Boletim de Ciências Geodésicas
ISSN: 1413-4853
ISSN: 1982-2170
Universidade Federal do Paraná

Ferreira, Italo Oliveira; Andrade, Laura Coelho de;
Teixeira, Victoria Gibrim; Santos, Felipe Catão Mesquita

State of art of bathymetric surveys

Boletim de Ciências Geodésicas, vol. 28, no. 1, e2022002, 2022
Universidade Federal do Paraná

DOI: https://doi.org/10.1590/s1982-21702022000100002

DOI 10.1590/s1982-21702022000100002

ORIGINAL ARTICLE

State of art of bathymetric surveys

Italo Oliveira Ferreira[1] - ORCID: 0000-0002-4243-8225
Laura Coelho de Andrade[1] - ORCID: 0000-0003-3693-2208
Victoria Gibrim Teixeira[1] - ORCID: 0000-0002-7279-110X
Felipe Catão Mesquita Santos[1] - ORCID: 0000-0002-9376-766X

[1]Universidade Federal de Viçosa, Departamento de Engenharia Civil, Viçosa – Minas Gerais, Brasil.
E-mails: italo.ferreira@ufv.br; laura.andrade@ufv.br; victoria.gibrim@ufv.br; felipe.mesquita@ufv.br

Received in 13th March 2021.
Accepted in 09th December 2021.

Abstract:

Technological advances in bathymetric equipment, positioning capacity, data processing, as well as the development of new ways of obtaining depth and other ways of exploring the submerged bottom, have been noticed in recent years. It is known that acoustic remote sensing is the most widely used technique for depth measurement. Survey systems can be embedded on various platforms and also provide different accuracies. Coupled to these systems are also Global Navigation Satellite System (GNSS), auxiliary sensors and speed profilers, improving the accuracy of the data obtained. Alternatively to the use of echo sounders, optical sensing (active and passive sensors) or satellite radar altimetry can be used to estimate depth. Thus, this study aims to present an overview of bathymetric survey methodologies, as well as the evolution of the use of sounding platforms, systems and sensors and various existing technologies. In addition, the main uncertainties involved and the advantages and disadvantages of the available solutions are also evidenced, providing the reader the ability to choose the most appropriate technique.

Keywords: Bathymetric survey; Hydrographic; Methods; Platforms; Seafloor mapping.

How to cite this article: FERREIRA, I.O.; ANDRADE, L.C.; TEIXEIRA, V.G.; SANTOS, F.C.M. State of art of bathymetric surveys. *Bulletin of Geodetic Sciences*. 28(1): e2022002, 2022.

1. Introduction

Obtaining the submerged relief has always been a concern. Navigation, port works, prospecting and exploration of marine resources are just some areas that demand depth information. Hydrographic surveying is the science directly related to the measurement of submerged morphology, it employs several methodologies that range from direct methods, such as the use of probing rods, to more sophisticated methods, such as inference of depth from the spectral response of orbital images. The growing need for bathymetric data that is increasingly more accurate and available in the short term has recently led to a worldwide effort to develop systems, sensors and alternative techniques for depth measurement. An example of this is the groundbreaking initiative "Nippon Foundation – GEBCO Seabed 2030 Project" which has mapped about 20% of the world's ocean floor (Mayer et al.2018). Furthermore, in this context, the news also has reported the challenges of searching the Malaysia Airlines MH370 - an airplane vanished into the Indian Ocean in 2014 - due to the poor knowledge of the bathymetry in the area pointed by the satellite (1,200 miles southwest of Perth, Malaysia) (Langewiesche,2019).

Basically, since 1970 remote sensing (acoustic, optical and radar) is the method more commonly chosen to investigate the underwater background. According to Menandro and Bastos (2020), for the decade of 1971-1980, one of the most recurrent terms written in the literature was "echo", for the 80's were "sonar" and "datum" and in the years between 1991-2000, the word "image" showed up, revealing the predominance of remote sensing techniques. Most of these indirect methods listed above are based on time measurement to obtain depth. Specifically, sensors are employed that emit a sound beam, light waves or radio, and measure the travel time interval of this beam to the submerged bottom. This time, multiplied by the speed of propagation, is used to estimate depth. Despite a simple concept, the measurement of speed, as well as the direction of emission and reception of the beam - especially due to the dynamic movements of the platform and some physical phenomena (such as refraction) - make this process quite complex. In addition, this depth needs to be referenced to horizontal and vertical datums, for this reason, a bathymetric survey will always require support data collections, such as tidal, oceanographic, geological, geodetic and topographic.

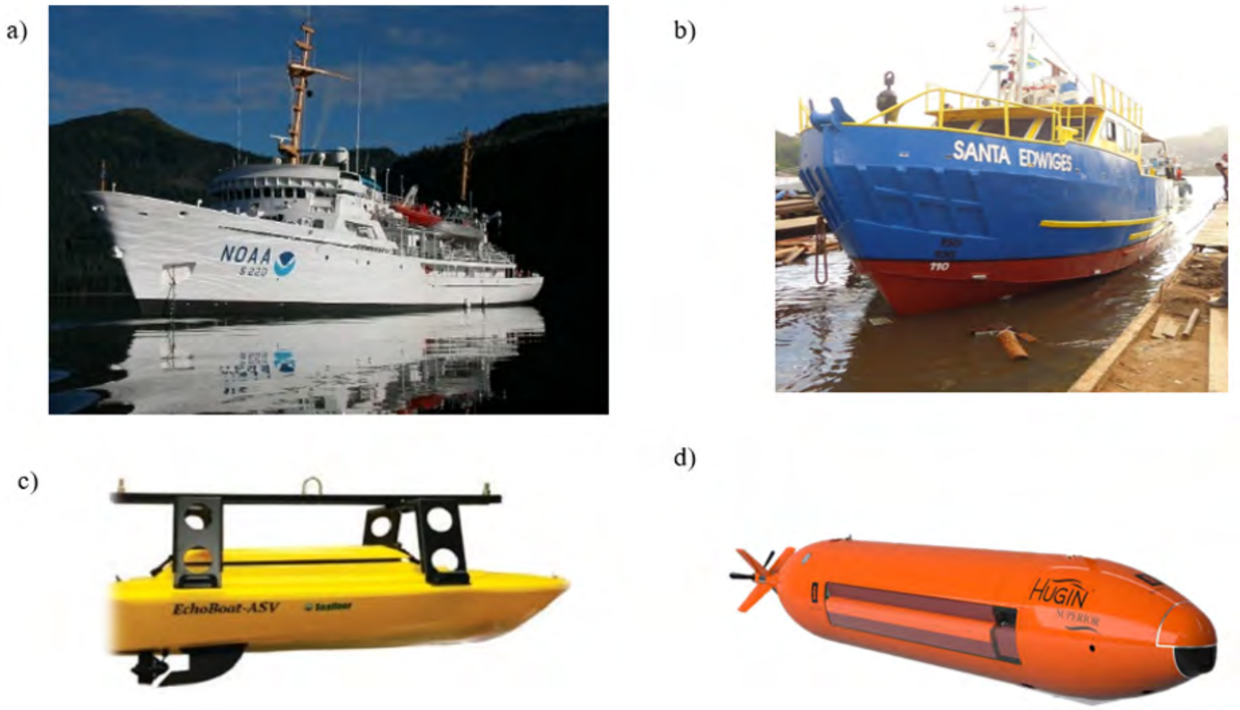
Depending on the technique adopted, it can be employed survey platforms sailing a few meters from the seabed to satellites at hundreds of kilometers of altitude. Each method provides a different spatial resolution and vertical uncertainty and can provide bathymetric information in places with a few centimeters of water column to places with kilometers of depth. In fact, limitations inherent to all methods point to the conclusion that no technique is ideal for measuring the complexity of submerged relief.

Given the above, this article aims to present a brief overview of the current state of the art of bathymetric survey methodologies, as well as the evolution of the use of sounding platforms, systems and sensors and various existing technologies. The main uncertainties involved and the advantages and disadvantages of the available solutions are also presented, which will grant the reader the ability to choose the most appropriate technique for each type of study.

2. Surveys platforms

Currently, bathymetric survey platforms include surface vessels, submersible platforms, aircraft and even satellites. In the context of the surface navigation, it is possible to observe from large ships, used in offshore surveys, to uncrewed vessels, remotely controlled or autonomous – preferably used in surveys of inland waters (rivers, reservoirs, etc.). As for submersible platforms, it is commonly used autonomous underwater vehicles (AUV) and also remotely operated vehicles (ROV) from a surface vessel, both used for high resolution mapping in deep water.

In these platforms, in particular, acoustic sensors are preferably onboard, although AUVs and ROVs carrying Light Detection and Ranging (LiDAR) systems and high resolution photographic cameras are already a reality in Brazil and in the world. Figure 1 shows four typical bathymetric survey platforms.



Source: (a) NOAA (2009), (b) The authors (2015), lent by UMISAN company (c)Seafloor Systems (2017), (d) Kongsberg (2015).

Figure 1: Platforms used in surveys: (a) NOAA Fairweather Ship for offshore surveys, (b) Small Vessel- Santa Edwiges- from the company UMISAN, (c) ASV Echoboat from the company Seafloor Systems, (d) AUV Hugin from the company Kongsberg.

The ship Fairweather of the National Oceanic and Atmospheric Administration (NOAA) is used in the offshore hydrographic surveys and port, mainly, the Seabat 8160 echo sounder of the company Reson, which reaches a depth of up to 3km. The vessel Santa Edwiges, from UMISAN Engenharia, has acoustic systems for high-precision bathymetric mapping, as well as seismic surveys in waters with a depth of less than 100 meters. Echoboat is a small ASV used in bathymetric surveys of inland waters and sheltered areas, performed using acoustic sensors. The Hugin AUV, from the Kongsberg company, has in addition to the EM2040 multibeam echo sounder, a laser profiler, coupled photographic camera, HISAS 1032 synthetic aperture sonar, among other systems and sensors.

Aircraft, crewed or not, are also used in bathymetric mapping. These platforms are basically equipped with passive sensors (aerophotogrammetric cameras), which allow estimates of depths through the spectral response of the submerged bottom (bathymetry by spectral response) and active sensors, such as Bathymetric LiDAR (Pastol 2011). Similarly, satellites also function as bathymetric survey platforms, either through the use of orbital images (bathymetry by spectral response), or through the use of altimetric radars (active sensors) (Gao 2009, Ferreira et al. 2016, Lamine et al. 2021).

3. Methods of bathymetric surveys

Modern bathymetric survey techniques are based on the use of sound waves (singlebeam and multibeam echo sounders) and electromagnetic waves, that is, visible light (aerophotogrammetric cameras, LiDAR systems) and radio waves (altimetric radars). Therefore, measurements are carried out in different media depending on the technique: in the aquatic environment in the case of the use of sound waves; in the air and in the aquatic environment when visible light is used and, only in the air, when bathymetry is derived from information from altimetric radars.

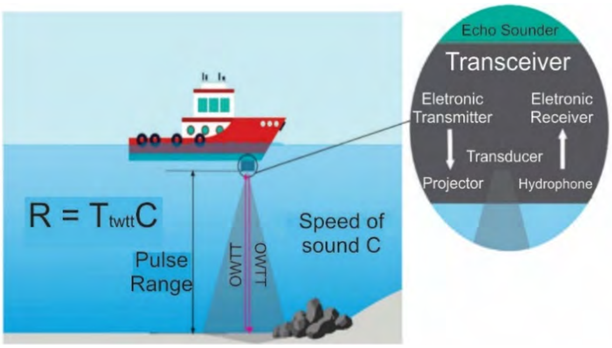
As will be described in this section, each method has advantages and disadvantages in relation to the characteristics of the survey areas and the resolutions and accuracies achievable (Table 1). Acoustic systems are used both in shallow water, around 1 meter deep, and in deep water, with kilometers of depth. It is the preferred method and provides more accurate data compared to other methods. Due to the high attenuation suffered by the wavelength of visible light in the aquatic environment, depth measurements employing optical remote sensing (active and passive) is limited to low depths. While aerophotogrammetric (short distance) and orbital images are employed for bathymetry at depths of up to 10 meters, LiDAR systems operating in the green wavelength can reach up to 50 meters in clear waters (2 to 3 times the depth of the Secchi-disk) (Hilldale and Raff 2008). These methods are widely used for the design of coastlines, surveys in waters that offer risks to surface navigation and mappings in which the need for productivity overlaps the spatial resolution. Finally, altimetric radars can also be used as tools for obtaining depth, these are applicable in deep waters, especially in places where bathymetric information is scarce or nonexistent (Brêda 2017).

Table 1: Main methods with respective scopes and uncertainties.

System/method	Estimated reach	Estimated uncertainty
Singlebeam Echo Sounders (Teledyne Odom Echotrac CV100 model) (Teledyne Marine 2018)	150m at 200kHz	1cm +/- 0.1% of depth at 200kHz
	600m at 33kHz	10cm +/- 0.1% of depth at 33kHz
Multibeam Echo Sounders (Kongsberg EM 2040P MKII model) (Kongsberg Maritime 2021)	600m at 200kHz	10 mm
Multibeam Echo Sounders (Kongsberg EM 124 model) (Kongsberg Maritime 2013)	11,000 m at 12kHz	Meets the minimum requirements of S-44 1st Order
LiDAR (Leica Hawkeye III) (Leica Geosystems 2015)	50 m	$\sqrt{(0.3m)^2 + (0.013 * depth)^2}$
Orbital images (Laporte et al.2020)	10 m	Worse than 1 meter

3.1 Acoustic sensors

Acoustic sensors or, as they are commonly known, echo sounders, consist of sound sources whose specialty is depth measurement. They work like a clock, measuring the time interval between the output and arrival of the same acoustic pulse (ping) to the transducer. Based on the two way travel time, an estimate of the distance to the reflected target is calculated. For this, it is necessary to know the speed of sound propagation. Figure 2 illustrates the operating principle of an echo sounder.



Source: Adapted from Clarke (2014).

Figure 2: Operation of an echo sounder. Where “R” is the Pulse Range, “T’ is the time interval spent by the sound to reach the bottom and back and “C” is the speed of sound in the water.

It can be noted by the Figure 2 that the measured quantity consists of the distance between the acoustic center (transducer face) and the submerged bottom (or equivalent). However, the transducer is installed submerged in water, generating an offset between the static water line and the transducer face, called draft. This amount needs to be added to the value calculated, as well as several other corrections need to be made (USACE 2013). The speed of sound propagation is a critical factor and should be measured with sufficient accuracy. Basically, the speed varies in time and space, so it is mainly dependent on salinity, temperature and pressure (depth).

Currently, the acquisition of the profile of the speed of sound is focused on the use of a Sound Velocity Profile (SVP), Conductivity, Temperature and Depth (CTD), Expendable, conductivity, temperature and Depth (XCTD), Expendable Bathythermograh (XBT), and, more recently, on Moving Vessels Profile (MVP), in which the variation of the velocity profile of the sound is monitored in real-time (LINZ 2010).

The echosounder has Sonar as his popular name and the first record of this equipment in history was more than 500 years ago, when Leonardo da Vinci used a tube in the water to detect big ships by positioning his ear in the tube. The word sonar is actually an acronym for SOund Navigation And Ranging, originated in 1942 as a phonetic analogue to the word radar, which in turn is an acronym for RAdio Detection And Ranging. There are passive and active sonars, the latter being used in depth measurement (IHO 2005; Jong et al. 2010).

Echo sounders consist of resonant sources, since they emit a certain frequency spectrum over a predefined time interval. They produce an acoustic signal with a known form, highly repetitive, which originates from the resonance frequency of the material used in the manufacture of the transducer. For depth measurement, in general, frequencies ranging from 12 to 400kHz are used, and can reach up to 700kHz. It is known that acoustic sensors are composed of two main parts: the transceiver (controller, SIM, etc.), responsible for controlling the transmission of the acoustic pulse, receiving and analyzing the echoes and generating the echograms and output data, and the transducer, responsible for converting the electrical pulses generated by the transceiver module into sound waves and, when the echoes return, converting the sound waves back to electrical energy. These can be used as projectors (emitters or transmitters) and receivers (hydrophones) (Urick 1975, IHO 2005, Matias 2010).

Although resonant transducers can be used both as a transmitter and receiver, some transducers are more efficient at turning electricity into pressure – these are called projectors and are used to emit the sound wave. On the other hand, those transducers that have ease in transforming pressure into electrical impulse are called hydrophones and are employed in the reception of the sound wave. A passive sonar consists only of a hydrophone. Thus, a transducer can be physically a single unit or separated into two units (projector/hydrophone) (Sherman and Butler 2007).

It is known that, according to IHO (2005), the projector is an equipment that transmits the acoustic wave, and the hydrophone, or also called a receiver, is a passive tool used only for reception of the acoustic wave.

Between 1920 and 1930 the world saw the development and implementation of singlebeam sonars that used (and use) sound to measure depth directly below the sounding platform. By running a series of lines at a specified spacing, singlebeam echo sounders greatly increased the speed of the survey process, allowing more data to be collected compared to direct methods. However, this method still left gaps in quantitative depth information between the lines of research.

Between the 50s and 80s, the advent of technology allowed the emergence of side scan sonars (SSS) and multibeam systems (beam formers). Lateral scanning sonar technology offered (and still offers) a qualitative means of obtaining the sonic equivalent of an aerial photograph and improved the ability to identify submerged shipwrecks and obstructions. These proved to be excellent aid tools for singlebeam surveys, since they allowed the search for submerged objects between the navigated lines. Beamforming multibeam echo sounder systems made it possible to obtain quantitative depth information for almost 100% of the submerged bottom.

Figure 3 illustrates, on the left, the scheme of a sounding platform equipped with a singlebeam echo sounder and a side-scan sonar, and on the right, the same platform now equipped only with a multi-beam system. Looking at the sketches, it is noticeable that the multibeam survey brings many gains compared to its predecessor, given that the SSS ideally provides only qualitative information, in addition, it is not always used in surveys with a singlebeam system.

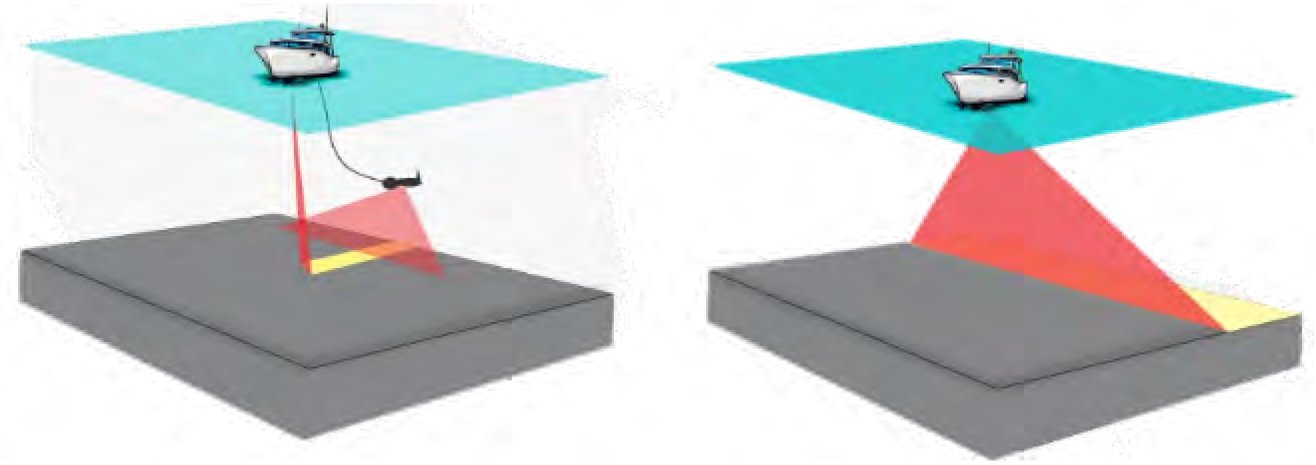


Figure 3: Singlebeam and multibeam bottom cover.

Singlebeam echo sounders are ideal for shallow water surveys and have excellent cost-effectiveness. Planning, operation, processing and analysis are quite simple. There is a huge range of equipment operating at low frequencies (12kHz-50kHz), high frequencies (100kHz-700kHz) and even at dual frequencies (24kHz/200kHz, 33kHz/200kHz, 50kHz/200kHz, etc.). Generally speaking, low frequencies are less attenuated in water and therefore have a greater range. Typical frequencies used in bathymetric surveys are, in general (IHO 2005, Sherman and Butler 2007):

a) frequencies above 200 kHz for depths below 200 meters;

b) frequencies between 50 and 200 kHz for depths below 1500 meters;

c) frequencies between 12 and 50 kHz for depths greater than 1500 meters.

When operating in shallow water, it should be noted that the submerged bottom is covered with layers of sediment and the use of a low frequency transducer can lead to a mistaken interpretation of the thickness of the water column. This is due to the fact that low frequencies penetrate into unconsolidated sediments. Moreover, not infrequently, an attempt to estimate the volume of unconsolidated mud is observed in many studies by means of singlebeam double-frequency echo sounders. However, this task requires numerous considerations, among which two main ones stand out: (1) There is no guarantee that the low frequency beam will penetrate all unconsolidated mud or beyond it; (2) The speed of sound propagation along sediments is slightly different from the speed of sound propagation in water, which generates uncertainties.

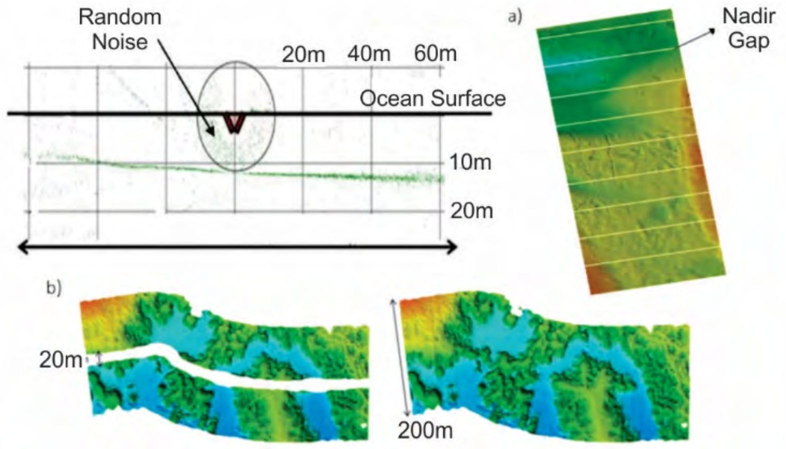
The evolution of singlebeam sounders culminated in the emergence of multibeam echo sounders (MBES). This technology, unlike its predecessor, allows almost 100% coverage of the submerged bottom. From the first instruments, the evolution and improvement in depth data, both in terms of resolution and accuracy, was already clear. While singlebeam systems perform a single depth record at each transmitted acoustic pulse, resulting in a line of points immediately below the vessel's trajectory, the multibeam performs several depth measurements with the same ping, obtaining measurements of the water column in a range perpendicular to the vessel's trajectory.

A growing number of hydrographic services have adopted multibeam technology as the main methodology for collecting bathymetric data for cartographic production and updating (IHO 2008, LINZ 2010, DHN 2017). Compared to singlebeam, multibeam systems provide greater coverage, productivity, resolution and accuracy, but have high cost and complex operation. In the market, there are multibeam systems with the most varied characteristics, basically the frequencies range from 12 to 700 kHZ, while the opening angle (swath) and the number of beams formed can reach, respectively, 165 and 1600 beams.

MBES traditionally obtain depth through the process of electronic beamforming (Demoustier 1996). Alternatively, some equipment employs "interferometry" to measure depth. These are popularly known as interferometric sonars, interferometric multibeam, interferometric sidescans, bathymetric sidescans or Phase Differentiating Bathymetric sidescan Sonar (PDBS). The latter term is theoretically the most correct, since only the first systems actually employed the process of interferometry.

Basically, the term "interferometry", in the bathymetric context, has been used to refer to sonars that employ the phase content of the signal to estimate the wavefront angle of the reflected signal and, with this, estimate the depth. In other words, a bathymetry system by "interferometry" employs two or more receiving elements and only one projector. The return signal coming from a certain direction arrives in each of the elements with different phases. These signals are summed up generating interference fringes that will provide information about the return angles. Known the arrival time and the speed of sound, the depth is determined. Thus, while MBES estimate the depth for a set of angles, i.e. estimate the Time Of Arrival (TOA) of return signals for a predefined angle of inclination, PDBS estimate the Direction Of Arrival (DOA) for a set of distances.

There are several advantages related to the use of PDBS, the main one is associated with background coverage, in some cases up to 12 times the nadir depth. This means that, at 4 m depth, interferometric sonar should be able to cover a range close to 50m, while a standard multibeam (120° swath), could cover about 12-16 meters at this depth (3 to 4 times). In fact, the technology of "interferometric" sonars has existed for decades, but some operational and technical problems have only been effectively solved recently. Historically, these systems had a large volume of data, but with a lot of ambient and internal noise and with unknown or insufficient accuracy, in addition, some models have a blind band in the nadir (Nadir Gap). The inability to differentiate between multiple return angles was a determining factor for limiting bathymetric resolution to ~2-3% of depth. Recently, improvements in advances in electronics and algorithms, combined with the use of a larger number of receiving elements, have greatly improved the accuracy of the technology and some manufacturers have presented a solution for the Nadir Gap (Brisson, Wolfe and Staley 2014) (Figure 4).



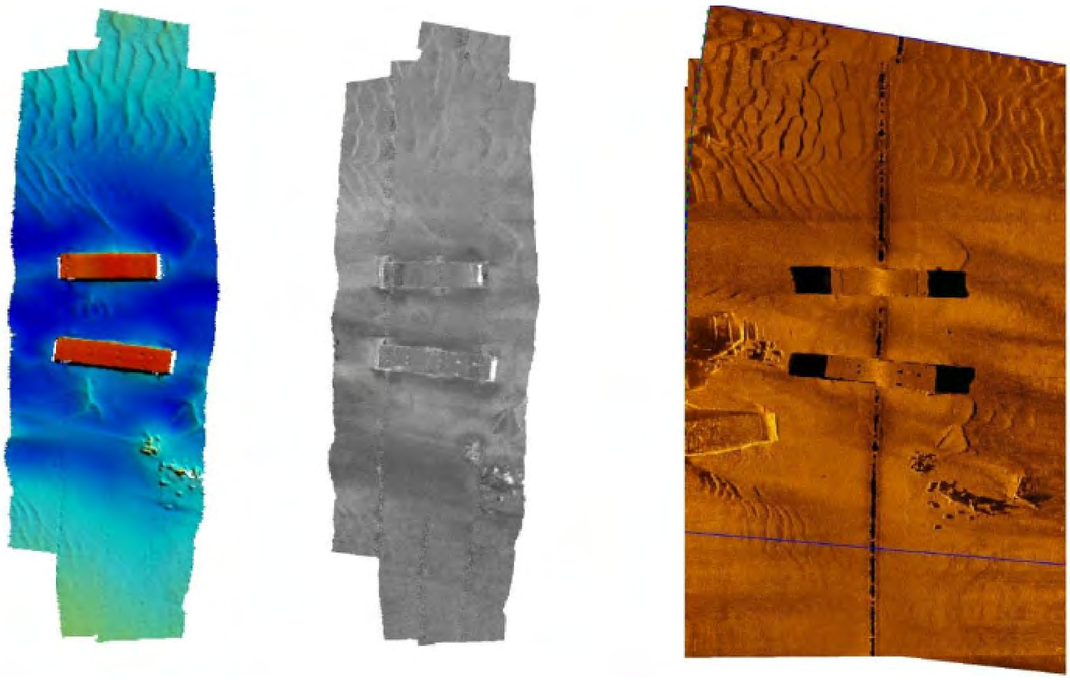
Source: Adapted from Brisson, Wolfe and Staley (2014).

Figure 4: Typical noise of interferometric sonars; b) Exemplification of the blind band in the Nadir and Nadir Gap Solution.

It can be concluded that the main advantage of this type of system consists in the widest sweeps, which generates a significant increase in productivity in shallow water. A problem still to be solved is the theoretical uncertainty model (*a priori*) of the PDBS. These models are complex and have been difficult to reconcile with the performance observed in practice. A reliable theoretical uncertainty model is required to apply sophisticated post-processing techniques, such as the combined Uncertainty and Bathymetry Estimator (CUBE) algorithm (Calder and Mayer, 2003).

Multibeam systems, whether MBES or PDBS, sample the seabed with the primary objective of obtaining bathymetric information, at first through pairs of distance (TOA) and angle (DOA). In addition to depth information, the systems allow recording information of the amplitude of the backscatter acoustic signal which, in turn, provides sound images that closely resemble SSS products. This information helps in determining the physical properties of the submerged bed and is widely used in bottom classification processes.

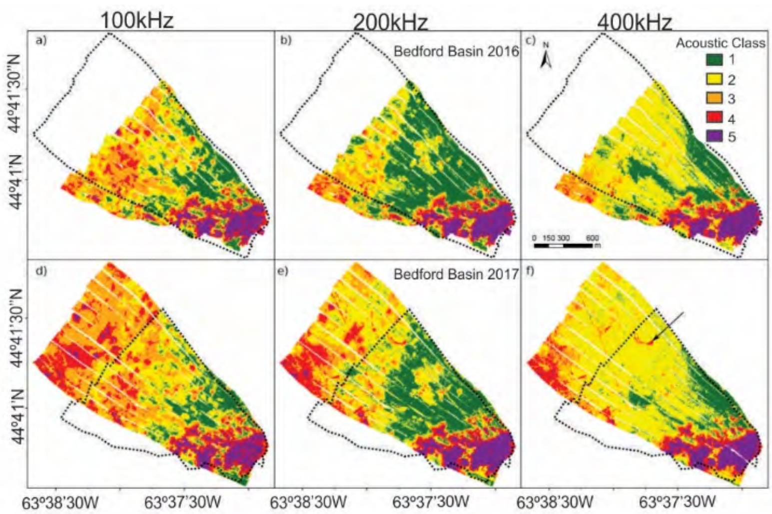
PDBS, in their essence, are SSS and for this reason can provide side scan sonar information integrated to bathymetry, in addition to the backscatter mosaic, as could be noted above. Together, this information allows for much more coherent processing and analysis. In Figure 5 is shown an example of the products supplied by PDBS, also of the EdgeTech system, seen from a different perspective.



Source: Edge Tech (2019).

Figure 5: On the left is the bathymetric model, in the center the backscatter mosaic and, on the right, the SSS mosaic.

Advances in acoustic mapping of the seabed also include multifrequency multibeam sonars (MBES), which allow data collection of the submerged bottom at different frequencies, in only one survey, which allows a better characterization of the submerged bottom. Gaida et al. (2018) and Brown et al. (2019) carried out research in this field and obtained results that showed that the use of this tool allows a better discrimination of existing sediments in the bottom, compared to the data obtained with a single frequency, in addition to presenting better efficiency (Figure 6).



Source: Gaida et al. (2018).

Figure 6: Acoustic classification map of the Bedford Basin region in Canada in 2016 and 2017.

As shown in Figure 6 , in a) and d) the frequency used is 100 kHz, b) and e) 200 kHz and in c) and f) is 400 kHz. According to the author, the white dots indicate the lack of data from that place in the nadir and the arrow shown in f) shows a feature found only at the frequency of 200 and 400 kHz, in the maps of 2017. It should be noted that the dotted regions represent the different raised areas.

Improvements in synthetic aperture sonar have also been noticeable in the past years. Recently the company Kongsberg launched HISAS 1032, a system capable of generating a range of approximately 1000 meters of coverage at 2.5 knots (or 1.3 m/s), with images of resolution 5cm. For bathymetry, HISAS1032 demonstrated a significant improvement over its previous version (HISAS 1030), in which a resolution of 50cm was obtained, and it is now possible to obtain a resolution of 20cm. The system is able to promote a coverage of approximately 4.5 km2/h, which is also high compared to previous versions.

Finally, in all cases, the primary disadvantage of surveys with acoustic systems lies in the high costs associated with vessels and crew. In shallow waters, a higher level of detail is always required which reflects a greater number of probed lines. In deep waters, on the other hand, the problem becomes the high costs involved with crew and large ships, even when using autonomous vehicles, there is the need for vessels to, for example, provide control of the uncrewed platform and acoustic positioning, when using AUVs.

3.2 Air and space-borne Remote Sensing

Despite the high attenuation suffered by electromagnetic waves in water, the visible portion of the spectrum can be employed in bathymetric mapping, especially where acoustic methods have limitations. In this context, depths can be measured in two basic ways, employing passive methods, which measure only the natural light reflected on the submerged bottom (spectral response bathymetry), and active methods, which use lasers to measure the distance to the seabed. The great advantage of applying these methods lies in the productivity that can be achieved (Figure 7).

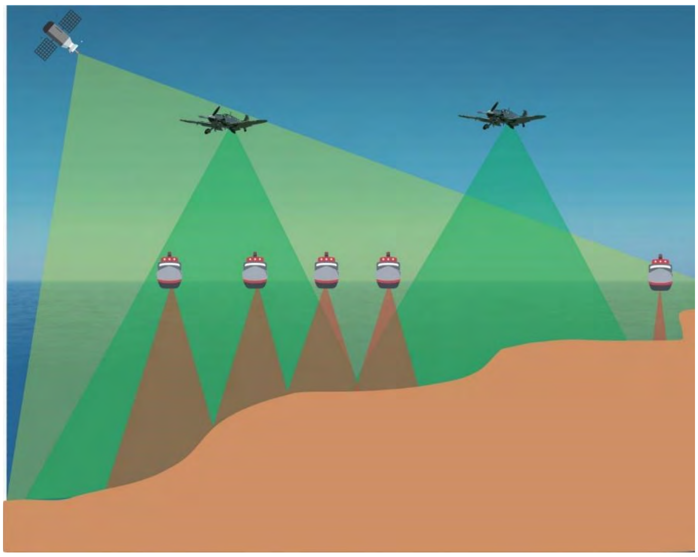


Figure 7: Different methodologies for extraction of bathymetry, exemplifying the high productivity of optical remote sensing.

As can be seen above, the range covered by a LiDAR system depends most on the height of flight, that is, it is more independent of depth, in contrast to multibeam sonars. Orbital imaging, on the other hand, can cover even larger areas with a single target. Bathymetry derived from aerophotogrammetric cameras embedded in crewed aircraft and uncrewed aerial vehicles (UAVs) are also the subject of recent studies (Aarnink 2017; Agrafiotsis et al. 2019; Andrade et al. 2020). Spectral information can also provide an estimate of the composition of the submerged bottom, as suggested by Zani, Assine and Silva (2008) and Ferreira et al. (2016).

3.2.1 Spectral response bathymetry

Part of the sunlight that reaches the submerged bottom is reflected and can be detected by sensors embedded in aircraft (crewed or uncrewed) and also by satellites. This radiation detected by these sensors can be used to measure depth and obtain bathymetric maps. Several authors have presented methodologies that employ orbital images to model the submerged relief, such as: Krug and Noernberg (2007), Gao (2009), Cheng et al. (2015), Gautam et al. (2015) and Ferreira et al. (2016). Researches related to the use of aerial images obtained especially by UAVs, in bathymetric mapping, were carried out for example by: Aarnink (2017), Agrafiotsis et al. (2019) and Andrade et al. (2020).

The principle of using orbital and aerial images for bathymetric mapping is not the same as that adopted by active sensors. In short, according to Casal et al. (2020) the extraction of bathymetry using multispectral images is based in three techniques: empirically-tuned physics based, empirical approaches and optimization-tuned physics inversion approaches.

Empirically-tuned physics base follows the principle that the intensity of the radiant energy, reflected by a water column and received by the sensor, is a function of the depth of the water, that is, the portion of solar radiation that penetrated the water column. In most cases, it is chosen to use the methodologies that employ the wavelengths of green (520 – 590nm) and near infrared (NIR) (760 – 850nm), for the generation of the index known as the Normalized Difference Water Index (NDWI) shown in equation (1) (MCFEETERS,1996):

$$NDWI \approx \frac{\rho(G)-\rho(NIR)}{\rho(G)+\rho(NIR)} \tag{1}$$

being $\rho(G)$ the spectral range corresponding to the green light of the visible spectrum and $\rho(NIR)$ the spectral range corresponding to the near-infrared region.

According to Mcfeeters (1996) and Xu (2007), these wavelengths aim to minimize the low reflection of water bodies in the NIR band and maximize the reflectance of water with green light, which due to low attenuation is able to penetrate up to a few meters in optically shallow waters. On the other hand, with infrared wavelength the water level is determined. This information is correlated with depth information derived from more robust methods (acoustic sensors) to provide a mathematical model in which bathymetry is obtained through digital levels.Through the equation obtained in the mathematical model, it is possible to find a new depth value. Moura et al. (2016) carried out a study with images from the Sentinel 2A and Landsat 8 satellites, separating bodies of water and land using the NDWI indices and also the Modified NDWI (MNDWI). For the extraction of spectral bathymetry, they used the method proposed by Stumpf, Holdereid and Sinclair (2003), where blue and green band reflectance values are used. Thus, the authors were able to detect navigation hazards that are up to 10 meters below the water level, as well as changes in port structures and coastlines. Zani, Assine and Silva (2008) applied methods of digital image processing and geostatistical analysis to obtain bathymetry of a river area with orbital data from the Aster sensor and concluded that depths extracted from the red wavelength (630nm to 690nm) were the ones that presented the greatest correlation with field data, presenting a standard deviation of 0.36 m. The authors also generated a Digital Depth Model with the estimated bathymetry.

From studies with RapidEYE satellite images, Ferreira et al. (2016) evaluated the use of these for optically shallow water bathymetry extraction, obtaining discrepancies less than 0.5 m. Work in this field has already been carried out also through artificial neural networks (ANN). Ribeiro, Centeno and Krueger (2008) used data from the Ikonos II system in combination with a two-layer hidden feed forward ANN and proved that the methodology generates results between 0.25 m and 0.50 m of maximum error, which according to the authors meets the technical specifications of the Hydrography and Navigation Directorate (DHN) for Surveys of 1st Order .

Another scenario is the empirical approaches, which are the newest methods (i.e machine learning techniques) and not widely used. In the optimization-tuned physics inversion approaches, according to Gao (2009), the application of the model requires the specification of a range of optical properties of the water and the seafloor, but no need in situ data for calibration.

In fact, with spectral response bathymetry it is possible to quickly collect data on large areas with low cost, however, the maximum depth reached is approximately 30 meters in clear waters (Dekker et al. 2011, Eugenio et al. 2015) and much smaller in cloudy waters. In addition, the information is still obtained with accuracies incompatible with current requirements, restricting its use for planning, recognition and environmental modeling purposes. Thus, in bathymetric surveys, the use of aerophotogrammetric and orbital images remains, mainly, as a recognition and planning tool in areas where bathymetric information is nonexistent or insufficient. On the other hand, images from orbital and airborne sensors are a very useful tool for the delineation of coastlines and mapping of port structures and navigation aid.

3.2.2 Bathymetric LiDAR

The Bathymetric LiDAR or Airborne LiDAR Bathymetry (ALB) is the most productive method for bathymetric mapping in shallow water (< 50 meters), it usually flies at 180 knots and the covered range is higher than the most modern MBES and PDBS.

Similar to acoustic systems, ALB also measure depth indirectly using the travel time of a laser pulse. LiDAR systems were first introduced in the mid-1960s, originally as a tool for topographic mapping. During the flights over lakes and coastal regions, the researchers noticed a double return, which allowed to conclude that the laser penetrated the water and that it could be employed in mapping the submerged relief (Hickman, Hogg 1969). Due to this, there has been an increasing development of ALB systems. The first system recognized as capable of collecting depths was designed in the United States and was from the Canadian manufacturer Optech (Tan et al. 2020). In the 1990s, the Airborne LiDAR system entered the commercial stage and was widely used in hydrographic monitoring and mapping.

In general, the basic working principle of the ALB consists in the emission of two laser pulses, the first in the infrared wavelength (1064nm), which allows the detection of the surface, since the penetration into the water is effectively zero, and the second in the green-blue wavelength (532nm), which despite a lot of dispersion, can reach the submerged bottom (Jerlov 1976). As with an echo sounder, a time series of light intensity (instead of acoustic intensity) is recorded. The typical scan interval is 1 ns (10-9 seconds) as opposed to ~ 1 ms to 10 µs (10-3 to 10-5) for acoustic signals. The echo envelope, in these cases, usually called a “waveform”, is then used to estimate the depth (Figure 8).

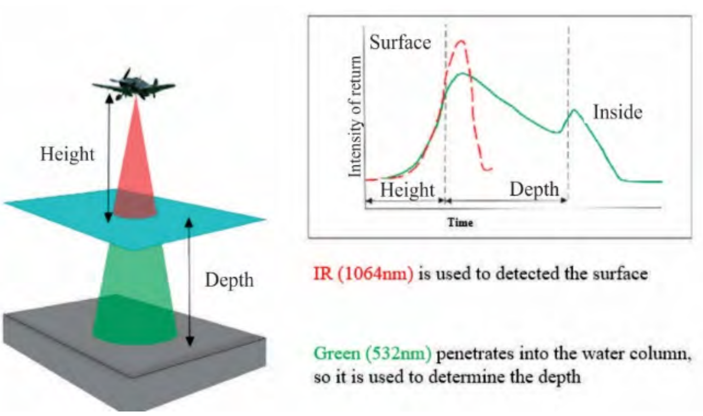


Figure 8: Operation of an ALB sensor.

As can be seen in Figure 8, the green wavelength records two returns, the first on the surface of the water and the second on the submerged bottom or equivalent target. This suggests that the laser at the red wavelength may be expendable. Equipment such as the Riegl VQ-840-G uses only the wavelength of green light to obtain topographic surveys (mainly on coastlines) and combined bathymetric.

The main limitation of these systems is penetration. As discussed, the biological, geological and physical conditions of the waters of rivers and seas significantly change the conditions of propagation of signals based on electromagnetic waves to the point of not allowing these waves, in general, with the exception of the visible light range, to be able to travel longer distances. The maximum depth of measurement is then determined by a combination of the optical properties of the water column and the submerged bottom. Under ideal conditions, depths of up to 60 m can be measured with LiDAR systems, but most applications are limited to depths of 40 to 50 m.

Generally, the penetration of the ALB is 2 to 3 times the depth observed with the Secchi disc and is determined *in situ*. Another way, technically more effective, would be to determine the attenuation coefficient at the wavelength used, which is able to describe the exponential decay of light with depth.

More modern systems are able to obtain a vertical and horizontal accuracy of about 20cm, with a spacing of 1 meter (Tan et al. 2020). Unlike multibeam systems, the range covered by the ALB is fixed and independent of depth (depends only on flight altitude). The laser commonly fires at a fixed rate (1000 Hz, for example) and thus the density of points depends above all on the flight speed and the aperture of the scanner's firing arc. According to Guenther (2007), a coverage of up to 70km²/hour can be obtained. At the end of 2019, RIEGL's VQ-840-G laser scanner system was launched,which has high spatial resolution due to the measurement rate of up to 200 kHz and high scanning speed of up to 100 scans per second. The system is optionally offered integrated with GNSS/IMU, as well as being compact and compatible with various UAVs.

ALB are, in fact, effective in mapping shallow environments, especially in places where acoustic mapping may prove to be ineffective or dangerous, such as in reef areas. In addition, the possibility of obtaining topographic and bathymetric data integrated and in the same mission are advantageous in order to offer more improved and robust management tools. Often, LiDAR systems are coupled with passive hyperspectral imagers to assess the bathymetric composition of the bottom simultaneously. The big disadvantage lies in the high costs involved, especially of the equipment, and in the still low resolution, compared to the multibeam systems.

3.2.3 Radar altimetry

The sending of radio pulses in the direction of the Earth's surface translates into the basic principle of operation of radar altimetry. According to Chelton et al. (2001), energy travels a distance back and forth with speed close to that of light. Thus, the time spent can be divided by two and multiplied by the speed of light itself in order to calculate the range of the beam. Subsequently, according to Gardini, Graf and Ratier (1995), one should subtract the altitude of the radar satellite relative to the ellipsoid, thus estimating the surface altitude below the sensor.

According to Seeber (2003), the satellite's altitude above the earth's surface can be inferred from equation (2).

$$A = c\frac{\mathrm{T}}{2} \tag{2}$$

Where "A" is the satellite's altitude above the surface, "c" is the speed of light in a vacuum, and "T" is the travel time of the signal sent by the radar.

In this sense, ignoring some corrections, the observations are related to an average altitude of the sea surface, which has a separation from the geoid which is known as dynamic topography, and by decreasing the value of the tidal effects from the dynamic topography, it is possible to find the topography of the ocean surface (H). The geometric altitude (h) can be derived by an orbit calculation with respect to a geocentric reference frame, with "N"

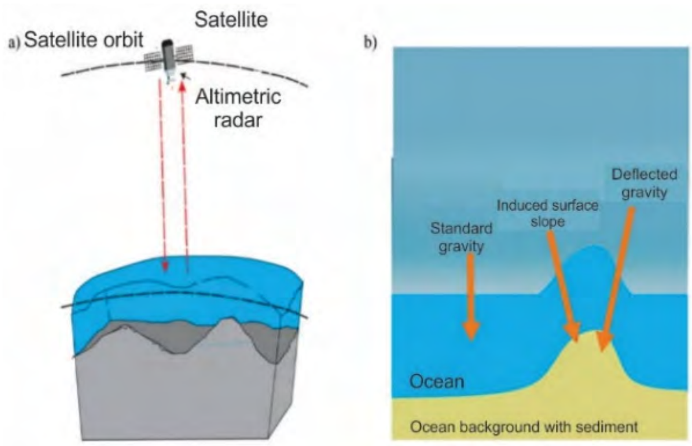
as the geoid undulation, "d" the discrepancy between the computed orbit and the current orbit, "a" the altimeter measurement and ϒ the tidal effects (equation 3).

$$h = N + H + \Upsilon + d + a \tag{3}$$

It is also important to point out that the term "a" needs to be corrected for atmospheric influences and must be referenced to the satellite's center of mass (Seeber 2003).

In the 70s, the main purpose of radar altimetry was to measure the ocean's surface that most closely approximates to the geoid (Mcgoogan et al. 1974). Thus, over the years several altimetric missions have been carried out to meet demands in the areas of Geodesy, Oceanography and Continental Hydrology. An example of this was the Geosat missions in 1985 and ERS-1 in 1991, which according to Smith and Sandwell (1997) obtained as results surface models of ocean topography of good quality.

It is known that on the surface of the ocean there are small depressions that mimic the topography lying below water. The extra gravitational pull of seabed resources, such as seamounts, produce variations in gravity which in turn produce small variations in the height of the ocean surface. These depressions can be mapped through an altimetric radar mounted on a satellite. In deep ocean basins, where sediments are thin and morphology simple, altimetric radar data can even be used to predict current bathymetry (Brêda 2017) (Figure 9).



Source: Adapted from Smith and Sandwell (1997).

Figure 9: a) Representation of the basic operation of an altimetric radar; b) Mountains on the sea floor verified at water level.

The Figure 9a above shows how the height of the sea surface can be measured from altimetry satellites. A mountain or depression present on the ocean floor will contribute to the force of Earth's gravity changing its direction subtly, which will therefore cause a small depression on the surface. For example, a mountain on the ocean floor 3000 m high will produce a depression on the sea surface of approximately 30 cm high (Smith and Sandwell 1997).

Although small, this amount can be quantified by altimetric radar. What delimits the final resolution of this method is the regional depths of the ocean. The schematic Figure 9b shows the slope of the sea surface induced by a seamount. The inclination in the direction of the gravity vector, called "deviation from the vertical", is equal to the inclination of the sea surface, and is measured in microradians. A deflection microrradian appears as a variation of 1 mm in height from the sea surface per 1 km of horizontal distance (Smith and Sandwell 1997). However, there are some limitations in the correlation between gravity and bathymetry data. This can be influenced by sub-surface geology and variations in sediment thickness. The correlation is therefore stronger in deeper oceans where the rugged topography is milder on continental margins and abyssal plains, in addition to the sediments being finer (Fu and Le Traon 2006).

In this context, it is noted that in continental platforms (where sediments are thicker and conventional bathymetric surveys are in abundance), the gravimetric methodologies used to estimate depth are of limited value. However, numerous bathymetric data were made together with gravimetric information derived from satellite, allowing an optimal interpolation of the depths (Chelton et al. 2001). This data is available online for free and can be used in a variety of areas, such as ocean current modeling and tsunami path forecasting. An example of application of this tool consists of the project called Seabed 2030 (Mayer et al. 2018), a partnership of GEBCO (The General Bathymetric Chart of the Oceans) with the Nippon Foundation of Japan, which aims to obtain bathymetry of all oceans by the year 2030. This initiative funds numerous scientific research and seeks to train several young hydrographers to disseminate the importance of knowing the depth and characteristics of the submerged relief. It is noteworthy that the aforementioned project, on June 21, 2020, announced the inclusion of 14.5 million square kilometers of mapped areas (equivalent to an area twice the size of Australia), totaling almost a fifth of the entire underwater world. However, it is necessary to remember that the study has several other technological tools to obtain depth, especially with the use of multibeam echo sounders.

Thus, it is evident that information derived from altimetric radars are not accurate for verification of risks to navigation and are also not functional in shallow water, where other techniques (such as LiDAR), would result in more reliable and better products. In addition, the data obtained only with radars are not able to provide the depth of fact, and correlation with bathymetric data is necessary, as is performed in the methodology for measuring bathymetry through the spectral response.

4. Conclusion

The knowledge of bathymetry advanced rapidly in the last century due to the rise of acoustics, optics and radar techniques. The emergence of new algorithms made it possible to collect more accurate data. The creation of GNSS improved substantially the accuracy of the planimetric data in just ten years (Krueger et al. 2020), which consequently increased the accuracy of the bathymetric survey. Inertial systems, of small format, with accuracy better than 0.1° for measuring the attitude of the sounding platform was also notorious in the area of Hydrographic Surveys. In addition, methodologies were developed capable of providing a better-quality control of the information acquired, together with the use of more robust and rigorous interpolators that led to forms of representation of the relief in a more realistic way.

However, despite extensive progress already implemented and in operation, there are still numerous technologies that can be studied and also some issues to be solved. As an example, there is the inability to monitor the spatial and temporal variability in the reduced scale of sound velocity in the water column, which in some way hinders the production of accurate maps of bathymetric morphology by means of multibeam systems. Connected to it, Wolf et al. (2019) pointed also the limitation of the bandwidth and high costs restricting the transfer of the large volumes of data. Beside that, these authors believe that in the future, the data processing and the products are going to be made automatically in the vessel, with a small size to be easily transferred.

In another scenario, it is important to mention the lack of knowledge in the context of bathymetry survey, mainly in an emerging country such as Brazil, where the research incentive is low. Related to this, the accomplishment of forums and conferences regarding this matter can shed a light on the importance of the understanding the seabed and consequently show the applications and consequences of the use of this science in global scale, encouraging governmental and non-governmental agencies to foment more research in this field.

The Seabed 2030 project, which foresees the underwater mapping of the entire ocean by 2030, will also contribute significantly to the creation of different technologies, methodologies and consequently to a better understanding of the dynamics of the oceans. Solving current problems, such as the monitoring of the speed of sound in the water column, as well as other issues that are still considered unknown to hydrographers.

Further improvements that are to come should include motion sensors, positioning systems and speed sensors, lifting platforms and sophisticated software, including algorithms that dynamically compensate and allow narrower beam widths at short distances, i.e. with higher spatial resolution. Another trend is the use of point density with robust techniques for cleaning spurious data, as well as more accurate tide models and methods based on unsupervised machine learning as well as deep learning to predict and classify the seafloor with orbital images with more accuracy, speed and no reliance on in situ data, also helping the development of related areas, such as biological, climatological and sedimentological studies. As pointed out by Menandro and Bastos (2020), as in the last decade most research and studies were focused on shallow waters environments, in the coming years a greater trend is expected for deep water studies and, consequently, for the development of techniques and methodologies that further facilitate the accurate submerged bottom recognition. The integration of information from different equipment and methodologies facilitates the interpretation and analysis of spatial data sets. If properly georeferenced and treated, these data sets can be presented in a way that does not compromise the quantitative aspects of the data.

AUTHOR´S CONTRIBUTION

Laura Coelho de Andrade contributed to the elaboration and consolidation of all phases of the manuscript under the guidance of Italo Oliveira Ferreira. The four authors had a very interactive involvement in the stages of writing and organizing the text, in the bibliographic research and scientific basis.

Victoria Gibrim Teixeira and Felipe Catão Mesquita Santos participated in the general supervision of the different stages, such as review and organization of the text, bibliographical research indications, research materials and analysis and discussion of results.

REFERENCES

Aarnink, J. 2017. *Bathymetry Mapping Using Drone Imagery*. Coastal Engineering MSc thesis, Delft University of Technology, Delft.

Agrafiotis, P. Skarlatos, D. Georgopoulos, A. and Karantzalos, K. 2019. Shallow water bathymetry mapping from UAV imagery based on machine learning. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*. XLII-2/W10, 9–16. https://doi.org/10.5194/isprs-archives-XLII-2-W10-9-2019

Andrade, L. C. D., Ferreira, Í. D. O., Medeiros, N. D. G., and Fonseca, I. G. R. D. 2020. Viabilidade do uso de imagens de RPA's para extração da batimetria em reservatórios de água rasos. [Feasibility of using RPA's images for bathymetry extraction in shallow water reservoirs.] *Geoprocessamento Aplicado à Análise de Ambiente*. 1st Ed. Editora Unesc.

Brêda, J. P. L. F. 2017. *Assimilação de altimetria espacial para estimativa de batimetria e rugosidade efetivas para modelagem hidrodinâmica*. [Assimilation of spatial altimetry to estimate effective bathymetry and roughness for hydrodynamic modeling.] Masters dissertation. Programa de Pós-Graduação em Recursos Hídricos e Saneamento Ambiental da Universidade Federal do Rio Grande do Sul.

Brisson, L. N., Wolfe, D. A. and Staley, M. 2014. Interferometric swath bathymetry for large scale shallow water hydrographic surveys. In: *Canadian Hydrographic Conference*. pp. 1-18.

Brown, C. J. Beaudoin, J., Brissette, M. and Gazzola, V. 2019. Multispectral multibeam echo sounder backscatter as a tool for improved seafloor characterization. *Geosciences,* 9 (3). https://doi.org/10.3390/geosciences9030126

Calder, B. R. and Mayer, L. A.2003. Automatic processing of high-rate, high-density multibeam echosounder data. *Geochemistry, Geophysics, Geosystems*, 4 (6). https://doi.org/10.1029/2002GC000486

Casal, G. Hedley, J. D. Monteys, X. Harris, P. Cahalane, C. and McCarthy, T. 2020. Satellite-derived bathymetry in optically complex waters using a model inversion approach and Sentinel-2 data. *Estuarine, Coastal and Shelf Science*, v. 241, pp. 106814. https://doi.org/10.1016/j.ecss.2020.106814

Chelton, D.B. Ries, J.C. Haines, B.J. Fu, L.-L. and Callahan, P.S. 2001. Chapter 1 - Satellite Altimetry. In: L.-L. Fu and A. Cazenave, eds. *Satellite Altimetry and Earth Sciences - A Handbook of Techniques and Applications*. Elsevier, pp.1–131. https://doi.org/10.1016/S0074-6142(01)80146-7.

Cheng, L., Ma, L., Cai, W., Tong, L., Li, M., and Du, P. 2015. Integration of Hyperspectral Imagery and Sparse Sonar Data for Shallow Water Bathymetry Mapping. *Geoscience and Remote Sensing*. IEEE Transactions on, 53 (6), pp. 3235-3249. DOI: 10.1109/TGRS.2014.2372787

Clarke, J. E. H. 2014. *Imaging and Mapping II: Submarine Acoustic Imaging Methods*. Notes of classes. Ocean Mapping Group. University of New Brunswick.

Demoustier, C. P. 1996. *Synoptic fine-scale surveys of the seafloor with the new Deep Tow instrument package.* PhD thesis. Acoustical Society of America.

DHN – Diretoria de Hidrografia e Navegação. 2017. NORMAM 25 – *Normas da Autoridade Marítima para Levantamentos Hidrográficos* [Maritime Authority Rules for Hydrographic Surveys]. Marinha do Brasil. Brazil.

Edge Tech, 2019. *Image Scan Gallery.* Available at: <https://www.edgetech.com/underwater-technology-gallery/>. [Accessed 4 June 2020]

Ferreira, Í. O., Zanetti, J., Gripp, J. S., and das Graças Medeiros, N. 2016. Viabilidade do uso de imagens do sistema Rapideye na determinação da batimetria de águas rasas. [Feasibility of Using RapidEye System Images in Determining Shallow Water Bathymetry.] *Revista Brasileira de Cartografia*, 68 (7).

Fu, L. L. and Le Traon, P. -Y. 2006. Satellite altimetry and ocean dynamics. *Comptes Rendus Geoscience,* 338 (14), pp. 1063-1076. https://doi.org/10.1016/j.crte.2006.05.015

Gaida, T. C., Tengku Ali, T. A., Snellen, M., Amiri-Simkooei, A., Van Dijk, T. A., and Simons, D. G. 2018. A multispectral Bayesian classification method for increased acoustic discrimination of seabed sediments using multi-frequency multibeam backscatter data. *Geosciences*, 8(12), 455 p. https://doi.org/10.3390/geosciences8120455

Gao, J. 2009. Bathymetric mapping by means of remote sensing: methods, accuracy and limitations. *Physical Geography*, 33 (1), pp. 103-116. https://doi.org/10.1177/0309133309105657

Gardini, B.; Graf, G. and Ratier, G. 1995. The instruments on envisat. *Acta Astronautica*. 37, pp.301–311. https://doi.org/10.1016/0094-5765(95)00050-A

Gautam, V. K., Gaurav, P. K., Murugan, P., and Annadurai, M. J. A. P. 2015. Assessment of Surface Water Dynamicsin Bangalore using WRI, NDWI, MNDWI. Supervised Classification and K-T Transformation. Aquatic Procedia, 4, pp. 739746. https://doi.org/10.1016/j.aqpro.2015.02.095

Guenther, G. C. 2007. Airborne lidar bathymetry. Digital elevation model technologies and applications: the DEM user's manual, 2, pp. 253-320.

Hickman, G. D. and Hogg, J. E. 1969. Application of an Airborne Pulsed Laser for Near Shore Bathymetric Measurements. *Remote Sensing of Enviroment*, (1), pp. 47–58. https://doi.org/10.1016/S0034-4257(69)90088-1

Hilldale, R. C. and Raff, D. 2008. Assessing the ability of airborne LiDAR to map river bathymetry. *Earth Surface Processes and Landforms*, 33 (5), pp. 773-783. https://doi.org/10.1002/esp.1575

IHO – International Hydrographic Organization. 2005. *C-13: IHO Manual on Hydrography*. Mônaco: International Hydrographic Bureau, 540p.

IHO – International Hydrographic Organization. 2008. *S-44: IHO Standards for Hydrographic Surveys*. Special Publication n. 44–5th. Mônaco: International Hydrographic Bureau, 36p.

Jerlov, N. V.1976. *Marine Optics*. Amsterdan: Elsevier Scientific Pub. Co.

Jong, C. D., Lachapelle, G., Skone, S., and Elema, I. A. 2010. *Hydrography*. 2nd ed. Delft University Press: VSSD, 354 p.

Krug, L. and Noernberg, M. 2007. O sensoriamento remoto como ferramenta para determinação de batimetria de baixios na Baía das Laranjeiras, Paranaguá – PR. [Remote sensing as a tool to determine the bathymetry of shallow waters in Baía das Laranjeiras, Paranaguá - PR.] *Revista Brasileira de Geofísica*, 25, pp. 101-105. https://doi.org/10.1590/S0102-261X2007000500010

Krueger, C. P. de Oliveira Junior, P. S., dos Anjos Garnés, S. J., Alves, D. B. M., and Euriques, J. F. 2020. Posicionamento GNSS em Tempo Real: Evolução, Aplicações Práticas e Perspectivas para o Futuro [Real-time GNSS Positioning: Evolution, Practical Applications and Perspectives for the Future]. *Revista Brasileira de Cartografia*, 72, pp. 1359-1379.

Kongsberg Maritime, 2013. *EM 124 Multibeam Echo Sounder Data Sheet*. Available at: https://www.kongsberg.com/globalassets/maritime/km-products/product-documents/discovering-the-redefined-em-multibeam-series [Accessed 19 June 2020].

Kongsberg Maritime, 2015. *Data Sheet of Hugin Autonomous Underwater Vehicle (AUV).* Available at: hugin-product-specification (kongsberg.com) [Accessed 4 February 2021].

Kongsberg Maritime, 2021. *EM 2040P MKII Multibeam Echo Sounder Data Sheet*. Available at: https://www.kongsberg.com/contentassets/2b09d642b1604c78941086c6ce60a9b0/em-2040p-mkii---data-sheet.pdf [Accessed 21 August 2021].

Lamine, B. O. M. Ferreira, V. G. Yang, Y. Ndehedehe, C. E. and He, X. 2021. Estimation of the Niger River cross-section and discharge from remotely-sensed products. *Journal of Hydrology: Regional Studies*, 36 (June), pp.100862. DOI:10.1016/j.ejrh.2021.100862.

Langewiesche,W. 2019. What Really Happened to Malaysia's Missing Airplane. *The Alantic*. Available at: Malaysia Airlines Voo MH370: Onde está? - O Atlântico (theatlantic.com) [Accessed 20 August 2021]

Laporte, J. Dolou, H. Avis, J., and Arino, O. 2020. *Thirty years of Satellite Derived Bathymetry: The charting tool that Hydrographers can no longer ignore.* The International Hydrographic Review. International Hydrographic Organization. Monaco. Publication P-1. pp. 129-154.

Leica Geosystems, 2015. *Leica HawkEYE III PaperSheet*. Available at: <https://leica-geosystems.com/pt-br/products/airborne-systems/bathymetric-lidar-sensors/leica-hawkeye> [Accessed 20 June 2020].

LINZ – Land Information New Zealand. 2010 Contract Specifications for Hydrographic Surveys. *New Zealand Hydrographic Authority*. 1 (2), 111 p.

Mayer, L. Jakobsson, M., Allen, G. Dorschel, B. Falconer, R. Ferrini, V., ... and Weatherall, P. 2018. The Nippon Foundation—GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030. *Geosciences*, 8 (2), 63 p. https://doi.org/10.3390/geosciences8020063

Matias, L. n.d. *Como funciona o Sonar: Medição da Velocidade do Som na Água* [How Sonar Works: Measurement of the Speed of Sound in Water]. Centro de Geofísica, Universidade de Lisboa. Portugal. Available at: <http://www.cgul.ul.pt/lmatias/fisica-geologia/Praticas/sonar-s.pdf>. [Accessed 11 July 2020].

Menandro, P.S. and Bastos, A.C. 2020. Seabed Mapping: A Brief History from Meaningful Words. *Geosciences*. 10 (7). 273 p. https://doi.org/10.3390/geosciences10070273

Mcfeeters, S. K. 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17 (7), pp. 1425-1432. https://doi.org/10.1080/01431169608948714

McGoogan, J. T. Miller, L. S. Brown, G. S. and Hayne, G. S. 1974. The s-193 radar altimeter experiment. *Proceedings of the IEEE*. 62 (6), pp. 793–803. DOI: 10.1109/PROC.1974.9519

Moura, A. Guerreiro, R. and Monteiro, C. 2016. As potencialidades da derivação de batimetria a partir de imagens de satélite multiespectrais na produção de cartografia náutica. [The potentialities of bathymetry derivation from multispectral satellite images in the production of nautical cartography.] *4as Jornadas de Engenharia Hidrográfica*. Instituto Hidrográfico Português, Lisboa, Portugal.

NOAA-National Oceanic and Atmospheric Administration. Introduction to multibeam – NOAA hydro training. 2009. Available at: <https://fdocuments.in/download/introduction-to-multibeam-noaa-hydro-training-2009-introduction-to-multibeam>

Pastol, Y.2011. Use of Airborne LIDAR Bathymetry for Coastal Hydrographic Surveying: The French Experience. *Journal of Coastal Research*. (62), pp. 6-18. https://doi.org/10.2112/SI_62_2

Ribeiro, S.R.A.; Centeno, J.A.S. and Krueger, C. P. 2008. Estimativa de profundidade a partir de levantamento batimétrico e dados IKONOS II mediante redes neurais artificiais. [An estimate of depth from a bathimetric survey and IKONOS II data by means of artificial neural network.] *Boletim de Ciências Geodésicas*, 14 (2), pp. 171-185.

Riegl. n.d. Laser Measurement Systems. RIEGL VQ-840-G Datasheet.2020. Available at: <http://www.riegl.com/uploads/tx_pxpriegldownloads/RIEGL_VQ-840-G_Datasheet_2020-04-07.pdf>. Accessed in 23 jun. 2020.

Seafloor System. EchoBoat DataSheet.2017. Available in: <https://90bad3e4-1784-40fb-a37b2016d39a0b4d.filesusr.com/ugd/7fd758_9f521ab5885a42c182f34b4c0949f03a.pdf>.

Seeber, G. 2003. *SatelliteGeodesy*. 2nd. ed. New York: Walter de Gruyter, 2003. 589 p.

Sherman, C. H. and Butler, J. L. 2007. *Transducers and arrays for underwater sound*. 1st Ed. New York: Springer.

Smith, W. H. and Sandwell, D.T. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277(5334), pp. 1956–1962. DOI: 10.1126/science.277.5334.1956

Stumpf, R. P. Holdereid, M. and Sinclair, M. 2003. Determination of water depth with high resolution satellite imagery over variable bottom types. Limnology *and Oceanography*, 48 (1), Part 2, pp. 547-555. https://doi.org/10.4319/lo.2003.48.1_part_2.0547

Tan, Y. Z. Zhou, G. Q. Zhou, X. Wei, J. D. Chen, J. L. and Hu, H. C. 2020. Overview of Chinese and American Marine Airborne LIDAR. The International Archives of Photogrammetry, *Remote Sensing and Spatial Information Sciences*, 42, pp. 111-115. https://doi.org/10.5194/isprs-archives-XLII-3-W10-111-2020

Teledyne Marine. Echotrac CV100 - Single or Dual Channel Echo Sounder. 2018. Product Leaflet. Available at:<http://www.teledynemarine.com/Lists/Downloads/EchoTrac%20CV100%20Product%20Leaflet.pdf>. [Accessed 3 September 2020].

Urick, R. I.1975. *Principles of Underwater Acoustics.* Toronto: McGraw-Hill.

USACE – U.S. 2013. Army Corps of Engineers. Hydrographic Surveying. Engineer Manual n. 1110-2-1003. Department of the Army. Washington, D. C. USA.

Xu,H. 2007. Extraction of Urban Built-up Land Features from Landsat Imagery Using a Thematicoriented Index Combination Technique. *Photogrammetric Engineering & Remote Sensing*, 73 (12), pp. 1381–1391. https://doi.org/10.14358/PERS.73.12.1381

Wölfl, A. C. Snaith, H. Amirebrahimi, S. Devey, C. W. Dorschel, B. Ferrini, V., ... and Wigley, R. 2019. Seafloor Mapping – The Challenge of a Truly Global Ocean Bathymetry. Front. Mar. Sci. 6. pp 1-16. doi: 10.3389/fmars.2019.00283.

Zani, H. Assine, M. L. and Silva, A. 2008. Batimetria fluvial estimada com dados orbitais: estudo de caso no Alto Curso do Rio Paraguai com o sensor Aster. [Fluvial bathymetry estimated with orbital data: a case study in the Upper Course of the Paraguay River with the Aster sensor.] *Geociências* (São Paulo), 27 (4), pp. 555-565.