Re-examining Rejected Lidar Waveforms

Filling in the Blanks: Seabed Depth, Extinction Depth or Opaque Depth?

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Abstract

The success of a bathymetric lidar operation depends heavily on both the propagation of the green laser beam towards the seabed and the reflectance of seabed material. The turbidity of the water column will limit the maximum achievable depth range, while the seabed reflectance, or backscatter, dictates the bottom detection ability. Both cases may result in an undetectable seabed, which to date is presented to the surveyor only as a sounding datagap.

Being able to distinguish between the causes of unsuccessful bottom detection, related either to water clarity and depth, or to seabed reflectance, would provide much improved confidence. This solution is particularly helpful where unsuccessful bottom detection occur due to a shallow but less reflective seabed rather than a deep seabed. The waveform of each unsuccessful bottom detection is herein examined to identify those waveforms that represent low reflectance seabeds within the lidar extinction depth. In such cases, an approximated depth is derived.

A SHOALS-3000 dataset collected in Baie des Chaleurs, Québec, Canada, was used for this experiment. This dataset included numerous locations where the green laser beam was tracking vegetation or where sounding datagaps occurred. Initially, ground truthing data such as acoustic volume imaging or aerial or underwater photography were necessary to reveal the cause of datagaps. Modifying the software made it possible to re-examine the waveforms at datagaps, thereby allowing one to determine if water clarity or seabed reflectance was the cause. In addition, where reflectance was the cause, the detection depths at weakly reflecting seabeds were approximated.

The ability of the lidar bottom detection is directly related to the seabed optical backscatter. It is therefore suggested that the seabed optical backscatter be incorporated in a yet-to-be-designed uncertainty parameter. By introducing an uncertainty parameter, the end user, rather than a processing system, will have the ultimate authority over accepted soundings. In addition, datasets are more versatile for users, who each have different quality criteria.

Introduction

The coastal zone is where many important seabed mapping operations take place. Human activity, such as shipping, fishing, and underwater construction, is common near the coast. In addition, natural offshore disasters (hurricanes, storm surges, and tsunamis for instance) leave their traces behind mainly where water meets the land. For all these coastal zone issues, there is a need to map both the shape and composition of the composition in the near shore zone. Survey areas are usually elongated along the coast, and maps need to be vertically seamless at the land/water boundaries. To fulfill these requirements, lidar is a favoured method for the collection of bathymetric and topographic data (Guenther [2007]). Unlike acoustic swath bathymetry, lidar maintains a constant sounding density and coverage rate, irrespective of the water depth (to its limit of optical penetration) and can map sub-tidal zones, which would be unreachable with ship-based surveys, or unnavigable waters, such as coral reefs and rocky coastlines.

These coastal areas are often populated with (sub-tidal) vegetation that grows near the seabed, and can float up into the water column. Previous work (Kuus [2008a], Kuus et al. [2008b]) has demonstrated that this aquatic vegetation poses a challenge for a bathymetric lidar system. The weak reflective vegetation both masks the underlying seabed and may or may not generate a misleading mid-water return. This results in false bottom tracking or datagaps that, in turn, result in incoherent and reduced sounding coverage. These datagaps are particularly frustrating since filling them in would require repetitive surveys or ground truthing measurements (e.g. acoustics or underwater imagery) thereby forcibly taking the risk of directing a vessel into uncharted areas. The datagaps also give the impression that the seabed is deeper than the extinction depth, which may be the case at the deep water limits of the coverage, but are unlikely at datagaps within the coverage. An improved confidence, however, can be given to the hydrographer by analyzing the waveforms associated with each datagap. Unfortunately, waveforms in the export files (LAS-format) are only attributed to soundings, not to datagaps. Modification of existing in-house software was necessary to access and analyze these rejected waveforms.

This paper will demonstrate, through re-examining the originally rejected waveforms, a method to determine the cause of bottom detection failure and, for the case of weakly reflecting seabeds, retrieve a least depth approximation.

Background

The SHOALS bathymetric lidar utilizes an infrared laser beam (1064 nm) from which, after frequency doubling, a green laser beam (532 nm) is produced. Both infrared and green laser beams are emitted simultaneously from the aircraft towards the sea surface under a constant angle away from nadir (~ 20°). The infrared laser beam will backscatter on the surface, while the green laser beam propagates the water column as far as the optical properties allow it to, until it either attenuates completely or hits its first reflector, in most cases the seabed (Figure 1). Differencing between the elapsed time of the infrared laser beam surface return and the green laser beam bottom return laser leads to a depth approximation. For a detailed description about the SHOALS lidar, the reader is referred to Guenther (e.g. 1985, 2000, 2007).

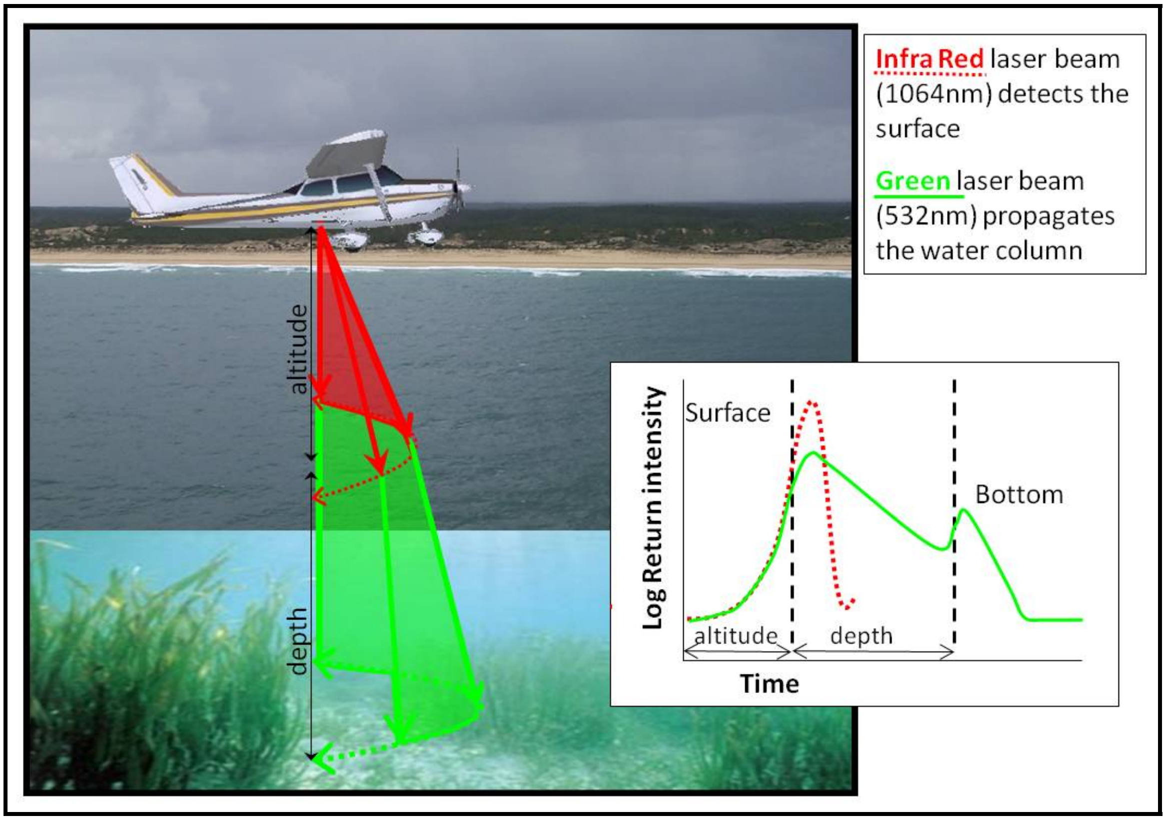


Figure 1 Principle of the SHOALS lidar system. It utilizes a near-infrared laser beam to determine the sea surface and a green laser beam to detect a reflector, ideally the seabed. A rotating mirror re-directs the laser, producing arc shaped swaths. The time series of a green laser beam typically shows a high peak identifying the sea surface return, and a second, usually smaller, peak as the bottom return. The returned signal decays as the range through the water column increases.

SHOALS Waveform Data

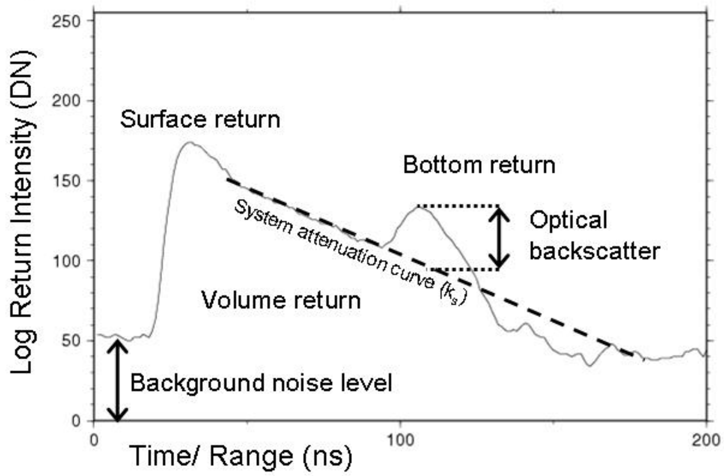
The SHOALS system records the waveforms of the received infrared and green laser beam returns in four channels: the infrared channel, two channels for the green laser beam at different fields of view (FOV) namely, the PMT (PhotoMultiplier Tubes) and GAPD (Geiger mode Avalanche PhotoDiode) channel, and the green excited Raman channel. The FOV can be described as the aperture angle of the receiver. It defines the area at the sea surface of incoming light that is recorded by one of the channels at the receiver. A narrower FOV allows less returned energy, thereby minimizing ambient sun glint, volume, and interface scattering, which in turn leads to an improved range resolution but also to a reduced range performance (Feygels et al. [2003]). Hence the GAPD (18 mrad) channel is used for shallow depth measurements, while the PMT (40 mrad) channel is used for deeper depth measurements.

The returned signal amplitudes are originally measured in linear intensity units. These are then logarithmically compressed into unsigned 8-bit digital numbers (0 - 255) to cope with the enormous dynamic range in the signal. The signal is digitized at 1 ns intervals, which translates to a range sampling interval of 0.115 m.

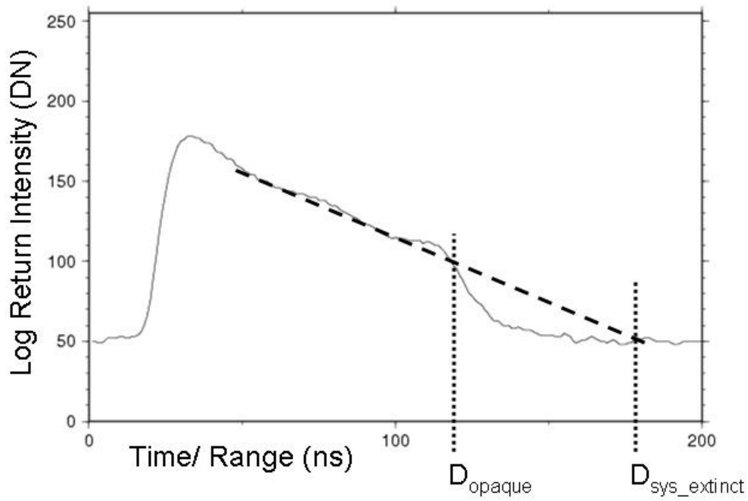
A typical green laser waveform suitable for bottom detection can be decomposed into three components: the surface or interface return, the volume return, and the bottom return (Figure 2a). The first peak in the waveform represents the surface return. The surface return is followed by backscatter over the water column, referred to as the volume return, and finally the bottom return. As the light propagates the water column, attenuation (absorption and scattering) will reduce the received volume backscatter. The decaying slope of the volume return describes the attenuation loss under certain environmental and operational conditions. This decay is therefore referred to as the system attenuation coefficient (k_s) and can be used as a descriptor for water clarity (Kuus [2008a]). Note that the received light intensity decays exponentially in linear space, but linearly in logarithmic space, as presented in the waveforms. The seabed is assumed to be located at 50% of the leading edge of the bottom return (Guenther [1985]). The excess above the extrapolate attenuation curve represents the seabed optical backscatter. Although other factors may influence the seabed backscatter, the seabed itself is the most significant contributor (Kuus [2008a]).

A weak reflecting seabed (Figure 2b) will produce a smaller or an undetectable bottom return, which ultimately leads to a datagap in the sounding coverage. Regardless of the seabed backscatter strength, the decaying volume return component of the waveform trace will be truncated to the background noise level once the green laser light reflects on an opaque medium. This behaviour was used in this work to identify a weak reflecting seabed. Although the precise depth of the seabed cannot be determined, it must be shallower than the point of truncation and therefore the depth of the opaque reflector can be approximated. Most importantly, a least depth can be determined, rather than leaving the impression that the seabed is beyond the extinction depth. If the seabed lies to deep for the lidar system to measure (Figure 2c), the waveform trace will follow the system attenuation curve into the background noise. This intersection represents the green laser beam extinction depth under the systemic and operational conditions at that moment. It is therefore referred to in this work as the system extinction depth ($D_{sys\_extinct}$).

a) Detectable bottom return



b) Weak reflecting seabed



c) Deep water

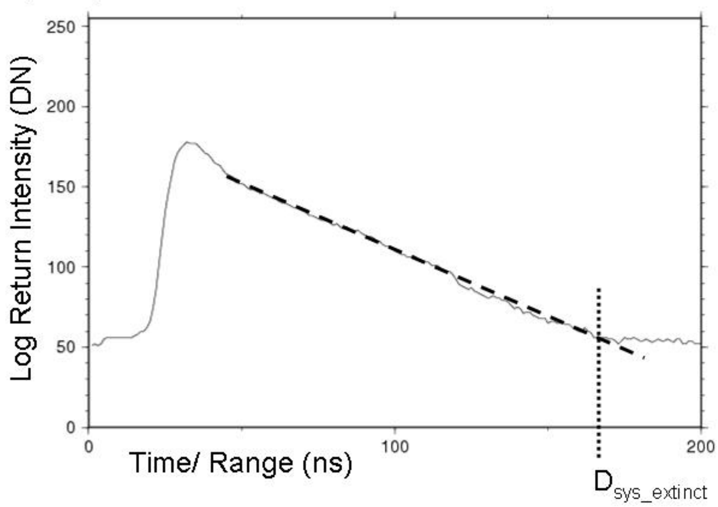


Figure 2 Waveforms were classified as (a) those with a detectable bottom return, (b) those with a undetectable bottom return from a weak reflective seabed, and (c) those where the attenuation curve sinks in the background noise.

Previous work

A SHOALS-3000 dataset collected in Baie des Chaleurs, Québec, Canada, in July 2006 was used for this experiment (Figure 3). Previous work with this dataset demonstrated that the green laser beam has considerable difficulties detecting the seabed in vegetated areas (Kuus [2008a], Kuus et al. [2008b]). Either the green laser beam tracked the canopy of seabed attached vegetation, or datagaps occurred. Datagaps are particularly concerning: beside the reduced effective coverage, datagaps were generally assumed to be allied to water clarity issues. Suggesting that a datagap represented a depth beyond the extinction depth, while, the datagap could, in fact, represent a marine life covered navigational hazard. Sub-merged vegetated areas could be well recognized from their low optical backscatter, or in combination with overlapping acoustical backscatter or lidar bathymetry slopes (Kuus [2008a]). At the time, lidar waveforms at sounding gaps were not retained for export and thus could not be read in by the software. Therefore, overlapping ground truthing data were necessary to retrieve information about the local seabed type within the datagaps. Recent software modifications at UNB make it now possible to also query the waveforms at sounding datagaps.

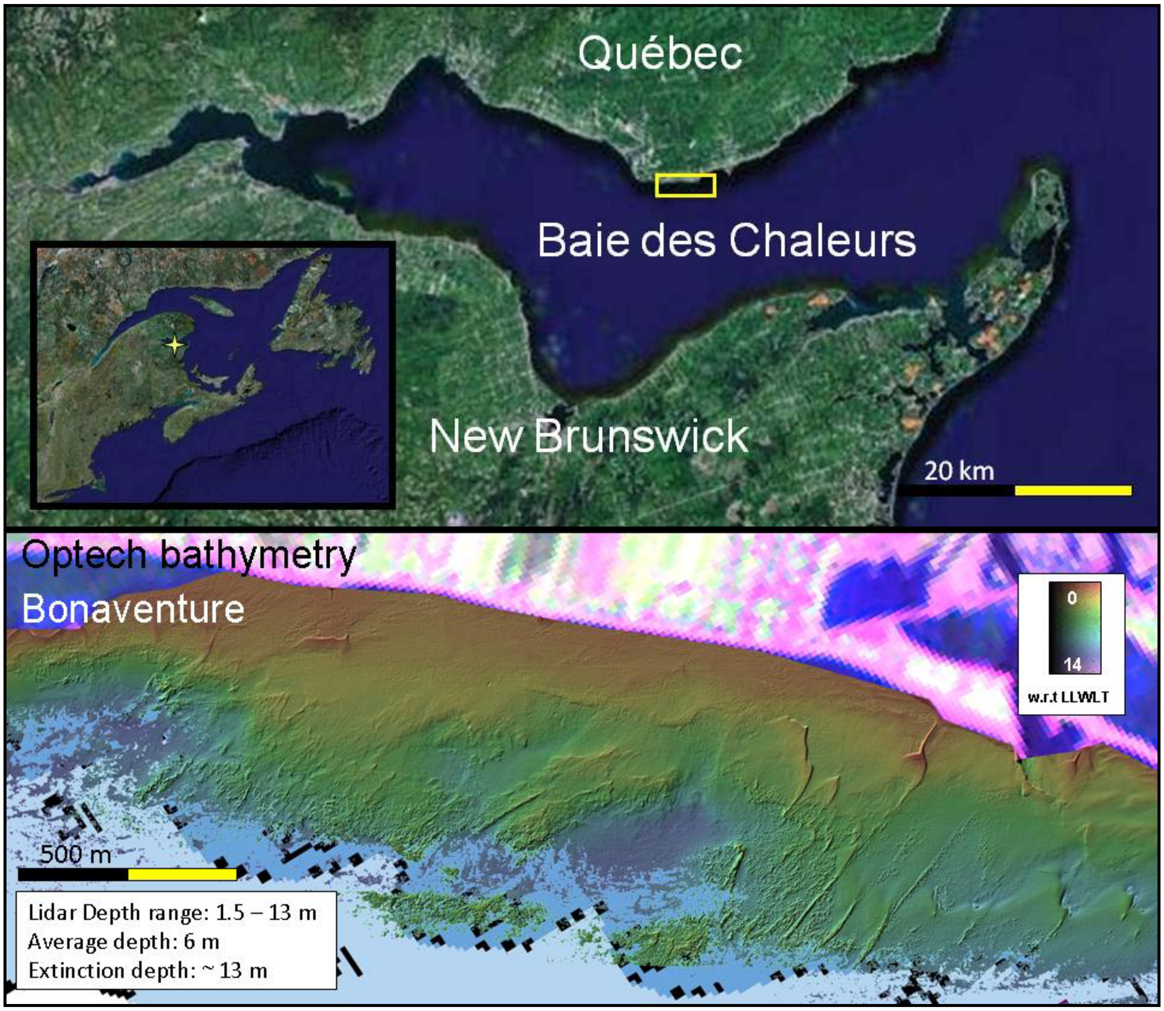


Figure 3 SHOALS data were collected July, 2006, in Baie des Chaleurs (top) near the town of Bonaventure (bottom). Note the datagaps within the coverage, rather than at the edges of coverage. Background LANDSAT imagery and CHS nautical chart (# 4486).

Methodology

Once all the waveforms are reformatted, they are viewed together with bathymetric data in "swathed", the Ocean Mapping Group's primary hydrographic tool. A function was designed to classify the rejected waveforms as type "weak" (e.g. Figure 2b) or "deep" (e.g. Figure 2c). Once spatially plotted, the classified waveforms illustrate where proper bottom detection was possible, and where datagaps occurred as a result of either low reflectivity or water clarity.

Depths are determined for waveforms with a detectable bottom return, for "weak" waveforms, and for "deep" waveforms by simply translating the two-way travel time, accounting for the refracted off-nadir angle, and applying tide corrections. In order to account for the absent leading edge of a "weak" classified waveform, a setback was determined to locate a "virtual leading edge". The setback is the ratio between the trailing and leading edge of waveforms with a detectable bottom return. This ratio, essentially the width of the bottom return, varies geographically (Figure 4); therefore, an average ratio is used from neighbouring waveforms with a detectable bottom return.

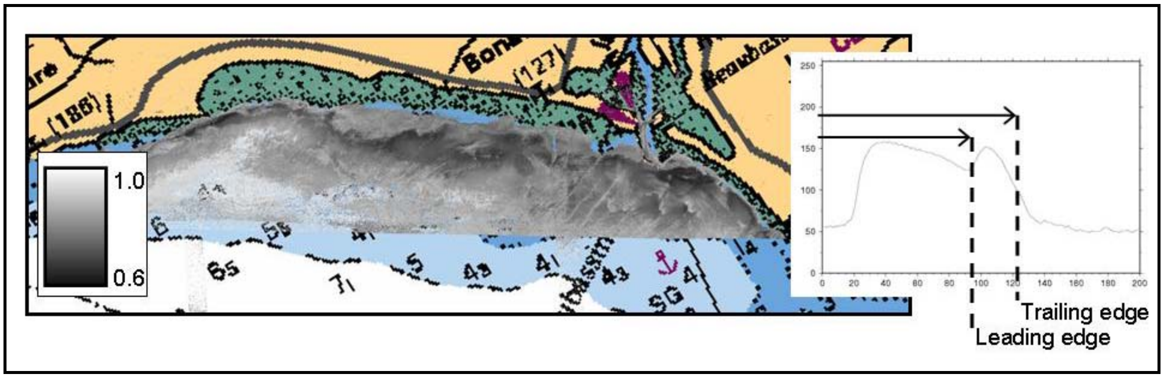


Figure 4 Varying ratio (presented in grey scale) of the trailing and leading edge from GAPD-waveforms.

For each green laser waveform, from both channels, we can determine the extinction depth and, depending on the classification, a seabed depth or opaque depth. The final depth to grid is then chosen based on a logic that compares the waveform type, presented in Table 1. This logic favours the GAPD channel when a bottom return is detected but will switch to PMT waveform derived depths when the associated GAPD waveform is classified as "deep". A correction is applied to the PMT depths to account for the poorer range resolution.

Table 1 The final depth to grid is chosen based on the classification of the waveforms of each channel. For example, when the GAPD waveform was classified as "deep" while the PMT waveform was classified as "weak", the opaque depth from the PMT channel is used.

			PMT channel		
			Detectable bottom return	Undetectable bottom return	
				weak	deep
GAPD channel	Detectable bottom return		GAPD seabed depth		
	Undetectable bottom return	weak	PMT seabed depth	shallowest opaque depth	GAPD opaque depth
		deep		PMT opaque depth	PMT extinction depth

Results and Discussion

Classifying Waveforms

The ubiquitous aquatic vegetation in the survey area lead to a considerable sounding data loss. Large volumes of the original waveform data could not be used by the lidar processing system for bottom detection. The great reduction of original waveform data becomes particularly apparent when all the waveform data, thus including those waveforms not used for bottom detection, are displayed spatially (Figure 5). Green areas in Figure 5 illustrate waveforms from which a depth was reported by the lidar processing system. Rejected waveforms are flagged as “weak” (red/magenta areas) or “deep” (orange areas). Reading in the rejected waveforms lead to 30 % more data in the area displayed in Figure 5 and 56% over the complete survey area.

Data loss at a deeper portion of a survey area would normally suggest the water clarity (or depth) to be the cause. However, by analysing the rejected waveforms, it becomes evident that water clarity is not the single cause for data loss. As can be seen from Figure 5, waveforms in the offshore direction are first flagged as “weak” and then as “deep”. This trend indicates that indeed in the deepest portion water clarity or depth limits the bottom detection, but a weak reflecting seabed also contributed. Figure 5 also demonstrates the FOV-effect. Since the PMT channel has an improved range performance, it may show a “weak” flagged waveform while a “deep” waveform was classified at the GAPD channel.

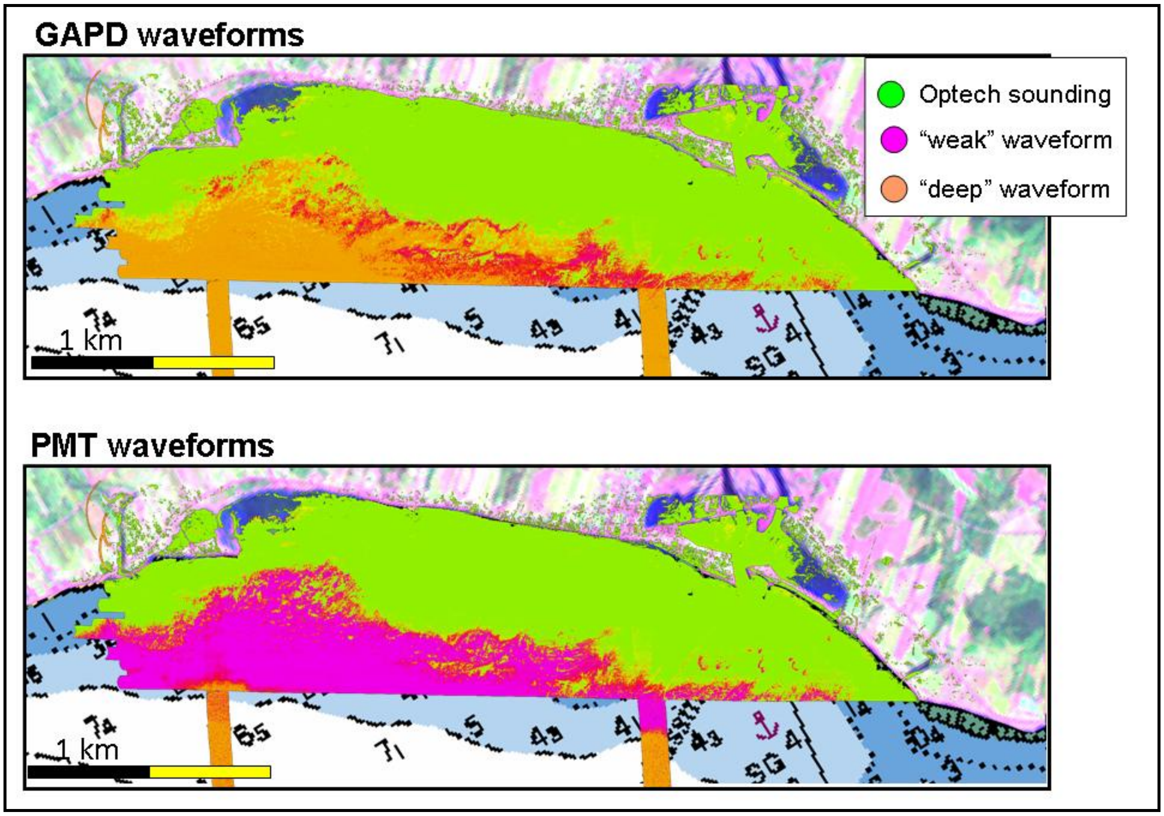


Figure 5 Classification of GAPD (top) and PMT (bottom) waveforms of the Bonaventure dataset. Magenta or orange coloured areas represent data that were originally rejected and therefore not associated with a lidar sounding.

Deriving Depths from Rejected Waveforms

The classification of the PMT waveforms in Figure 5 (bottom) illustrates a large portion of the waveforms being classified as “weak”. This implies that, although these waveforms were originally rejected by the SHOALS processing system, these waveforms remain valuable, as they yield an opaque depth. Once all the waveforms from each channel are classified, the depths are derived and gridded as described above. The new derived depths presented in Figure 6 illustrate two important differences compared to the original bathymetry (Figure 3): 1) reduced near shore coverage and 2) extended offshore coverage. Waveforms near shore are collected in extremely shallow waters (< 2 m). In these waveforms the surface and bottom return are merged or located very close to each other. The bottom detection algorithm used for this work does not take advantage of other research utilizing the Raman channel (Pe’eri and Philpot [2007], Yang et al. [2007]) and is thus unable to distinguish between the surface and bottom return at these waveforms. The extended offshore coverage is mainly contributed by re-examining the originally rejected but “weak” classified PMT waveforms. The smooth bathymetry seen in the extended cross lines illustrate the transition to coherent extinction depths, thus equivalent to the “No Bottom At”-depths (NBA) that used to be reported by the LADS systems.

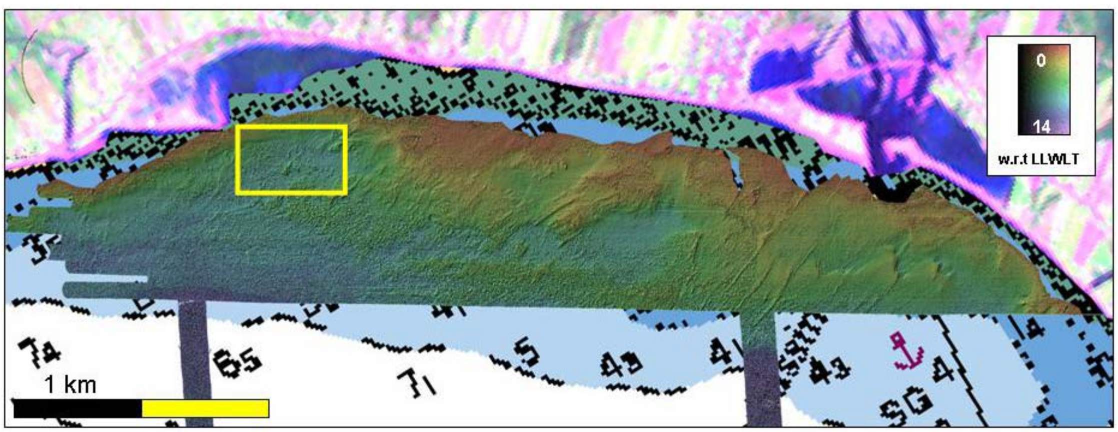


Figure 6 Bathymetry of waveform derived depths (including the rejected waveforms). The box refers to Figure 6. Note background chart depths in fathoms and feet and reduced to Lowest Normal Tide.

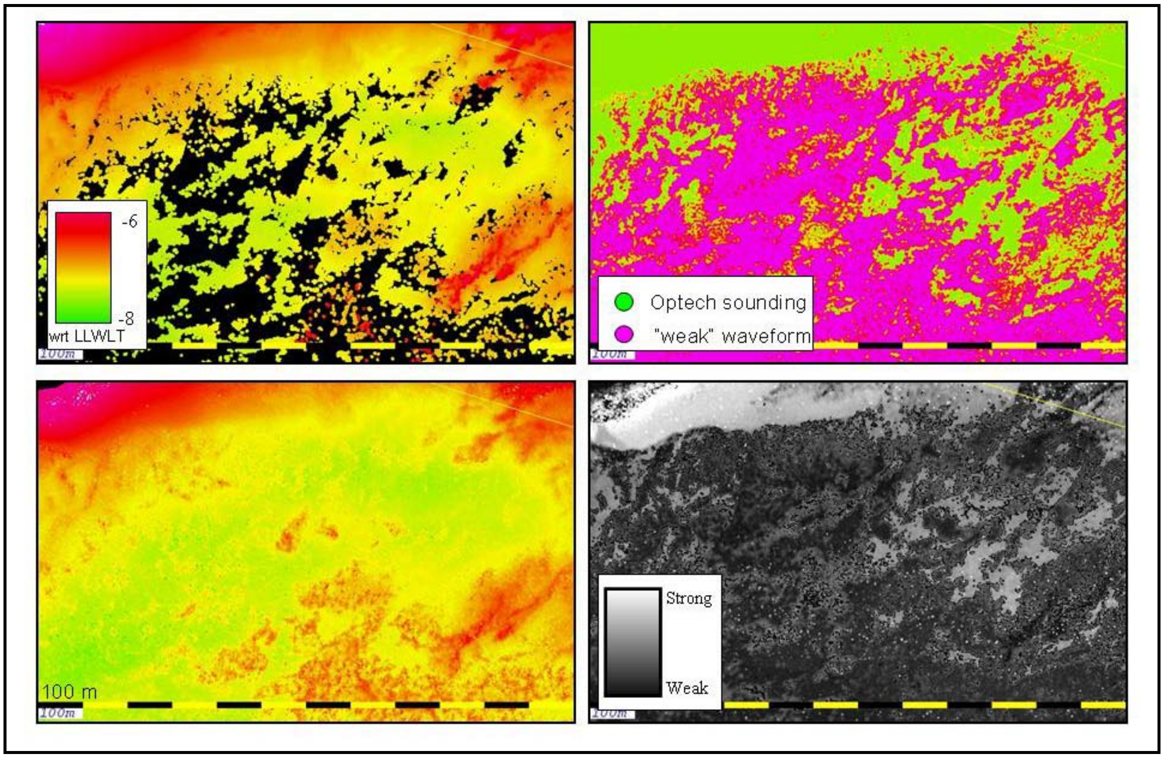


Figure 7 Original Optech bathymetry (top left), PMT waveform classification (top right), PMT optical backscatter (bottom right), and waveform derived depths (bottom left). Note a corridor of shallow soundings in the original bathymetry (top left, located south east) having weak optical backscatter although still accepted.

A closer look at the new derived depths illustrates that predominantly shallow measurements occur at the original datagaps (Figure 7, left), indicating that the green laser backscattered from the vegetation. Re-examination of the rejected waveforms at these situations yielded an opaque depth. Indeed, the opaque depth represents the measurement of the vegetation canopy, but the actual benefit is a least depth measurement. We are now confident that the seabed is not shallower than the opaque depth, which is a large improvement compared to no depth estimates at all. However, the true seabed with respect to the extinction depths remains uncertain; the seabed may lie beyond the extinction depth, as we are unsure about where the vegetation starts to grow. We also have to be aware that, although we can now retrieve a least depth, we do not know what the vegetation was masking. Bearing in mind that vegetation presence is often correlated with a hard substrate, caution is required.

It should also be noted that a turbid layer in the water column may cause a different attenuation, represented in the waveform as a change in decay of the volume return. These waveforms would also be classified as “weak”, but in these waveforms the kink would not represent a weak reflective object but the transition to a different water mass.

Uncertainty

The bathymetry in Figure 7 (bottom left) depicts not only the shallow depths derived from rejected waveforms but also shallow depths measurements from accepted waveforms. All these shallow measurements were the direct result of false bottom tracking; however, some were accepted and others rejected. Although the author does not know why the waveforms are rejected for bottom detection by the SHOALS processing system, it is clear the criteria are ultimately related to the waveform bottom return. It either has a significant optical backscatter, or lies within the system extinction depth. Failing one of these criteria would lead to classification of a “weak” or “deep” waveform. It thus appears the SHOALS processing system makes a binary decision whether the data are acceptable for the user. This conservative approach reflects the pressure placed on laser bathymetric developers to provide only data that meets the highest standards (e.g. IHO Order 1), a larger uncertainty is simply not acceptable. However, this uncompromising approach also leads to data being rejected while the cause for bottom detection failure remains unknown. Moreover, soundings from weaker reflective seabeds (e.g. vegetated covered) may by accepted, thereby resulting in a shallow biased terrain model.

Ideally, each sounding would by associated with an uncertainty value, by which the user has ultimate control of the soundings used for the end product and the complete dataset becomes more versatile towards other users with different quality criteria. A suggested variable to incorporate in a yet-to-be-designed uncertainty parameter is the optical backscatter derived from the waveform bottom return. Indeed, other environmental factors may contribute to the optical backscatter, but previous work has demonstrated that these influences are marginal; the seabed reflectance is the most dominant factor (Kuus [2008a]). Since the seabed optical backscatter is directly related to the detection of the bottom return, weak reflective seabeds would be associated with a larger uncertainty. Soundings on vegetation (e.g. Figure 7 bottom right) will be attributed with a larger uncertainty, thereby warning the hydrographer of the presence of for shallow biased soundings. When the waveform seabed return is not discernable, D_{opaque} can be calculated. Attributed by a large uncertainty, D_{opaque} may still have a value for certain users or products, but, more importantly, the originally rejected waveform yields a least depth.

Conclusions and Recommendations

A re-examination of rejected waveforms not only reveals the cause for a datagap but may also yield a least depth. These two solutions represent an improvement compared to the original datagaps. The re-examination is relatively simple and inexpensive in contrast to ground truthing measurements or repetitive surveys that would present similar information. Our original SHOALS bathymetry was stored in a file structure (LAS) that does not include the rejected soundings, which complicated reading in the associated waveform data. It is therefore recommended to include all soundings in the LAS-file, regardless of the bottom detection success. In order to allow the user to reject or accept a sounding, an uncertainty parameter is required. In this way, the end user rather than the processing system has ultimate control over the quality of the soundings.

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References

Feygels, V.I., Wright,W.C., Kopilevich, Y.I., Surkov,A., (2003). “Narrow Field of View Bathymetric Lidar: Theory and Field Test.” *SPIE Ocean Remote Sensing and Imaging II*, volume 5155, 11 pp.

Guenther, G.C., (1985). Airborne Laser Hydrography, *System Design and Performance Factors.* NOAA, Rockville, U.S.

Guenther, G.A., Cunningham, A.G., LaRocque, P.E., Reid, D.J., (2000). “Meeting the Accuracy Challenge in Airborne Lidar Bathymetry.” *Proceedings of EARSeL – SIG – Workshop LIDAR, Dresden/FRG*, June 16 – 17, 27 pp.

Guenther, G.C., (2007). “Digital Elevation Model Technologies and Applications: The DEM Users Manual”, 2nd Edition, Chapter 8 Airborne Lidar Bathymetry, pp 253-320.

Kuus, P., (2008a). *Bottom Tracking Issues and Recognition Thereof using SHOALS-3000 Green Laser in Dense Fields of Zostera Marina and Laminaria sp.* M.Sc.Eng. thesis, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, N.B., Canada, 230 pp.

Kuus, P., Hughes Clarke, J., Brucker, S., (2008b). “SHOALS-3000 Surveying Above Dense Fields of Aquatic Vegetation – Quantifying and Identifying Bottom Tracking Issues.” *Proceedings of the Canadian Hydrographic Conference and National Surveyors Conference*, Victoria BC, Canada, 5-8 May, 2008, 19 pp.

Pe’eri, S., Philpot, W., (2007). “Increasing the Existence of Very Shallow-Water LIDAR Measurements Using the Red-Channel Waveforms.” *IEEE Transactions on Geoscience and Remote Sensing*, volume 45, number 5, May 2007, 7 pp.

Yang, E., LaRocque, P., Gunether, G.C., Reid, D., Pan, W., Francis., K., (2007). “Shallow Water Depth Extraxtion – Progress and Challenges.” *Proceedings U.S. Hydrographic Conference*, Norfolk, Virginia, U.S., 14-17 May, 2007, 13 pp.

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