ACOUSTIC AND LASER BATHYMETRY SYSTEMS

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This paper discusses acoustic and lasers based bathymetric systems in terms of their applicability in diverse circumstances. The advantages and disadvantages of each method are compared in terms of capabilities, cost and accuracy. None of these systems can provide full bottom coverage in all circumstances but could be supplementary to each other. Information has been presented in support of this conclusion. Acoustic bathymetry is suitable at deeper waters whereas laser bathymetry may be used in shallow clear coastal waters. A hybrid option has been suggested with the mix of these systems for higher survey efficiency and lesser costs. This paper is of interest to persons involved in ocean acoustics study and survey projects planners as well as to the developers of laser instruments for study ocean water and bottom properties and object detection such as wracks, boulders and other objects.

INTRODUCTION

Ocean bathymetry is used primary to produce precise marine navigation charts needed particularly in shallow water. Other applications include dredging operations, oil and gas exploration, underwater constructions and bottom object detections like boulders, wracks etc. Acoustic multibeam swath bathymetry (MSB) is widely used in the developed countries. The system generates hundreds of narrow beams over which sound pulses are transmitted towards to and reflected from the bottom to cover a wide swath during a single transect. Bathymetric surveying is an expensive and labour intensive task. This is one of the reasons for the large hydrographical backlogs being experienced by many countries [1].

Airborne Lidar Bathymetry (ALB) is the other possible approach that could offer quick and accurate survey for both large and small areas, at lower cost but applicable only to shallow, clear waters. The development of ALB from the 1970's parallels the development of MSB. Early systems were rather slow and ponderous but advancement in underlying technologies has made both ALB and MSB much more effective.

In this paper, technical parameters of selected systems are presented, which allows for comparison between airborne lasers and acoustic based systems in terms of cost, accuracy and capabilities. This paper is of interest to people involved in ocean studies and survey projects planners and to the developers of laser instruments to study water bottom properties and object detections.

1. AIRBORNE LASER BATHYMETRY

ALB is a technique suitable for moderately clear, coastal waters and lakes from a low-altitude aircraft using a scanned, pulsed laser beam [3, 4]. ALB uses the travel time of the short laser pulse to calculate the water depth. A scanner aims the laser pulses to cover the survey area with a pre-defined spot pattern. Lasers themselves are relatively accurate in their ranging capabilities, combined with precise geo-referencing systems and properly designed scanning mechanisms, airborne LIDAR can provide accurate coordinate of the depths to a few tens of centimeters precisions as shown in Tab.2.

Two laser pulses are used for each sounding; one green (532 nm) and one near infrared (near-IR, 1064 nm); transmitted from the aircraft at known angle toward the water surface. The green pulses are transmitted at 1 kHz rate while infrared pulses at 8 kHz rate. These pulses are sent simultaneously and in parallel so that they strike the water surface at the same location and at the same time. Infrared pulse is reflected from water surface to provide a reference point. The green pulse penetrates the water surface and propagates into the water column towards bottom where it is reflected back. A portion of this reflected light propagates upward through the water column and surface to be received at the aircraft. The precise timing and intensity of the reflected light is monitored as illustrated in Fig.1 and Fig.2. From those data a depth of ocean can be calculated over a swath.

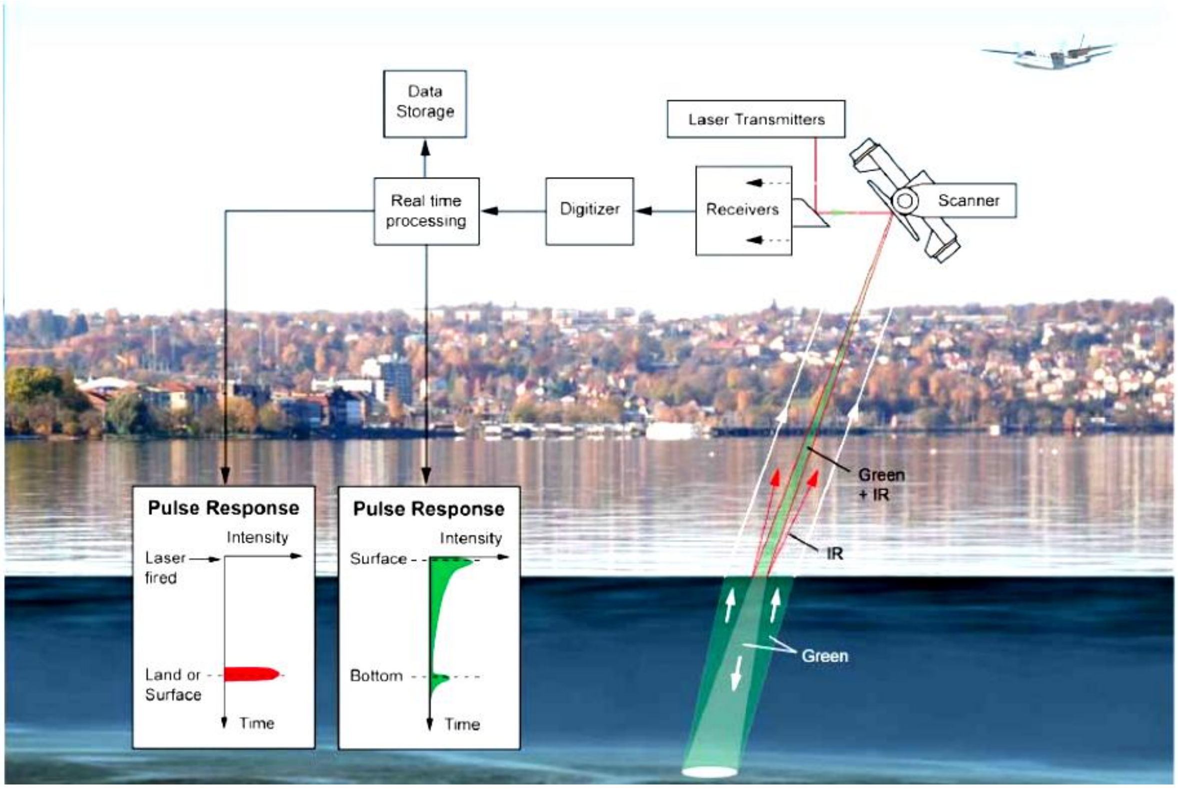


Fig.1. The working principle of ALB system [2].

ALB has the ability to perform survey where it would be difficult, dangerous or impossible to use water-borne techniques. It is capable of measuring the water depth from 20 cm down to 60 m, depending on the water clarity [5].

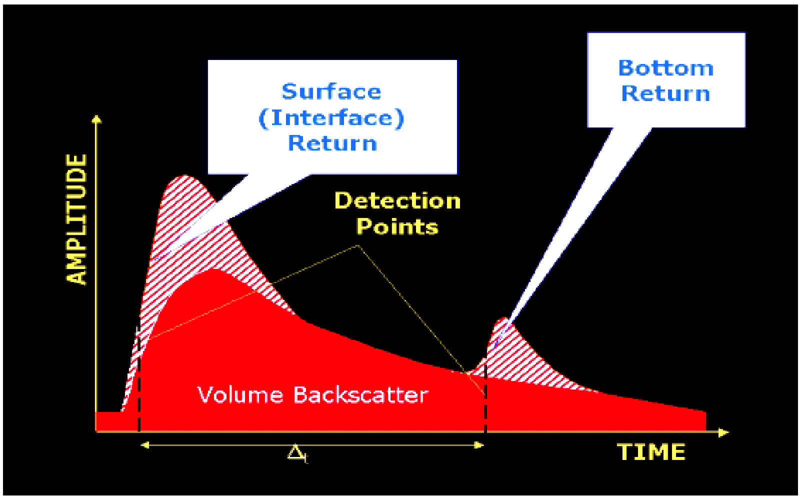


Fig.2. Sample waveform for ALB [2].

It provides the capability to map environmentally sensitive or dangerous coastal areas such as the areas offshore from the rain forests of Puerto Rico to sensitive sandgrass dunes to the rocky coasts of Hawaii or New Zealand efficiently and with minimum disruption of the environment [6]. It was also possible to survey with minimal impact on fauna and flora in extremely shallow waters (depths less than a meter) in Florida Bay. It has also improved the ability to map various terrestrial maps in a multitude of environments [9, 10].

2. MULTIBEAM SWATH BATHYMETRY

Acoustic MSB is complex but convenient method for surveying the sea bottom. It has revolutionized geological mapping [12, 13] with the wide swath advantage and was successfully used to map benthic habitats [14]. This technology effectively covers the sea floor with acoustic pulses that provide an array of measured depths. It uses a transducer to transmit a fan shaped array of pulsed energy divided into a series of narrow receiving beams. The return signal is associated with an individual transmit-receive beam. This makes each beam unique and derives a separate sounding and measurement of the seafloor reflection.

Modern multibeam systems might have up to 800 beams varying from 0.5 degrees to 2.0 degrees in width. Additional configurations and variations among systems can lead to “double pings”, resulting in twice the number of soundings per beam. Various transmit frequencies are utilized by different multibeam sonar systems depending on the sea depth. For example, low frequency (12 kHz) systems can operate swath soundings at full ocean depths, many up to 11,000 meters. In contrast, high frequency systems (300+ kHz) are utilized for swath bathymetry in depths of less than 50 meters. For a sample see Tab.1.

The swath footprint of the sonar ping on the seafloor increases with the depth. It is generally one tenth of the water depth. There are many instances however, when bathymetric data misrepresents the actual seabed topography, due to survey and processing errors and biases. In [16] Miller described in details the adverse effects of various survey parameters on acoustic seabed coverage.

Tab.1. Specifications of Multibeam Bathymetry SEA BEAM Systems.

	Shallow water		**Medium water**					**Deep water**	
Model	**1185**	**1180**	**1055/1050**	**1055D**	**1050D**	**3050**	**3030**	**3020**	**3012**
Parameters									
Sounding rate (Pulses/s)	180	180	50/50	50/180	50/180	50	30	20	12
Number of beams	126	126	126/126	126/126	126/126	918	918	301	301
Max^{m} swath coverage sector	153°	153°	153°/153°	153°/153°	153°/ 153°	140 °	140 °	140 °	140 °
Max^{m} depth (m)	300	600	1500/3000	1500/ 1500	3000/ 3000	3000	7000	8000	11000
Along-ship beamwidth	1.5 °	1.5 °	1.5 °/1.5 °	1.5 °/1.5 °	1°,1.5° or 3°/ 1°,1.5° or 3°	1°, 1.5° or 3°	1°, 1.5° or 3°	1° or 2°	1° or 2°
Across-ship beamwidth	1.5 °	1.5 °	1.5 °/1.5 °	1.5 °/1.5 °	1° or 2°/1° or 2°	1° or 2°	1° or 2°	1° or 2°	1° or 2°
Pulse length (ms)	0.15 -3	0.15 -3	0.15 – 10/ 0.15 – 10	0.3, 1.3, 10/0.15, 0.3,1.3	0.3, 1.3, 10/0.15, 0.3, 1.3	0.15 - 10	0.40 - 10	3 - 20	3 - 20
Weight (kg)	183	183	365/365	110/110	110/110	750	750	>1000	>3000

3. ADVANTAGES OF AIRBORNE LASER BATHYMETRY

Airborne Laser Bathymetry is designed for surveying the ocean depth but can also be used to detect rocks, sunken ships or men made objects under the water. Unlike the MSB systems, ALB can be used only for shallow waters but it can be used safely for areas with rocks or other objects which threaten the vessel [17]. It is light that allows operation from small aircrafts. Some systems have demonstrated capacity to collect both hydrographic and terrestrial measurements in a single survey [15].

Accuracy and ability to detect objects. ALB has proven that its accuracy meets the International Hydrographic Organization (IHO) standards [7] of order-1 or greater (see Tab. 2). Specifically, underwater objects were detected within less than half a meter from their actual locations. As a bathymetric tool ALB is capable of measuring water depth from 0.2 m down to 60m, depending on the water clarity [18]. The results obtained from laser and sonar surveys have been compared by different experiments. According to [19], 95% of data are within 0.24 meters for a LADS Mk II benchmark of 84,500 points for depths ranging from 6-30 meters. This significantly exceeds IHO Order-1 vertical accuracy requirement of 0.50 m. Positive reports were also available from the SHOALS experiment in the United States coastal areas [20, 21]. Subsequently, SHOALS results were compared with an operational National Oceanic and Atmospheric Administration (NOAA), National Ocean Service sonar survey in Tampa Bay up to 20-m depths [22]. The accuracy of SHOALS in that test was determined to be 0.28 meters at the 95% confidence level and greatly exceeds IHO Order-1 requirements. IHO standards

Tab.2. Minimum Standards for Hydrographic Surveys [7].

Order →	Special	1a	1b	2
Description of areas	For areas where under-keel clearance is critical and requires full sea floor search.	Areas shallower than 100 m where under-keel clearance is less critical but features of concern to surface shipping may exist and requires full sea floor search.	Areas shallower than 100 m where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area and does not require full sea floor search.	Areas generally deeper than 100 m where a general description of the sea floor is considered adequate and does not require full sea floor search.
Horizontal accuracy (m)	2	5 + 5% of depth	5 + 5% of depth	20 + 10% of depth
Depth accuracy for reduced depths (m)	a = 0.25 b = 0.0075	a = 0.5 b = 0.013	a = 0.5 b = 0.013	a = 1.0 b = 0.023
Feature detection	Cubic features > 1 m	Cubic features > 2 m, in depths up to 40 m; 10% of depth beyond 40 m.	Not Applicable	Not Applicable
Recommended maximum line spacing	Not defined as full sea floor search is required.	Not defined as full sea floor search is required	3 x average depth or 25 m, whichever is greater. For bathymetric lidar a spot spacing of 5x5 m.	4 x average depth.
Positioning of fixed aids to navigation and topography significant to navigation(m)	2	2	2	5
Positioning of the coastline and topography less significant to navigation(m)	10	20	20	20
Mean position of floating aids to navigation (m)	10	10	10	20

Tests of the Japan Coast Guard SHOALS-1000 also have demonstrated horizontal and vertical accuracy well within IHO standards [22]. FugroPelagos [23] indicated LIDAR depths matching the multibeam control results to within IHO accuracy requirements at the 98% confidence level for normal bottoms and 93-94% for bottom with wrecks.

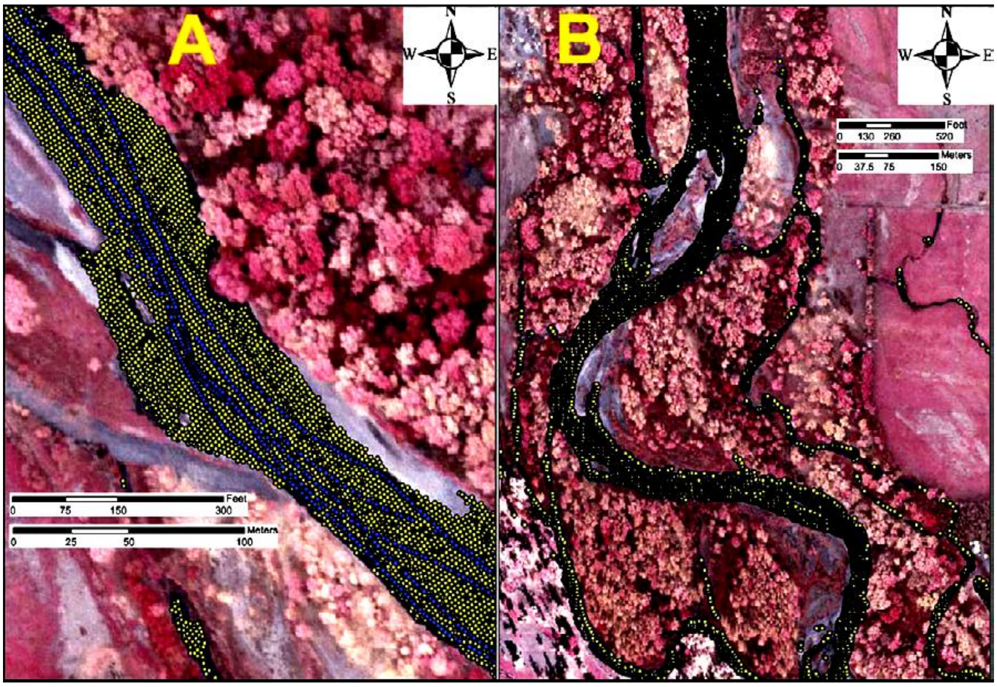
Cost. Cost is affected by area size, distance from the base station, resolution and accuracy required, environment etc. Flat, smooth, nearby coastlines such as the Gulf Coast of the U.S. are cheaper to survey than the remote, rocky coastlines of Alaska by a factor of two or three. The average cost of $123/km^2 for ALB and $772/km^2 for MSB, was estimated in [24]. According to [25] study, contractor-operated ALB system predicted a cost benefit ratio for ALB versus MSB of 2.7 with ALB costing \$4980/km^2 and sonar costing of \$13,460/km^2. These statistics were consistent with the MSB contractor values reported in [26]. For depths under 50 meters the cost ratio between MSB and ALB is 3 to 10 in favour of ALB. Tab.3 presents the estimated operation and maintenance (O&M) costs per unit area (in \$ per km^2). This information was obtained from [27] and does not include transit or mobilization costs from a distant location. It is observed from the below table that, for low depths ALB techniques are highly viable.

Tab.3. Estimated O&M Cost per unit area in k\$/km^2 [27].

	Depth (m) /Applicable order						
Systems	4/1	8/Special	8/1	8/2	16/1	16/2	32/2
ALB (HawkEye)	0.4	2.5	0.4	0.25	0.3	0.2	0.2
MSB systems	16	13	8	4	2.5	1	0.5
Ratio MSB/ALB	43.5:1	53:1	21.7:1	15.3:1	7.2:1	5.1:1	2.4:1

Coverage rate. ALB has higher survey coverage rate (up to 77 km^2/hour) compared to multibeam systems. The coverage area depends on survey density, laser pulse repetition rate, speed, angle etc. On the lower end, a system with an aero craft speed of 185 km/hr and 110m swath width gives a survey coverage rate of 20.4 km^2/hr. This is approximately 6 to 8 times that of a multibeam system. On the higher end, at 296 km/hr speed with a 230-m swath gives 68 km^2/hr coverage rates. These values are common with latest ALB systems. For example, LIDAR system (SHOALS) is capable of obtaining full coverage up to 70 km^2/hr with bottom coverage at densities up to 2m × 2m [28]. HawkEye II can survey even faster than that rate. If the detection of small objects with a size on the order of a 1-meter cube or slightly larger on the bottom is required, surveys may have to be conducted slower with a special scanner pattern to achieve higher sounding densities.ALB can also operate in a wide range of temperature. Survey has been conducted worldwide, both in northern and southern hemispheres including the Western Australia, Norwegian sea, middle east, Canada and many parts of USA by using this method [30, 31]. Specifically, survey has been performed in environmental conditions ranging from -10 ºC overnight in Stavanger, Norway at 50 meters depth in the cold sea to 50 ºC in the Tarmac in Doha, Qatar at 35 meters depth in the hot waters of the Middle East.

ALB can conduct survey of water channels that are numerous and too shallow. Aerial photographs of survey coverage in Yakima River, Washington are illustrated in Fig.3 to compare ALB and MSB system.



(a) (b)

Fig.3. Survey coverage using ALB (yellow) and boat-mounted acoustic depth sounder (blue) Ability of ALB to obtain coverage in wetted-side channels, Yakima River, Washington [2].

Tab.4 presents various technical parameters of three modern ALB systems (HawkEye II, SHOALS-1000 and SHOALS-1000T).

Tab.4. Specifications of ALB systems.

	SHOALS-1000	HawkEye-II	SHOALS-1000T
Sounding rate (pulses/s)	1000	4000	1000
Sounding footprint diameter (m)	2,3,4,5	1.7 to 3.5	2,3,4,5
Minimum depth (m)	0.2	0.3	Not specified.
Maximum depth (m)	50	70	65
Aircraft altitude (m)	200-400	250-550	200-400
Swath width	Up to 0.58 × altitude Typical (215m at 4m Diameter)	100-330 m	60-230 m
Weight	210 kg	190 kg	162 kg
System power requirements	60 A at 28 VDC	50 A at 28VDC	50 A at 28VDC
Depth accuracy	IHO order 1 (25cm, 1σ)	IHO order 1 or better (±0.25m)	IHO order 1 or better
Horizontal accuracy	IHO order 1 (2.5cm, 1σ)	IHO order 1 or better (±2.5m)	IHO order 1 or better
Camera	1600×1200 Pixels	1600×1200 Pixels	1600×1200 Pixels

4. LIMITATIONS OF AIRBORNE LASER BATHYMETRY

Green and infrared lasers are used in ALB system. The amount of energy required to transmit a green laser pulse is much higher than that of an infrared laser pulse. Due to the requirement of eye safe condition the spot size at surface must be sufficiently large (more than 1.7 m in diameter) to reduce power intensity. However, this will decrease accuracy and resolution of the system.

Surface foam caused by ocean waves can make water penetration difficult. In these cases the productivity of ALB is greatly reduced [32, 33]. Its spatial resolution is not as good as for modern high frequency MSB. For these reason small targets may not be detected even if illuminated [34]. The effective approach for increasing the detection probability for small target is to increase the survey density. However, it should be noted that it is also difficult for MSB to detect one-meter cubes on the bottom [35]. A major limitation for ALB systems is surface and water clarity, bottom reflectivity and solar background. These limit the maximum penetration depths. Other environmental factors, such as rain, high winds, high waves, surf zone, fog, very steep slopes etc. also cause problems with ALB survey [36]. In the rainy days ALB surveys do not take place because backscatter by the raindrops. It is also preferred not to survey through fog and clouds. In order to reflect the off-nadir laser energy from the water surface back to the receiver, the capillary waves are needed for non-specular laser reflection and for this reason a certain low winds are needed. However, the modern ALB systems can overcome this issue, as they use Raman scattering from infrared laser.

5. ADVANTAGES OF ACOUSTIC BATHYMETRY

Depth sounders are affected by platform motion. Modern multibeam systems however use stabilized beams and heave compensation. Measuring the movement and position of the vessel is imperative to preserve the accuracy of the data because the position of the sounding will change as the vessel moves in the water due to roll, heave, pitch and yaw. Horizontal and vertical positioning is precisely measured through the use of GPS and inertial measurement units (IMU). Sophisticated IMU is used to compensate the errors caused by the vessel movements. MSB can map swaths of the bottom in the time it takes for the echo to return from the farthest angle. The SEA BEAM 2100, a multibeam sonar system generates up to 151 beams at 1° apart with each ping, and can cover areas tens of kilometers wide in depths of a few kilometers [37]. It also collects backscatter information, which can provide information about the seafloor. Backscatter is characterized by the intensity or strength of the returned signal. It is a helpful tool for precision mapping of the seabed. The information is useful for characterizing the seabed material properties and detecting small features not visible in the sounding data. This system employs approximately 20% overlap to ensure good quality data and complete coverage of the seafloor. Smaller footprints are always expected for higher resolution. A narrower beamwidth results in a small sonar footprint on the seafloor. Most MSB use a beamwidth that can vary from 0.5 degrees to 2.0 degrees. Depending upon the application, it is useful to combine 2 or 3 multibeam systems operating at different frequencies into one system. A higher frequency instrument will have better resolution and accuracy than a lower frequency instrument. In summary the main advantage of a modern MSB is its ability to provide simultaneously a high-resolution accurate bathymetry map and a backscatter image of the surveyed area.

6. LIMITATIONS OF ACOUSTIC BATHYMETRY

The bottom echo is generally affected by the side lobes of the beams and reverberates on all the beams. At distances longer than the bottom depth, a strong background noise appears, due to this side lobe effect and multiple paths of these bottom echoes [29].

MSB systems are labour intensive and time consuming. It is also not possible to apply this method everywhere, due to the limitation of ship routes. Further limitations of MSB are due to minimum depth requirements for the vessels and possible motor restrictions on rivers. Very high frequency systems (300 kHz and above) are required for collecting swath bathymetry in shallow water of 50 meters or less. The coverage of MSB is a function of swath width. Most systems provide coverage of two to approximately seven times the water depth.

7. DISCUSSION

The hydrographic charts for many of the world's coastal areas are either out of date or nonexistent [38]. On the other hand, the use of coastal areas by commercial and recreational concerns is growing at a rapid pace. The coastal bathymetric data is also use for environmental hazards study. However, a huge backlog exists. Due to the budget cut, NOAA now has only four hydrographic ships in operation (Thomas Jefferson, Rainier, Rude and Fairweather). There is clearly a need for faster and cheaper approach to provide coverage of less demanding surveying areas. Survey planners are increasingly challenged to identify the types and locations of surveys needed and to assign the appropriate mix of data collection sensors in order to improve survey efficiency and reduce the cost. Many survey planners are still not fully aware to the relative merits of ALB. The following discussion will aid the decision makers to choose the accurate type of survey methods for their survey. In general, the accuracy of any ALB system degrades somewhat from the mentioned values for cases of weak signals near the penetration limit, for situations with extremely dirty water and for depths associated with steeply sloping bottoms and small targets [19, 39, 40]. Steep bottom slopes represent a vertical and horizontal measurement problem for LIDAR as they do for MSB. Results will also vary somewhat depending on the direction of flight with respect to the slope because of the off-nadir beam angle [41]. ALB survey O&M costs depend on survey scenarios, project location, size, horizontal density requirements, survey accuracy requirement, re-flying, the physical shape of survey area and if it includes surf zone or high cliffs, the positioning method employed and environmental conditions on site. Many of these same factors also apply to water borne bathymetry survey costs. The size of the survey must be large enough to amortize these costs. In general, large areas are cheaper to survey per unit area than small areas. Typically acoustic bathymetry incurs k$20 to k$150 per day during their survey. The O&M area cost ratio between ALB and multibeam sounders appears a factor in between 3 and 10 in favour of ALB for depths under 50 meters. Regardless of the exact number, it is quite clear that ALB offers a significant cost advantage in addition to its other advantages. In case of water turbidity and organic matters ALB performs better than MSB, because of the existence of several color laser lights which result less attenuation [42]. Research can be conducted to solve the problem in the design of a laser bathymetric that involves the precise and reliable determination of the location of the air/water interface considering a wide variety of environmental [43, 15]. The complexity of the environment and interactions of the LIDAR beam with the environment (such as returns from fish, zoo plankton and underwater scattering layers) made it impossible to compute all depths with highest accuracy and reliability in real time [33]. However, for many applications in water less than 50 m deep, where the assured detection of small-objects is not as important, the ALB is a preferred option.

8. CONCLUSION

Acoustic methods are old but convenient for ocean bathymetry. In deeper water acoustic is required, but is limited in shallow water. Modern ALB systems have sophisticated algorithm and efficient data processing packages; still there are cases where the output could not meet the IHO standards. Both sonar and ALB have pros and cons. Improvements in the systems will attract more users. The overlapping boundaries of finest performance provide the opportunity for cooperation, rather than competition, to maximize overall survey efficiency and safety. It was experienced that, laser and sonar, have been used together with success [11]. The Royal Australian Navy has achieved long term cost reductions to 20-30% of traditional total survey cost by using laser airborne depth sounders in combination with its survey vessels [8]. The combined methodology also followed in Lake Tahoe on the California- Nevada border. In short, ALB is not, and was not intended to be, a general replacement for MSB. It is, rather, a new tool that can be utilized, with benefits under the proper circumstances, as an adjunct to MSB.

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