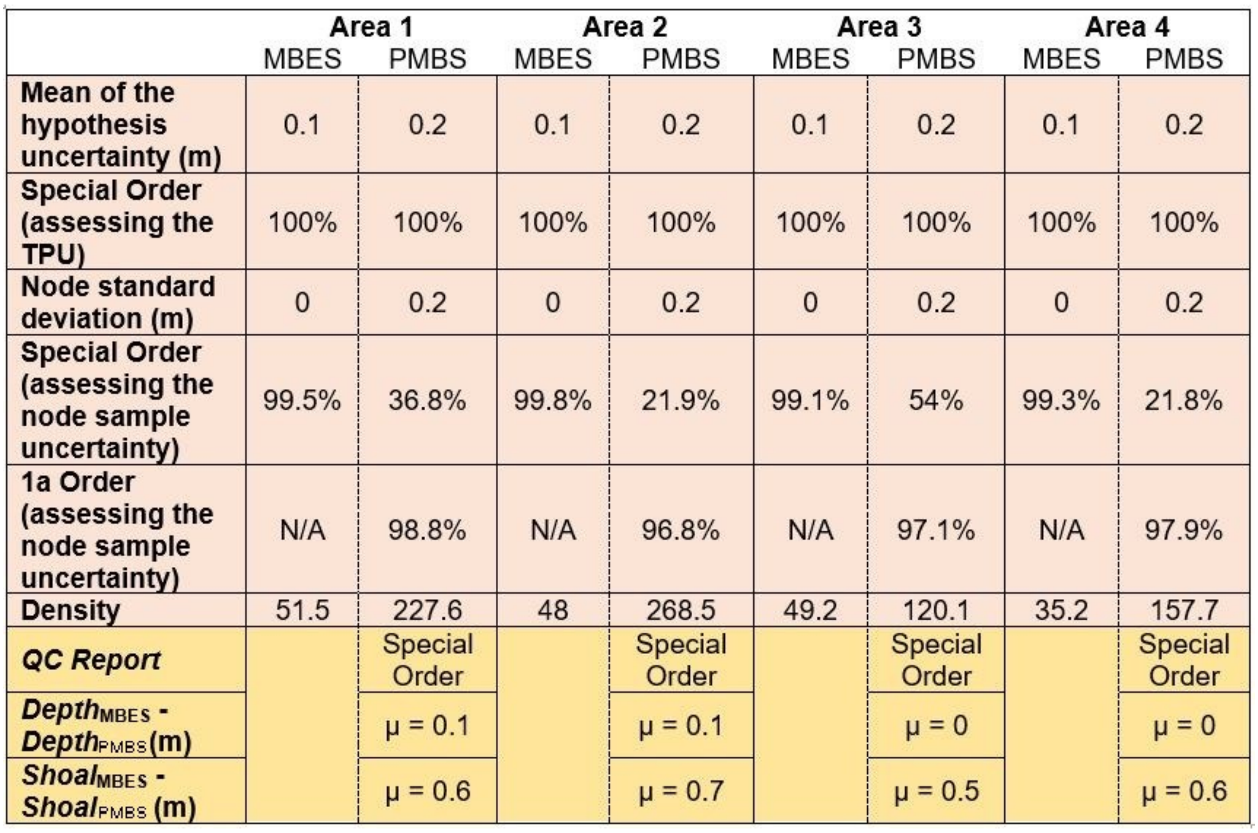
The difference surface is calculated by subtracting the values of the MBES and PMBS depth layer ($\text{Depth}_{\text{MBES}}$ - $\text{Depth}_{\text{PMBS}}$). Such procedure provides a qualitative comparison opportunity.

The layer containing the difference of the shallowest depth is very useful for hydrographic services. In Brazil, to ensure navigation safety, the surface layer used to create the nautical chart is the one that contains the shoalest depths found at each node. Although this surface may not be the most accurate or suitable when it comes to the real seafloor identification, it is useful to guarantee there will be no obstacles shallower than those selected and reported during the data processing.

4. Results

Table 1 gives an integrated perspective of the results. It is possible to observe that the analysed criteria from all areas have very similar statistical results.

Table 1 – Statistical Results for all surveyed areas. Organized by the authors.



	Area 1		**Area 2**		**Area 3**		**Area 4**	
	MBES	PMBS	MBES	PMBS	MBES	PMBS	MBES	PMBS
Mean of the hypothesis uncertainty (m)	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
Special Order (assessing the TPU)	100%	100%	100%	100%	100%	100%	100%	100%
Node standard deviation (m)	0	0.2	0	0.2	0	0.2	0	0.2
Special Order (assessing the node sample uncertainty)	99.5%	36.8%	99.8%	21.9%	99.1%	54%	99.3%	21.8%
1a Order (assessing the node sample uncertainty)	N/A	98.8%	N/A	96.8%	N/A	97.1%	N/A	97.9%
Density	51.5	227.6	48	268.5	49.2	120.1	35.2	157.7
QC Report		Special Order		Special Order		Special Order		Special Order
$\mathit{Depth}_{MBES} - \mathit{Depth}_{PMBS}$ (m)		μ = 0.1		μ = 0.1		μ = 0		μ = 0
$\mathit{Shoal}_{MBES} - \mathit{Shoal}_{PMBS}$ (m)		μ = 0.6		μ = 0.7		μ = 0.5		μ = 0.6

Regarding the accuracy of each test site, it is possible to observe that the mean hypothesis uncertainty calculated by the CUBE algorithm was lower than the one recommended for Special Order for both methods, so that all surface nodes satisfy this requirement. Regarding the node standard deviation, the MBES showed a considerably smaller deviation (***Figure 2b***) than the PMBS (***Figure 2c***)., meaning that the valid data from the second sensor (PMBS) are more scattered. Due to the small dispersion of the node standard deviation, the MBES data was classified as Special Order, while the PMBS data can only be classified as Order 1A. Another aspect to be observed is that the average density of the pings per node was 2.4 to 5.6 times greater for the PMBS than that of the MBES.

When the accuracy is analyzed, it is observed the PMBS surface reached Special Order. The difference between the depth surfaces (Depth layers) ranged from 0 to 0.1m, with the MBES surface being shallower. This indicates that the two sensors estimated the depths in a remarkably similar way. The situation changes when we consider the difference between the Shoal layers. In this case, the difference varies between 0.5m and 0.7m proving again the dispersion of the PMBS data. If the data considered valid from the PMBS had cohesion like the MBES, the range of depth difference between the Shoal layers would be equivalent to the differences observed for the Depth layers.

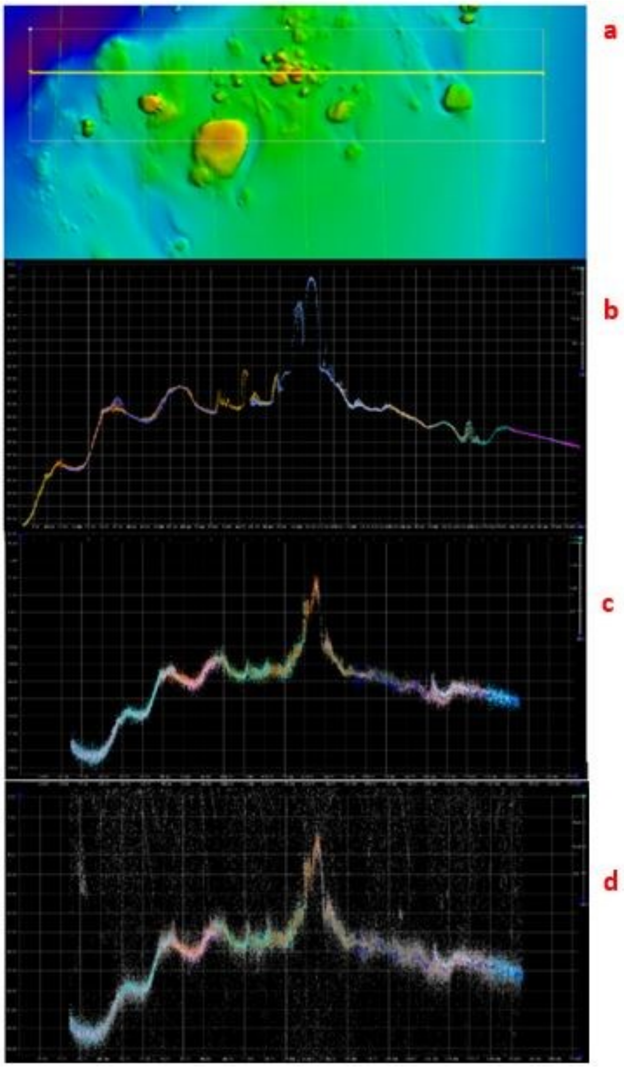


***Figure 2** – **a)** Rock outcrops in Test Area 1. The yellow line marks the profiles shown in the frames bellow; **b)** a MBES data profile; **c)** a PMBS data profile; **d)** a PMBS data profile with the reject data*

4.1 AREA 1 AND 2 – LAYOVER EFFECT STUDY CASE

A layover effect occurs when two different echoes arrive at the same time at the transducer. As there are no sectoral angles of reception, as in the multibeam, the sensor processes the two signals as noise. Sometimes, this ambiguity also happens when the sonar beam reaches the top of a tall feature before it reaches the base of it and is more critical in nadir and steep gradient regions. From ***Figure 3***, one can better visualize how this effect occurs in sloping features. In this figure, the seafloor is represented in blue, an imaginary seafloor with higher slope represented by the dotted green line, the sensor by the yellow dot and the wavefront in orange. It is possible to notice that, in the case of the blue seafloor whose slope is smaller than the opening angle θ, the “echo B” will have traveled a greater distance than the “echo A”. If the green seafloor is considered, we have the opposite situation and “path B” would be shorter than “path A”, arriving at the sensor at the same time as some other echo reflected by the seafloor, creating ambiguity and, therefore, noise. Thus, it can be concluded that if the distance travelled “B” ≤ “A”, there will be information ambiguity, and that if the slope of some seabed feature is greater than the complement of the grazing angle α, the layover effect of will occur.

The PMBS useful swath is 10 to 12 times the water depth, so there are incident angles ranging from approximately 90° to 5.7° to 4.3°. Thus, it is known that features with slopes approximately greater than 85.7° will always be subject to layover effect.

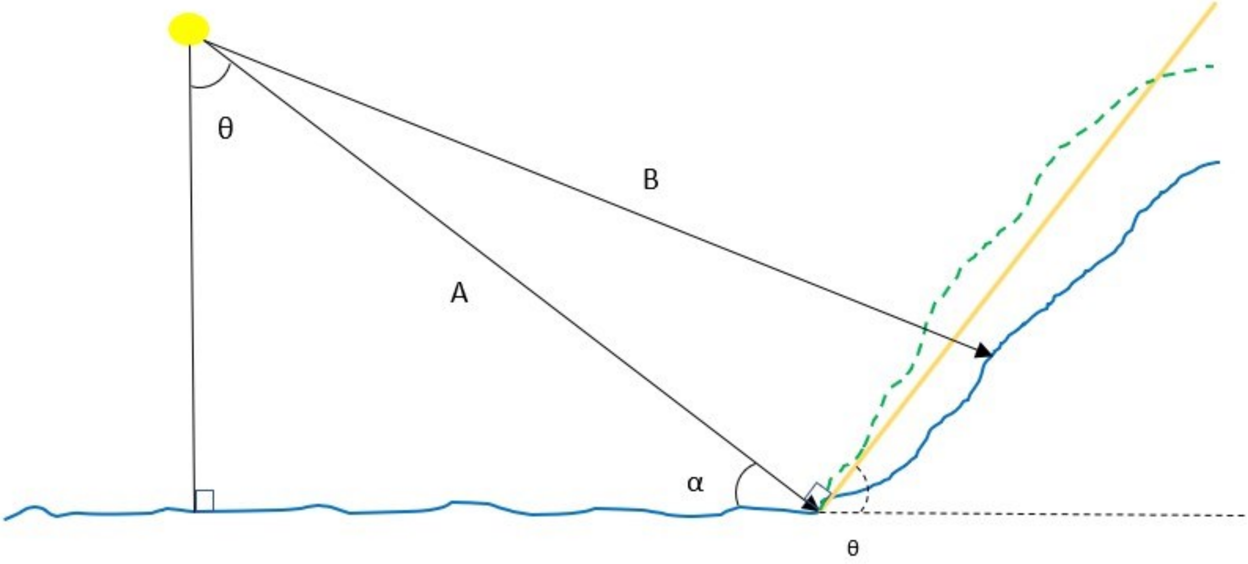


***Figure 3** – Layover Effect principle*

However, adjacent survey lines tend to reduce the layover effect if the gradient is not so abrupt. In a 200% coverage situation, the terrain will be ensonified at least by two swaths that will have points with different aperture angles, so that while one of the swaths may show layover effect, the other may not. When the seafloor or target has a slope greater than the maximum incident angle (around 5°), this effect cannot be remedied. Therefore, this effect was not seen in Area 2, where the seafloor slope is very low, but can be seen in the rock outcrops of Area 1 where the slopes of the rock edges are larger than the PMBS maximum transmission opening angle. An interesting example is the rock shown in ***Figure 4a*** (inside the red circle). On the softer gradient side, there is no layover effect, while in the most abrupt side it was evident.

It can be observed in the Shoal Depth surfaces difference (***Figure 4a)*** that the shape of the rocks does not get very well defined in the PBMS data compared to the MBES data (***Figure 4b***), resulting in depth misestimation. The largest ones lie exactly at the steep edge of the rocks (***Figure 4a***). Because these areas are very steep, they are susceptible to the layover effect. In Test Area 2, due to the softer gradients (less than 15 degrees of slope), the differences between the Depth layers are not so noticeable.

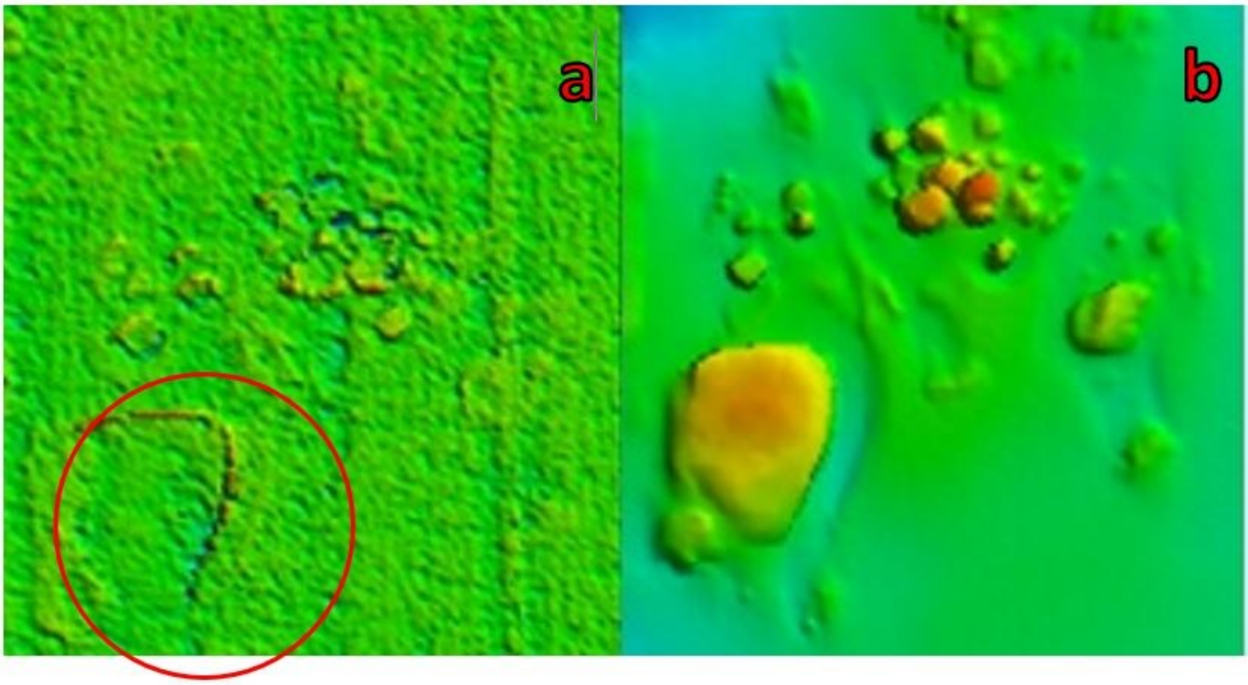


***Figure 4** – **a)** Shoal Difference Surface Layer with the rock's edges highlighted; and **b)** MBES Depth Layer showing the analyzed rocky field in the Test Area 1.*

Probably the layover occurred in both areas, but due to the overlapping of the survey lines, it was not noticed in Area 2. In Area 1 (***Figure 4b***), despite the overlapping of different swaths, the slope of the stone edges is beyond the grazing angle, a situation in which the layover will always appear, independent of overlaps.

4.2 AREA 3

Area 3 stands out for the existence of the bridge pillars (***Figures 1, 5a*** and ***5b***). These features simulate targets with a vertical projection that reaches the water surface, making it impossible for the survey vessel to approach to the abutments.

The detection of these objects by the PMBS is more pronounced than in the MBES, as can be seen through the of comparative bathymetric profiles (***Figure 5c***) between the surfaces generated by both sensors. The Shoal layer in the PMBS shows that this sensor could image and quantify the height of bridge pillars almost to the water surface, although they were not totally identified in the Depth layer. This is the result of different acquisition technology and data processing technique. Automatic processing was not able to detect the abutments, requiring manual operator intervention. However, once this parameter is adjusted, it is observed that the PMBS was able to detect the targets to approximately 0.5m below the sea surface. The MBES Shoal layer depicts the targets to approximately 10m water depth, while the Depth layer recorded only a small elevation.

Due to the proximity between the pillars of the bridge, another situation that can be simulated is the survey of a narrow channel or river, with no space to run adjacent lines. In the lines with no swath overlapping, the nadir gap is visible (extreme left and right of ***Figure 5b***). In these cases, the area immediately below the sonar has a lack of bathymetric information, which is a disadvantage of the PMBS system relative to MBES.

It is also noticeable the PMBS swath is larger. This makes it easier to survey in the vicinity of targets or features that pose risks to the vessel and in places very close to river banks or to the coast. In these cases, the PMBS imaging will cover a larger area thus posing less risk to the equipment and survey team.

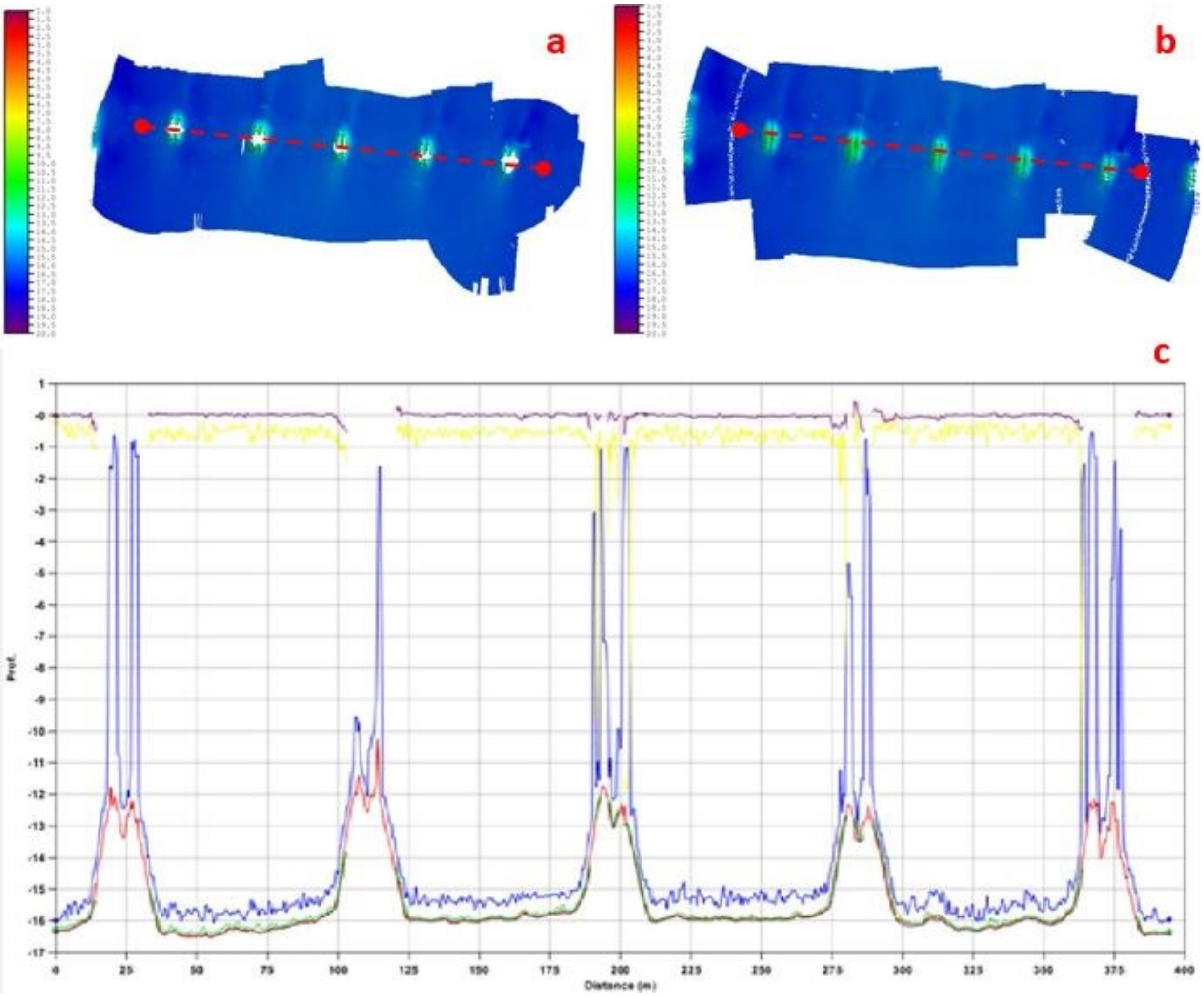


*Figure 5 – **a)** The MBES Depth layer surface; **b)** The PMBS Depth layer surface. In the a) and b) frames, the depths are ranging from 1m – dark red – until 20m – violet. The red dashed line indicates the profile in frame c; and **c)** A comparative frame showing the profiles. There are six different profiles: MBES Depth layer (black), MBES Shoal layer (green), PMBS Depth layer (red), PMBS Shoal layer (blue), Depth difference layer (purple) and Shoal difference layer (yellow).*

4.3 AREA 4

This area is characterized by the presence of a shipwreck (***Figures 1, 6a*** and ***6b***). The multibeam shoal layer is slightly shallower than the corresponding PMBS shoal layer (***Figure 6c***), reflecting the amount of noise captured by the PMBS system during acquisition. Although the target has been fully ensonified, the true depth information was neither properly quantified nor transformed into a real bathymetric information. The masking of true depth information is quite common on such situations when the data is rejected as noise due to inconsistencies in the depth determination in a way similar to the layover effect.

In flat or low gradient areas over the wreck, on both layers (Depth and Shoal), the bathymetry acquired with PMBS is shallower than that acquired with MBES, as observed in the other areas.

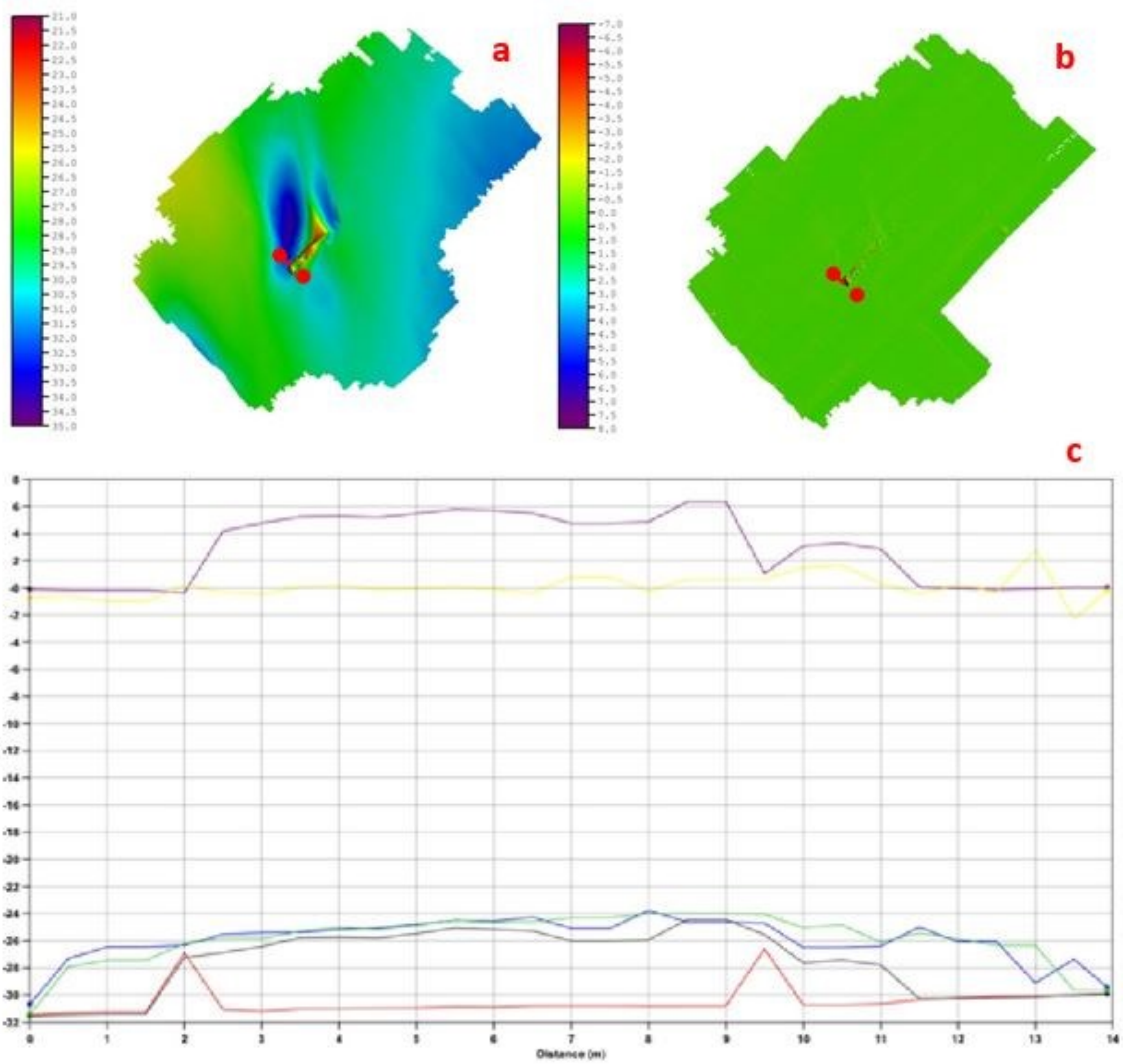


Figure 6 – The stern of the wreck. ***a)*** *The MBES Depth layer surface;* ***b)*** *Shoal Difference layer surface. The red line indicates the profile in frame c; and* ***c)*** *A comparative frame showing six different bathymetric profiles: MBES Depth layer (black), MBES Shoal layer (green), PMBS Depth layer (red), PMBS Shoal layer (blue), Depth difference layer (purple) and Shoal difference layer (yellow).*

4.4 AREA 5

The efficiency test has the objective of comparing the time to survey a given area or the size of a surveyed area in a given time. In this work, we used the second approach.

It is known the PMBS and the MBES swath may be different for a given water depth. ***Figure 7*** shows that the PMBS was able to practically achieve full coverage using the same swath width. For a better analysis of the results, the area was divided into 3 sectors: from 25.2m to 15m (***Figure 8a***), from 15m to 5m (***Figure 8b***), from 5m to 2m (***Figure 8c***). ***Figure 8a*** shows the

PMBS was able to easily cover 100% of the area with no need to change the swath. Meanwhile, it is clear the MBES would need more survey lines and, therefore, more time, to totally cover the same area. ***Figure 8b*** shows that MBES leaves huge gaps between the survey lines, whereas the PMBS shows only small nadir gap. In ***Figure 8c*** the gaps between the MBES lines are much more pronounced, while the gap between PMBS lines is practically non-existent.

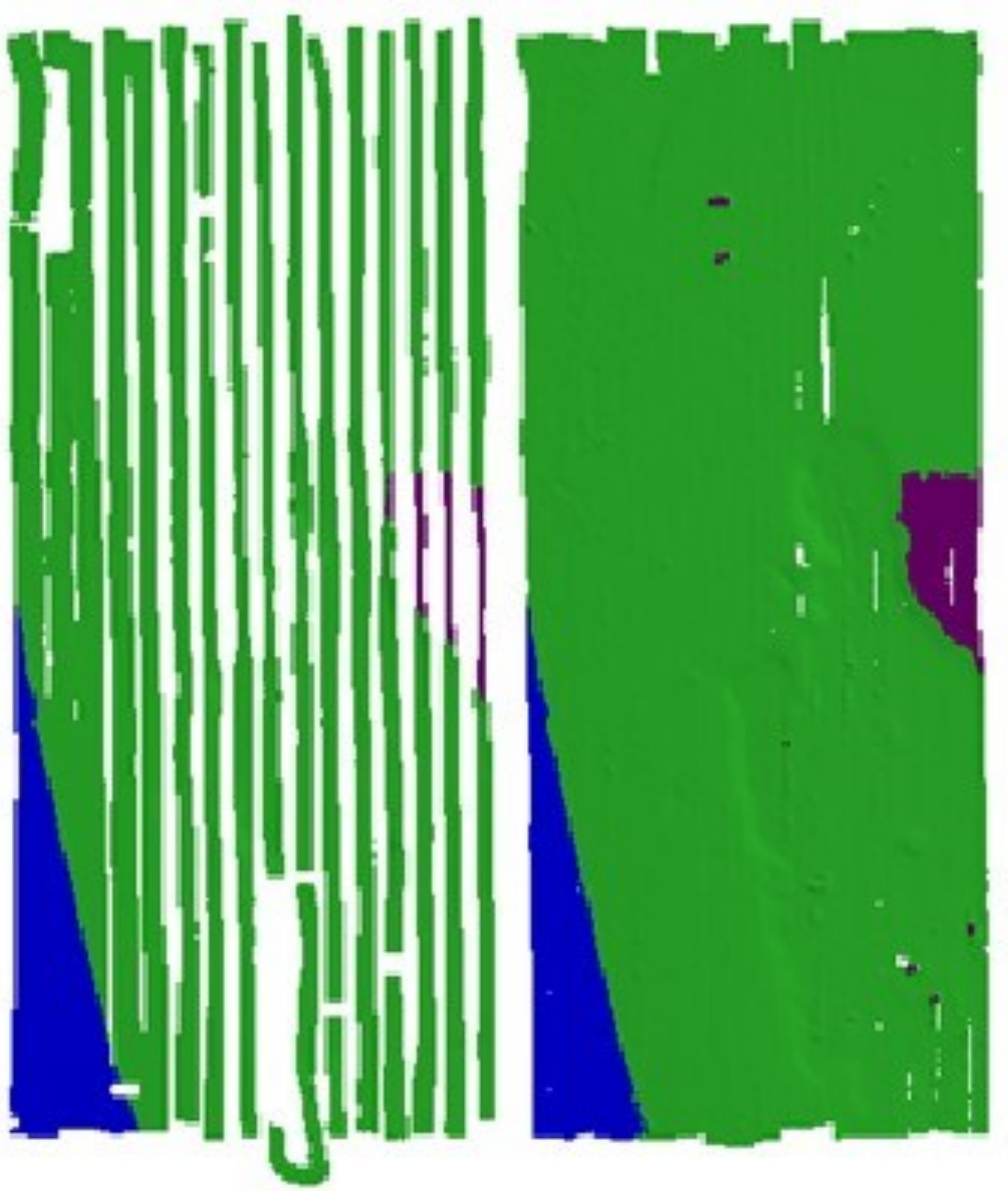


***Figure 7** – In the left, the MBES depth layer surface and in the right, the PMBS depth layer surface. The colours are related to depths ranging. From 25.2m until 15m in blue, from 15m until 5m in green and from 5m until 2m in purple.*

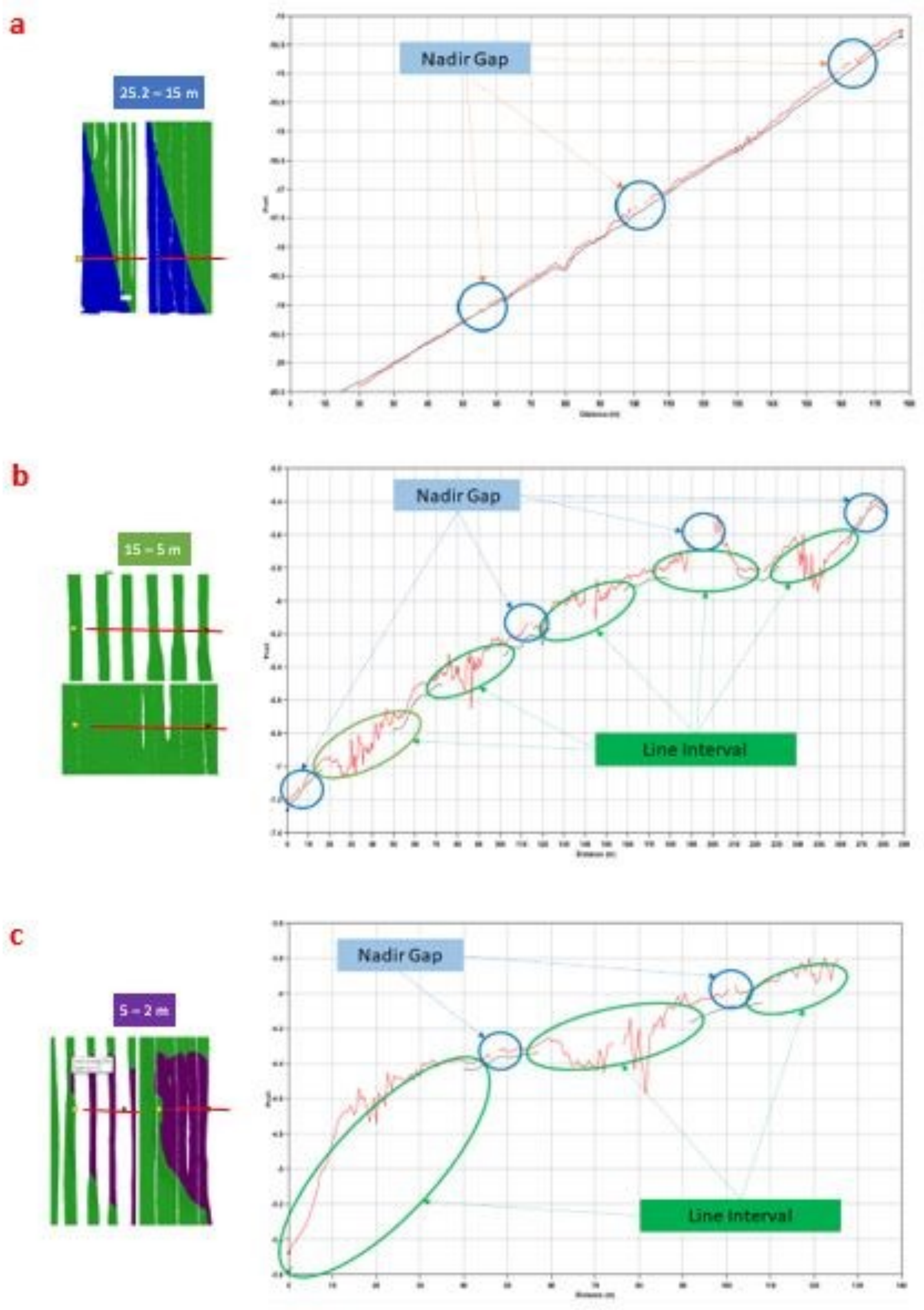


Figure 8 – a) *Test Area 5 field, where the depths vary from 25.2 to 15m;* ***b)*** *Test Area 5 field, where the depths vary from 15 to 5m; and* ***c)*** *Test Area 5 field, where the depths vary from 15 to 5m. In frames a), b) and c), the red line indicates the where the profile was taken. In the profiles graphic, there are two different lines: MBES Depth layer (black) and PMBS Depth layer (red).*

While the MBES had a constant swath of approximately 3 times the water depth for the whole area, the PMBS achieved swaths of approximately 3.4 times the water depth in areas 20m deep, 6.7 times the water depth in areas 9m deep and 12 times the water depth in areas 3.5m deep. Therefore, the test showed that PMBS is more efficient when the water depth is 15 meters or shallower. When the whole area is considered, the PMBS efficiency was 37.4% higher than the MBES.

4.5 RESOLUTION TEST

For the resolution test, it is interesting that the areas have noticeable bathymetric features. Thus, we will only address different resolutions in the Areas 1 and 4.

Table 2 correlates resolution and ping density per node for both areas. In a first analysis, we used a quantitative approach to evaluate the surfaces considering that, according to Calder and Mayer (2003), in the CUBE interpolator, the minimum desirable number of pings to compose a cell is 11. According to this criterion, resolutions of 0.1m on both sensors and 0.2m on MBES are discouraged.

Table 2 *– Data density per node for different resolutions. Organized by the authors.*

Resolution	Density per node – Area 1		Density per node – Area 4	
	MBES	**PDBS**	**MBES**	**PDBS**
0.1 m	2.1	9.7	1.9	7.4
0.2 m	8.3	36.6	5.7	25.5
0.3 m	18.6	82.2	12.7	57.1
0.5 m	51.6	227.6	35.2	157.7
1.0 m	98.9	448.7	139.9	625.9

Nevertheless, surfaces must also have their resolutions assessed qualitatively through visual analysis by observing how the morphological features behave in each image shown in ***Figure 9***. As the resolution improves, there is an increase in the number of blanked areas and noise. In contrast, it is possible to have a better notion of the seafloor features, as well their details and texture.

Another aspect to be explored in the image visualization is the difference in the target's size. Bigger targets (such as seen in Area 4) tend to be noisier, masking some target details (***Figure 9***, Test Area 4, PMBS frames). In general, despite the greater number of pings per node the PMBS data provided greater statistical robustness, the data is more scattered, generating noise. If we degrade the resolution to suppress the noise, details are also be smoothed.

Achieving a trade-off between the size of blanked areas, amount of noise and the visualization of target details is what will provide the optimal resolution for each case. Factors such as target size, depth, survey purpose should also be considered when defining the resolution to be used during the survey. Although the PMBS can produce a much larger number of pings per node than MBES, it presented a much noisier data, making it difficult to work with resolutions better than 30cm.

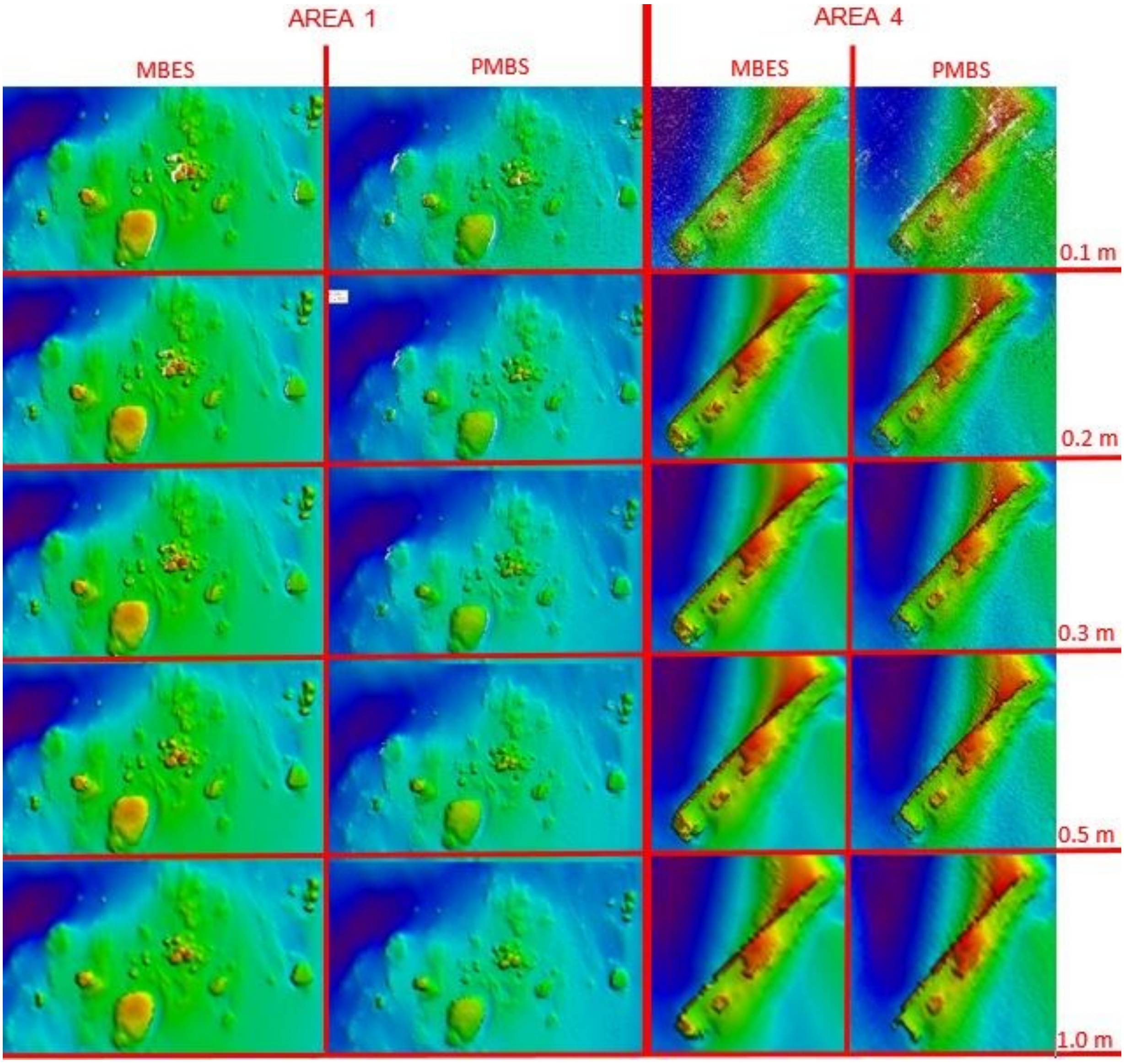


Figure 9 *– Different depth layers resolutions for Test Areas 1 and 4. The rocky images are from Test Area 1 and the wreck images are from Test Area 4. The resolutions are in the right side.*

5. Discussion

The sensors were evaluated for their relative precision in different conditions. The assessment was done in two different ways: with respect to the hypothesis and the node sample uncertainties. The first was meant to verify how the TVU was propagated, while the second was focused on the evaluation of the data dispersion. The results showed that MBES data was able to achieve Special Order on both criteria. The PMBS hypothesis uncertainty also matched Special Order since all the information that supported the bathymetric information had low uncertainty. However, its data showed high dispersion level, making the node sample uncertainty not able to reach Special Order standard, but only Order 1A. To better understand this issue, ***Figure 10*** depict the MBES and PMBS hypothesis and node sample uncertainty for Area 1.

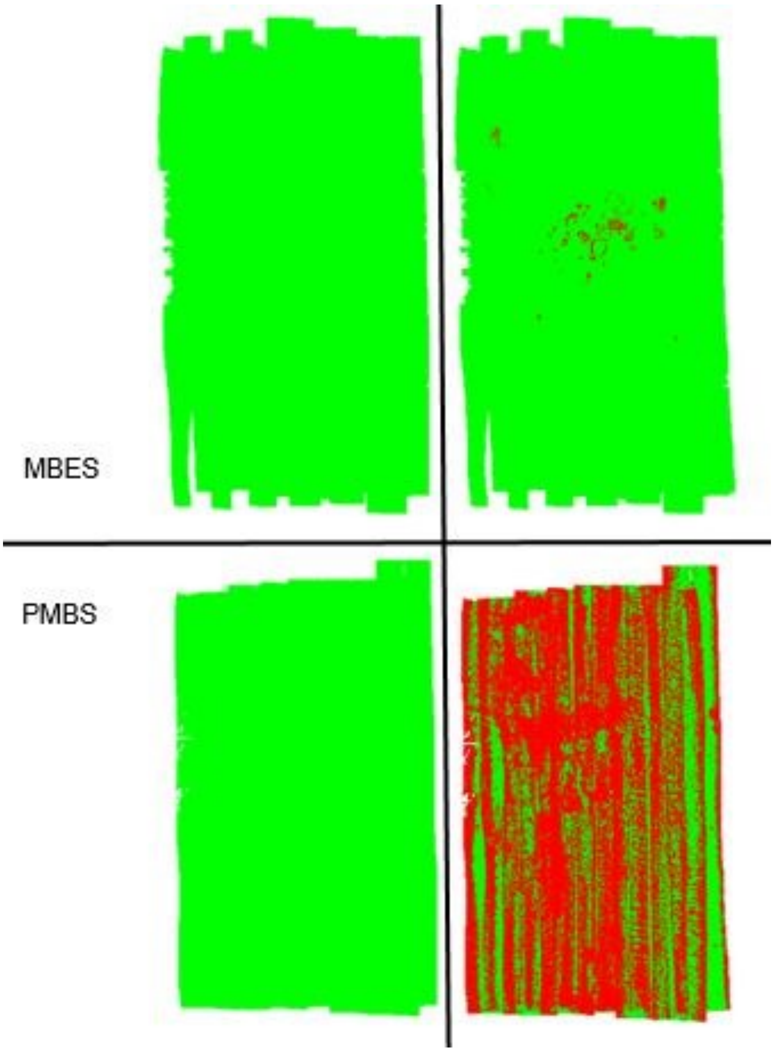


Figure 10 – *MBES and PMBS surface assessed for Special Order. Left column is the result for hypothesis uncertainty. Right column shows the results for node sample uncertainty. The nodes that achieved Special Order in each criteria are in green. The ones that did not are in red.*

It was expected to see the nodes related to a very steep seafloor in red in all situations and for both systems, as seen for the existing rock outcrops in this area. The relevant fact here is that PMBS surface achieve Special Order in the hypothesis uncertainty criteria, but did not for the node sample uncertainty, even under flat seafloor condition. This shows that not only is the PMBS data dispersion is to high, as demonstrated by Brisson; Wolfe; Staley (2014); Jerram and Schmidt (2015b) and NOAA (2017), but also how careful one must be when evaluating a bathymetric surface. ***Figure 11*** shows, on the other hand, that PMBS data matched Order 1A of the IHO standard, indicating that these systems may be used if the demands for the survey are not so rigorous (***Table 1***).

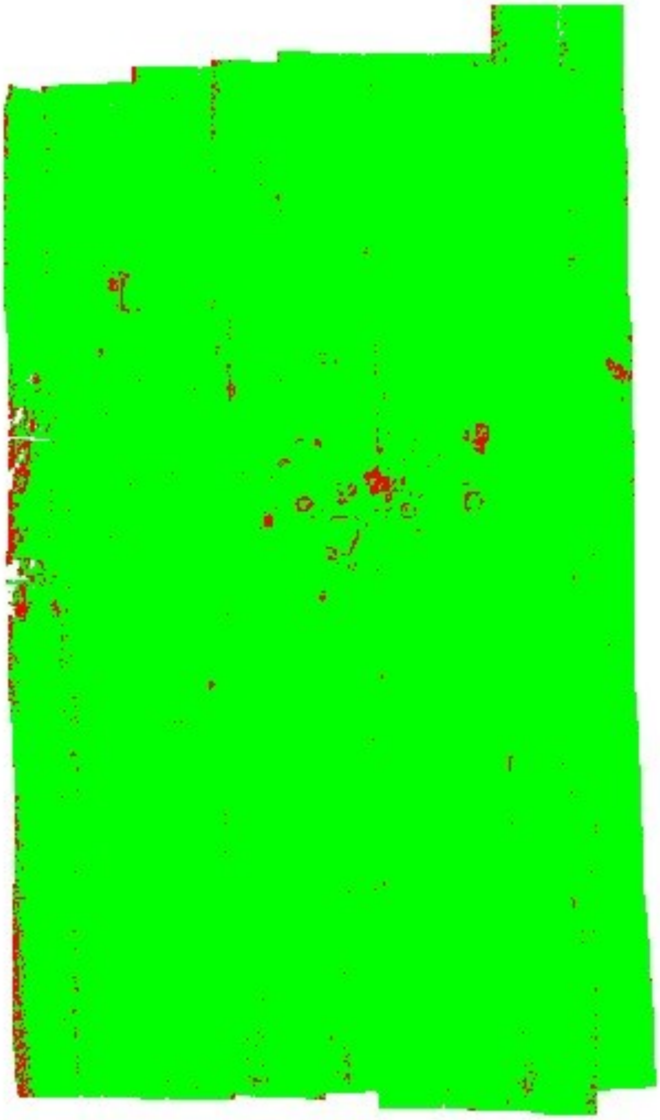


***Figure 11** – PMBS surface assessed for Order 1a in the node sample uncertainty criteria. The nodes that achieved Order 1a are in green. The ones that did not are in red.*

The **accuracy** was analyzed in 3 ways (***Table 1***). First, using CARIS HIPS & SIPS QC Report tool, it is observed that all areas surveyed with the PMBS were within the Special Order. The second way was to compare the Depth layers surface generated with MBES and PMBS data. This showed that the depth difference ranged between 0 and 10cm, with the PMBS layer always representing shallower depths. The third way was by comparing the layers representing the shallowest depths (shoal layers), since this is the preferential data exported to the nautical charts. In this case the depth difference ranged among 0.5m to 0.7m for all study areas. This results from the data dispersion level, which is high for the PMBS Shoal layer. The problem here is that exporting the PMBS Shoal layer to the nautical chart would decrease the risks to navigation safety, but would have an impact by decreasing the navigable draft of a channel

Another important aspect is the amount of noise in the raw data. The whole PMBS data shows a large amount of noise (see ***Figure 2d***), as already demonstrated in Dodd (2013) and Jerram and Schmidt (2015b). This noise can be generated by several factors: ambient noise, the vessel and the equipment itself (Lurton, 2000); multipath (mainly in shallow and targeted locations) (Denbigh, 1989); shifting footprint effect, baseline decorrelation effect (Lurton, 2000); and layover effect (Ărăcin and Calin, 2000; Saucan et al., 2015; Woock and Frey, 2010). In our research the layover effect was mainly observed in the edges of very steep morphological features, while noise is mostly widespread in the data

In this work, it was considered that a good resolution for the PMBS would be 0.3m. Despite delivering a higher data density than the multibeam (USACE, 2013; Jerram and Schmidt, 2015a; Jerram and Schmidt, 2015b; Ma; Xu; Xu, 2016), the PMBS has a very large amount of spurious data, which became more evident in surfaces with higher resolutions. This fact limits the resolution improvement, restricting the PMBS to the MBES surface resolution level. The resolutions of 0.1m and 0.2m did not provide the minimum amount of pings (***Table 2***) to ensure the node's statistical robustness according to Calder and Mayer (2003). At the same time, these resolution levels enhance the noise in the data, giving the surface a very "rough texture". On the other hand, surface resolution of 0.4m or higher decrease the ability of the data to show the targets details resulting in a "out-of-focus" surface (***Figure 9***).

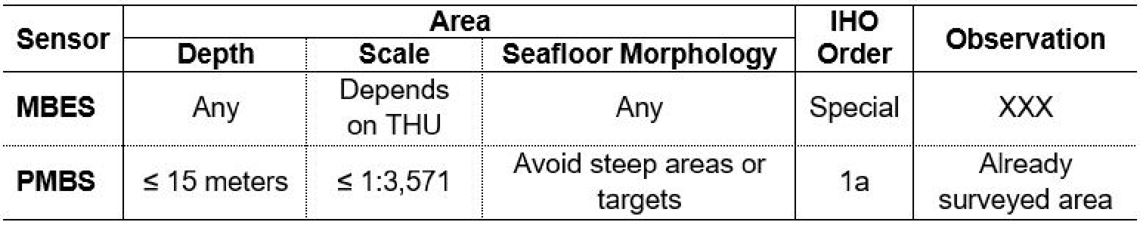
The PMBS efficiency was greater than the MBES especially at depths shallower than 15 meters. This is essentially due to its larger swaths in shallower regions (Brisson; Wolfe; Staley, 2014; Gostnell, (2005); Jerram and Schmidt, (2015b)). When tested in a flat area, the nadir gaps observed in the PMBS data, makes the need for 100% overlapping mandatory as stated by Dodd (2013) and Ma, Xu, Xu (2016).

Due to the amount of bad data in the PMBS (***Figure 2a***), manual processing is practically impossible. Automatic and statistical processing, despite being strongly recommended, can still exhibit flaws. We suggest that data processing shall be done statistically, to have most of the noisy data rapidly cleaned, and manually, to further clean the data and better delineate the bathymetric features. The development of a better automatic technique for PMBS data cleaning is a challenge that must be addressed in order to reduce the processing time needed to generate the final bathymetric surface.

Thus, based on the results of the present study and considering the PMBS characteristics presented above, it is possible to conclude that PMBS is mostly recommended for restricted areas, with relative low gradients, shallower than 15 meters, which have been already mapped, since small features or structures edges can be masked by the noisiness or layover effect.

In an area where the dangers to navigation are already known, the PMBS can be used, since the uncertainties related to the target's shape can be diluted in the sounding selection or absorbed by the scale of the nautical chart. As an example, in this survey, the edge's uncertainty (when compared to the MBES surface) of the rock outcrops seen in Area 1 was around 1m. Considering the graphic reduction value in Brazil is 0.28mm, the scales that can address such uncertainty would be the ones smaller than 1:3,571 (1/0.00028). If the edge uncertainty cannot be properly estimated, one can use the THU (Total Horizontal Uncertainty) as the value for graphic reduction. Considering the maximum recommended THU for the order 1A (5m + 5% of the depth), the scale would be even more restrictive. In this case scales approximately ≤ 1: 25000 would be accepted. However, this parameter must be based on the analyst's experience and the purpose of the survey. ***Table 3*** summarizes all the conclusions of the present work.

Table 3 – PMBS surveying area suggestion. Organized by the authors.



Sensor	Area			IHO Order	Observation
	Depth	Scale	Seafloor Morphology		
MBES	Any	Depends on THU	Any	Special	XXX
PMBS	≤ 15 meters	≤ 1:3,571	Avoid steep areas or targets	1a	Already surveyed area

It should also be noted that countries that accept bathymetric sidescan sonars have more specific standards which are more restrictive in their criteria and requirements than the IHO S-44 itself. Despite accepting PMBS surveys, the United States (NOAA, 2017), Canada (CHS, 2013) and New Zealand (LINZ, 2010) are examples of countries that are in the situation above. Brazilian hydrographic standards, especially NORMAM-25 (Rev. 2), mostly replicate the specifications and the Orders recommended in S-44 (5th Edition) (IHO, 2008), being more lenient than the standards of the aforementioned countries. The adoption of PMBS systems for Special Order surveys in Brazil must be followed by more systematic tests with methodical hydrographic rigor.

6. Conclusion

A hydrographic survey is a complex process of obtaining information about the environment. The bathymetric measurement, as an integral part of any hydrographic survey, stands out in its complexity, due to the different variables involved and the high level of precision and accuracy required. In turn, end users are continuously demanding more reliable, accurate and less expensive surveys, since the financial and administrative consequences are high.

In this context, the PMBS arises as an option to the existing traditional MBES method. It intends to provide greater efficiency and cost reduction. However, a closer analysis reveals that one technology is not capable to simply replace the other, at least for now.

The PMBS technology has advantages and disadvantages compared to the MBES. We concluded that it is possible to operate and perform bathymetric surveys using PMBS systems, but under less restrictive conditions.

There are other factors that may drive to different results: changes in the bottom type and operating frequency may affect the bottom detection level; survey platform - using PMBS systems on an AUV would deliver very different results, especially due to the its acoustic positioning; rougher sea state and weather conditions demand more sophisticated attitude sensors affecting depth accuracy. It is important that users and equipment technicians be aware of the PMBS limitations and potentialities, exploiting its advantages to the maximum and minimizing its disadvantages. Some drawbacks, like the amount of noise and consequently the dispersion of valid data, can be mitigated by processing (filters or other algorithms) and remain an issue for future investigations.

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