Article

Empirical Object Detection Performance of Lidar and Multibeam Sonar Systems in Long Island Sound

By LCDR Shepard M. Smith, NOAA, NOAA/NOS
Coast Survey Development Laboratory, USA

Abstract

A comparison of object detection capability of side scan sonar, multibeam sonar, and Lidar was conducted by NOAA in Long Island Sound. The seafloor is characterised by thousands of glacial erratics–boulders varying in size from cobbles to 10m on a side. The water turbidity varies from Secchi depth of 3.5m to 6m. A set of 93 features was selected from the side scan data and was compared with data from the multibeam sonar and the Lidar. The percentages of targets detected by the different systems were compared as a function of target size, target height, and water depth.

Résumé

La NOAA, à Long Island Sound, a effectué une comparaison entre les capacités de détection des objets à l'aide du sonar à balayage latéral, du sonar multifaisceaux et du Lidar. Le fond marin est caractérisé par des milliers de galets irréguliers dont la taille varie et peut atteindre 10 m d'un côté. La turbidité de l'eau diffère, selon la profondeur de non visibilité du disque de Secchi, de 3.5m à 6m. Un ensemble de 93 éléments a été sélectionné à partir des données du sonar à balayage latéral et a été comparé avec les données du sonar multifaisceaux et du Lidar. Les pourcentages de cibles détectées par les différents systèmes ont été comparés à l'aide des critères suivants : taille, hauteur et profondeur de la cible.

Resumen

NOAA efectuó una comparación de la capacidad de detección de objetos del sonar de barrido lateral, el sonar multihaz y el Lidar, en el Pasaje de Long Island. El fondo marino está caracterizado por millares de bloques de hielo erráticos, cuyo tamaño varía desde cantos rodados de 10m por lado. La turbidez del agua varía de 3.5 a 6m de la profundidad de Secchi. Se seleccionó una colección de 93 objetos de los datos de barrido lateral y se comparó con datos del sonar multihaz y el Lidar. Los porcentajes de los blancos detectados por los diferentes sistemas fueron comparados en función del tamaño y la altura del blanco y la profundidad del agua.

Introduction

In 2004-2005, a combination Lidar/multibeam survey was conducted in Long Island Sound.
The National Oceanic & Atmospheric Administration (NOAA) has contracted for numerous hydrographic Lidar surveys to support nautical charting in Alaska, but this is the first such survey on the US East Coast since 1996. Most East Coast surveys require object detection because of the comparatively larger areas of critical under-keel clearance and the greater prevalence of wrecks and other manmade seafloor features.

However, there have been few published studies which compared object detection performance of Lidar systems, and only a few published studies which compared object detection performance of multibeam sonar systems.

A theoretical object detection study was conducted by NOAA, using geometric parameters typical of the SHOALS and LADS systems in use at that time (Guenther et al 1996). The study was designed to estimate "to what extent small obstructions or 'targets' such as rocks or coral heads are capable of being discriminated and or detected in the presence of the frequently much stronger bottom return." In their study, there were two types of detections. In Type 1, a separate peak was seen in the waveform, and the feature was recognised as distinct from the seafloor. In Type 2, "for small targets (on the order of 1m high), the target and bottom returns may be merged into a single 'inflected' pulse without two distinct peaks." This target was considered 'detected' if an accurate least depth was determined (within 10cm), even if the target was not recognisable.

Some of major findings of the study were the following. Guenther et al (ibid.) identified four factors which affected the object detection capability of the Lidar system:
1) sounding (spot) spacing
2) water clarity
3) water depth
4) target size.

Guenther et al (ibid.) found that "Because target returns are frequently much weaker than the adjacent bottom return, they could easily go unrecognised unless the waveform processing software is specifically designed, first, to detect small objects on the bottom, and, second, to retain information on the detection." They also determined "Significant gains can be obtained in many cases by decreasing the average linear sounding (spot) spacing to 3m."

In 1995, NOAA conducted a comparison between SHOALS Lidar system and a sonar-based survey (Riley, 1995). The depth information compared well between the two systems, but the object detection capability of the Lidar did not detect any of the three objects selected for comparison. They were 2m-, 1.5m- and 1m-high coral covered rocks. The author concluded that "each one of the three rocks examined were too small in their areal extent to trigger automatic detection."

The primary purpose of the subject study was to assess the accuracy and object detection capabilities of the present day Lidar and multibeam sonar systems in coastal waters with varying water turbidity and a seafloor characterised by objects varying in size from cobbles to boulders 10m on a side. The study was conducted in Long Island Sound during 2005 onboard the NOAA Ship Thomas Jefferson using two different multibeam sonar systems and one Lidar system. Tightly navigated side scan sonar was used for reference. The second purpose of the study was establish whether NOAA's side scan requirement can be relaxed, and under what conditions. The results and conclusions of the comparisons between the

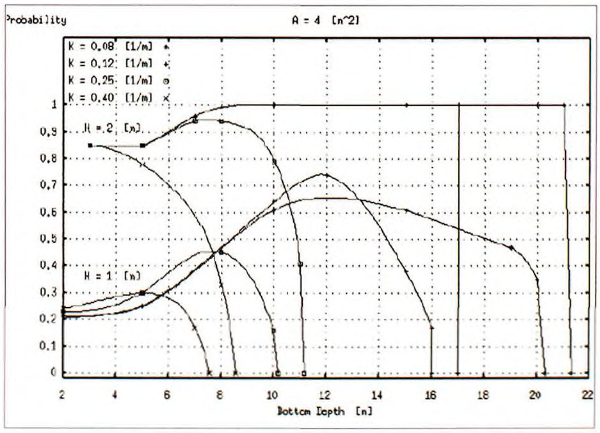

Figure 1: From Guenther et al (1996). Detection probabilities for 4-m^2 circular cylinders in various water clarities, for 1m and 2m target heights, using a 20-degree scanner nadir angle on a 4m X 4m sounding grid.

three systems are presented after a brief description of the systems and study area and methodology.

Note on Terminology

The study used two multibeam sonar systems (Reson SeaBat 8101 and SeaBat 8125) and one hydrographic Lidar system (Tenix LADS) as examples of the two classes of bathymeters. While there are other sonar and Lidar systems in use, this study investigates object detection performance between classes of depth measurement systems and not within each class. There are more differences between classes than within each class, since certain physical limitations and operational methods apply equally to all systems. For example, all Lidar systems describe their density of soundings in terms of spot spacing on the water surface, and the refraction and scattering of sound and light are independent of system. No studies which compare object detection performance of Lidar systems have been published, and only a few unpublished studies comparing object detection performance of multibeam systems are available. There are differences in signal processing and quality assurance which may have a significant effect on the results of each technology, but these effects are beyond the scope of this paper. Therefore, throughout this paper the generic descriptions (Lidar and multibeam) for these systems are used.

Description of Hydrographic Survey and Study Area

Tenix LADS, Inc. was contracted by NOAA's Office of Coast Survey to survey an area of Eastern Long Island Sound on the Connecticut coast. The survey was intended to update the nautical chart efficiently and safely. The larger area covered per unit time and the ability to survey shallow, potentially dangerous areas remotely are particularly attractive to NOAA. The normal practice established between NOAA and Tenix has been to complement the Lidar survey with a multibeam survey in deeper water and in areas where the Lidar data is ambiguous (Sinclair, 2005).

Long Island sound is an estuary, fed by multiple rivers, the most significant of which are on the Connecticut (northern) side. In addition, there is a strong tidal flow. The result is a variably turbid environment with Secchi disk measurements from 3.5m to 6m in the survey area. Tenix measured the turbidity throughout the year, and chose a period of best water clarity in January (ibid.). Based on this, expected depth limits were between 9-18m. In practice, the depth was limited to 10-14m in most of the survey area.

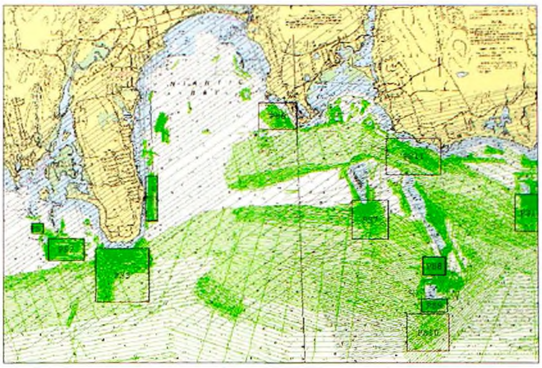

Figure 2: Study Area. Green lines are multibeam track lines, grey lines are Lidar track lines. 3 x 3m spot spacing is to the east. The small boxes were chosen for their high concentration of seabed objects.

The half of the area closest to deep draft traffic was surveyed with 3 x 3m laser spot spacing, and the other half was surveyed with 4 x 4m spot spacing. The expectation by Tenix LADS, Inc. and NOAA was that the 3 x 3m spot spacing area would provide improved object detection performance, though object detection was not a performance requirement in the contract.

In areas with expected small isolated objects or where man-made obstructions may exist, NOAA typically assigns a field unit to conduct side scan sonar surveys to ensure that all small objects are found. In these cases, the side scan system must be designed and operated to enable the reliable detection of a 1m cube. Special Publication No. 44 (S-44) Order 1 specifies that the survey be able to detect a 2m cube (International Hydrographic Organisation, 1998).

Based on the work of Guenther et al (1996), the expected object detection performance of a Lidar system in Eastern LIS would be between 22% and 90% of objects to be detected (Figure 1). This is based on a k=0.25 (1/m) and object heights between 1m and 2m. (This value of k is consistent with the observed extinction limit of around 10m which was the upper bound of water quality experienced during the Lidar survey.) One would expect higher objects and objects with larger horizontal area to be detected more frequently; and objects in 5-10m (vs. 0-5m) of water to be expected to be detected only slightly more frequently.

Comparison Methodology

Since NOAA considers side scan sonar to be the standard for object detection, side scan sonar data were collected over the entire survey area from 5 to 20m water depth in order to establish the existence of various objects of interest.

THOMAS JEFFERSON's launches are equipped with the capability to acquire side scan sonar data with a hull mounted transducer. This arrangement minimises position errors due to fish position and heading. Mosaics created from the side scan data were examined, and small areas were selected for further investigation. Because the entire study area was in less than 20m of water depth, fish height was within the NOAA standard of 8% to 20% of range scale to ensure shallow grazing angles.

These small geographic areas (referred to as 'postage stamps') were chosen in areas with a large number of objects of a wide variety of sizes and in a variety of depths, down to the 10m limit typical of the Lidar system. In addition, they were split evenly between areas covered by 3 x 3m spot spacing Lidar and areas covered by 4 x 4m spot spacing Lidar.

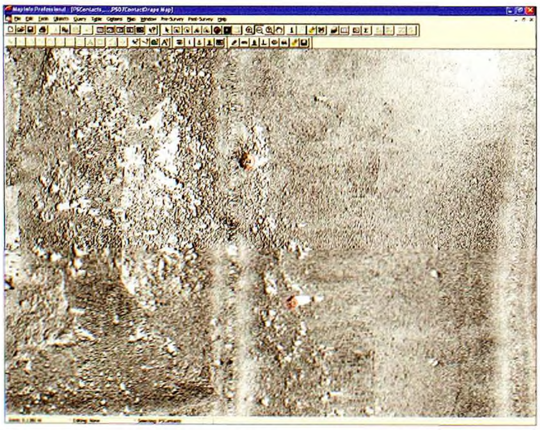

Figure 3: Side scan mosaic used to choose objects for comparison.

Within each area, a representative number of objects were chosen of various sizes. Objects were only selected if they could be easily distinguished from their neighbours. Each object's horizontal area was measured, with reasonable symmetry assumed to estimate the extent of the feature in the shadow area. Each of these features was put into a spreadsheet and the square root of the area was calculated. Because hydrographers typically describe the horizontal size of an object as a linear length, as opposed to an area, the square root of the area was used as the 'size' of each object for the remainder of the study, hereafter called the 'characteristic length.'

Using normal procedures and line spacing appropriate to the depth of water for each postage stamp, a full coverage multibeam survey was done using a RESON SeaBat 8101 system and a RESON SeaBat 8125 system. These data were gridded using CARIS HIPS and SIPS (Fredericton, NB) version 6.0, using the Combined Uncertainty Bathymetric Estimator (CUBE) algorithm (Calder, 2003). The grids were used for reference while making object-by-object comparisons (see Figure 4 example).

For each object, all soundings from each source (LADS, RESON SeaBat 8101 and RESON SeaBat 8125) were counted in subset mode. All soundings above the general grade of the seafloor in the area were selected for counting. The least depth on each feature from both multibeam sonars was noted as well. An object was considered to be detected by a multibeam system if it had 10 or more soundings on the object. This is a somewhat arbitrary number, and is higher than most Hydrographic Offices specify. However, this detection treshold is not important to this analysis because all the objects examined had many more multibeam soundings than required by this threshold. Because of the additional waveform information available in the Lidar data, one accepted sounding was considered to be sufficient to constitute detection.

All information was compiled into a spreadsheet. During analysis, some objects were discarded from further consideration for the following reasons:
- there was insufficient Lidar coverage in the area (generally deeper than 10m),
- the feature fell to seaward of the line reported by Tenix as the limit of quality data,

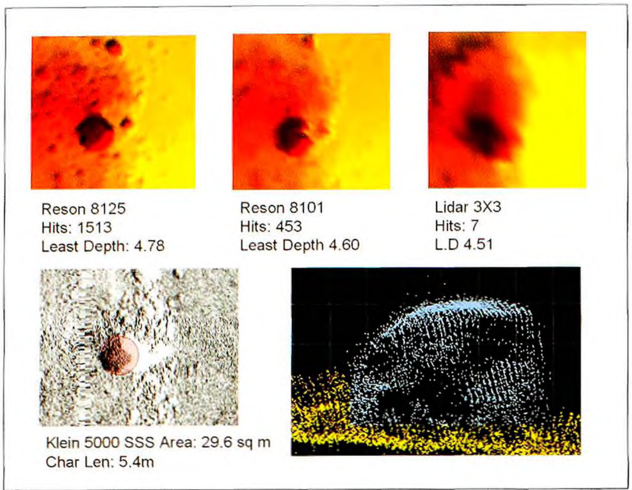

Figure 4: In this example, the Lidar accurately determined the least depth of the object. Soundings above seafloor grade from each system were counted for each object.

- the feature was not distinct from its neighbours as viewed in subset mode, and
- there was no multibeam coverage in the area (generally shoaler than 4m).

After all the analyses were complete, the spreadsheet included 93 objects, varying in size from 1m to 14m (characteristic length), with most objects between 2m and 5m (Figure 5).

Results

Overall, both multibeam systems detected all objects selected (Figure 6). All 8101 and 8125 least depths agreed within IHO Order 1 accuracy limits. Of the 93 objects selected, 28 were detected by the Lidar system. Of these 28, 12 had least depths within IHO Order 1 accuracy limits of the RESON 8125. Only 3 of the objects were flagged as ambiguous by the Lidar system operator, and two of these were well resolved.

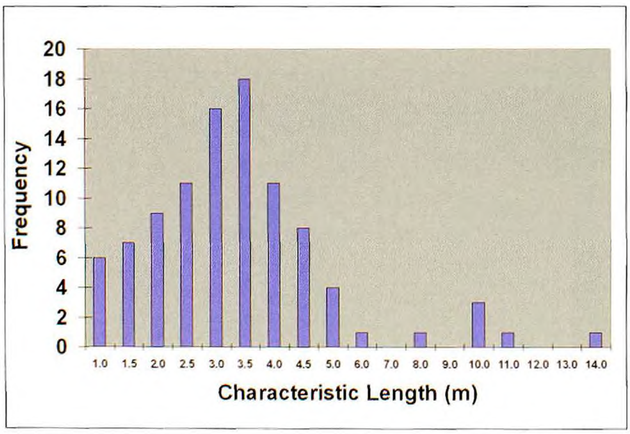

Figure 5: Histogram of feature size for the 93 features chosen for this study. The characteristic length of each feature is the square root of its area.

In example 1 (Figure 7), there were no valid soundings on the object, and it appeared that the soundings that should have been on the object were missing from the set of accepted soundings. The Lidar data density was normal in the vicinity of the object and the depths were well within the Lidar system operating depth range. This object was classified as not detected by Lidar system.

In example 2 (Figure 8), there were two Lidar system hits on the object, and it was classified as detected by Lidar system. However, the least depth was 0.8m deeper than the 8125 system least depth. It was classified as detected, but fails to meet the IHO Order 1 accuracy limit for least depth. The Lidar system least depth is circled in red. The ratios of sounding density between the multibeam and Lidar system on these features are typical of those examined in this study, around 2000:1 for the 8125 system, and 1000:1 for the 8101 system.

In example 3 (Figure 9), there were no accepted Lidar system soundings on the submerged crane. Though this was not in one of the postage stamp areas and was not included in the analysis, it was the only feature compared which was man-made. Because of the large extent of the scour around the crane, Lidar delineated the scour accurately.

Relationship of Object Size to Object Detection Performance

By sorting the objects by characteristic length, one can begin to identify the size of objects that can be reliably detected by each system. The percentage of objects detected is graphed against the characteristic length by sensor type and is depicted in Figure 10. Because of the low number of

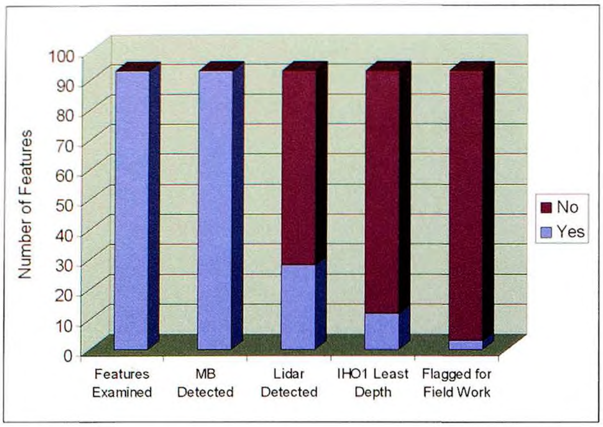

Figure 6: Summary of results.

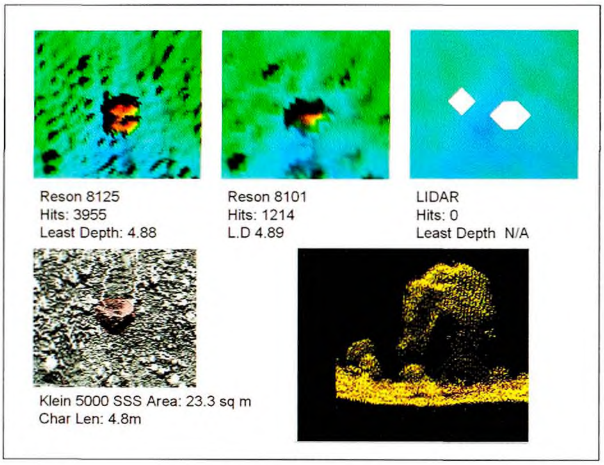

Figure 7: Example 1. In this 3m x 3m spot spacing area, the soundings on this feature appear to be missing from the final data set.

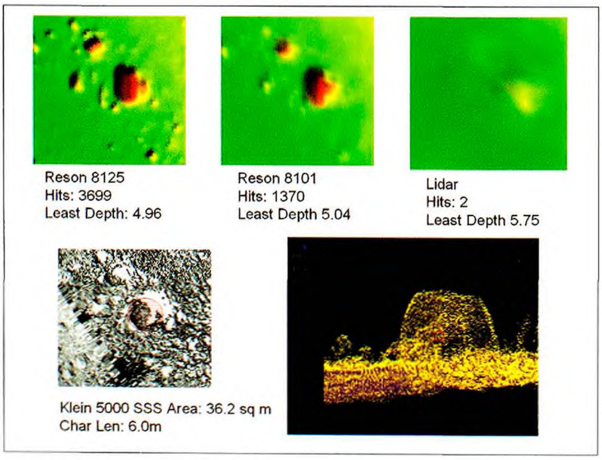

Figure 8: Example 2. This object was detected, but the least depth was not accurate to IHO order 1.

larger objects available, these objects were aggregated into wider groups. Both multibeam systems detected all the features selected. This is not surprising considering the relatively shallow water and large object sizes selected. The remainder of the paper focuses on Lidar target detection. Multibeam data are not included in subsequent graphs.

Note on Confidence Intervals

It should be noted that there is no widely accepted confidence interval for describing object detection performance in the context of hydrographic surveys. The Fourth Edition of S-44 (IHO, 1998) uses 95% (approx 2 sigma) for reporting depth sounding accuracy, but specifies no confidence interval for object detection. NOAA similarly does not specify an acceptable percentage of significant objects that can remain undetected in an object detection survey. It would seem that most Hydrographic Offices would set this confidence interval at a high value given the importance of these features. For the purposes of this study, the 95% confidence interval will be used for discussion.

Effect of Density of Spot Spacing on Object Detection for Lidar

Figure 11 shows object detection performance as a function of spot spacing. As expected, the 3m x 3m spot spacing outperformed the 4m x 4m spot spacing. It is interesting to note that the trend of object detection performance does not clearly increase with the size of the objects between 2m and 5m, though much larger (10m) objects are reliably detected.

Effect of Depth of Object on Object Detection for Lidar

Lidar system object detection by size and depth range is depicted in Figure 12. There is no clear difference in the object detection performance in these two depth ranges. This is consistent with Guenther et al. (1996).

Object detection by feature height is given in Figure 13. There is a peak of detection at around 1.5m high. Guenther et al (1996) predicted improved performance with increased

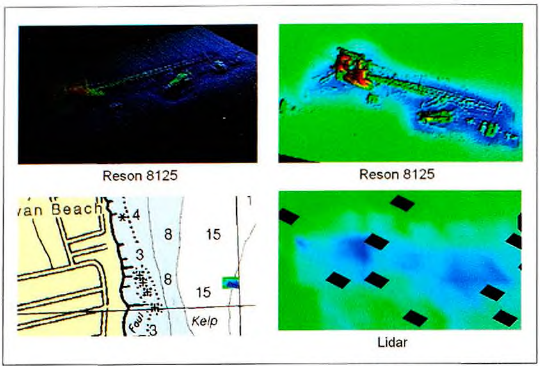

Figure 9: Man-made obstruction. This crane on the seafloor in 6m of water was not detected by the LiDAR.

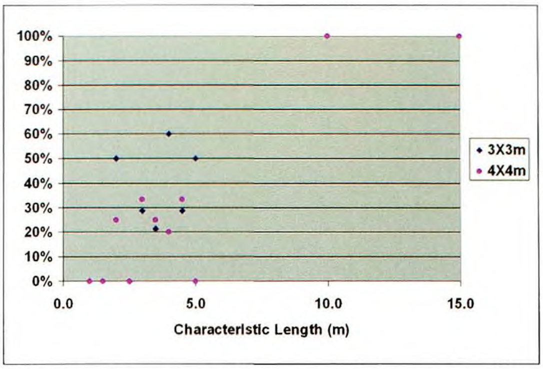

Figure 11: Percentage Lidar detection vs feature size and Spot Spacing. While no clear trend line could be established, the 3 x 3 spot spacing outperformed the 4 x 4 spot spacing.

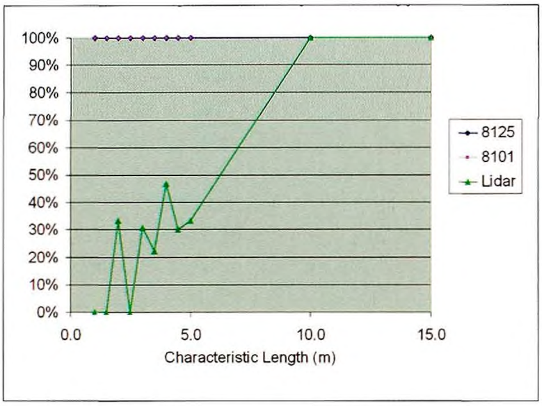

Figure 10: Overall percentage of objects detected.

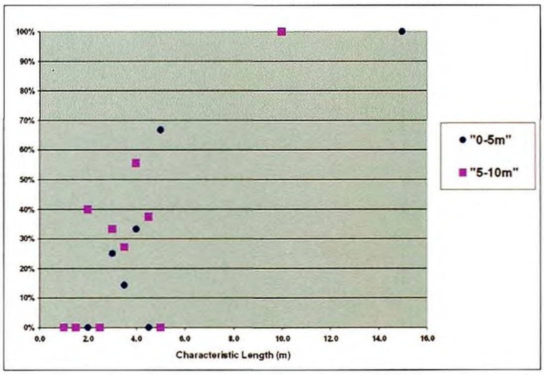

Figure 12: Lidar system object detection by size and depth.

object height, since there is more likely to be a distinct peak in the return signal that represents the feature. Some part of the explanation could come from the fact that some of the highest features happen to fall near the deepest (and therefore weakest) regions of the Lidar system coverage. However, this trend also raises the possibility that significant features were removed from the cleaned dataset, either by filter or by hand editing. It should also be noted that the author observed few, if any, false feature detections by the Lidar system.

Comparison of DTMs from Each System

For the following comparison, a Digital Terrain Model (DTM) was made using the soundings from each system. For the soundings from the multibeam sonar systems, the CUBE algorithm integrated into CARIS HIPS was used at the resolution specified (0.4m) by NOAA's draft gridded data specifications. For the Lidar data, the weighted grid function built into HIPS was used. The model was made at a higher resolution than the data supported in order to capture all possible detail. It was then interpolated to appear smooth. The area chosen for comparison is in 5-10m of water and was surveyed by 3 x 3m spot spacing Lidar.

Figure 14 shows two DTMs, one created from multibeam data and the other from Lidar system data for an area strewn with glacial erratics. It is clear that it is only possible to *recognise* a few of the features from the multibeam DTM in the Lidar DTM. However, the liberal definition of detection used by Guenther et al does not require recognition, only accurate least depth measurement, so the comparison implied by Figure 14 does not establish lack of detection.

To establish whether the least depth was meas-

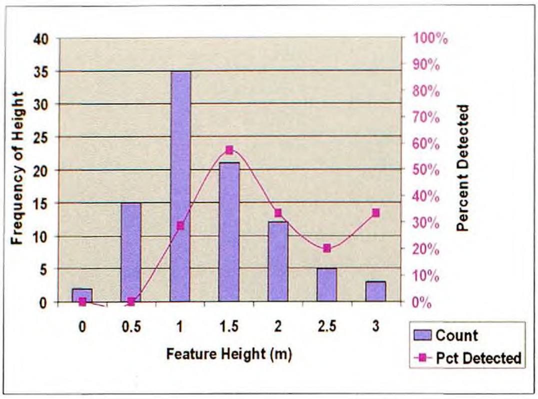

Figure 13: Object detection vs object height. Note the apparent peak of object detection performance at 1.5m.

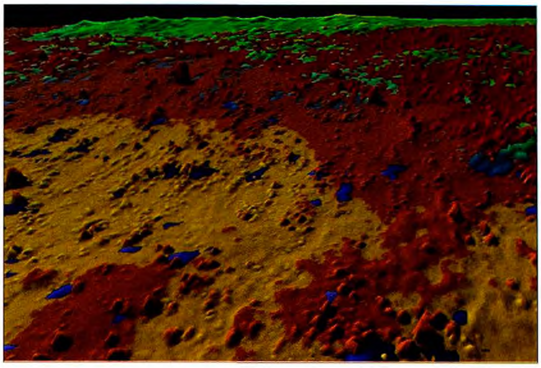

Figure 15: Co-registered dual DTM display. The warm colors are the multibeam DTM, and the cool colours are the Lidar DTM for an approximately 300m x 300m area in Eastern Long Island Sound.

ured accurately in the absence of recognition, both DTMs are displayed in the same 3-dimensional space using Fledermaus (IVS 3D, Fredericton, NB). Figure 15 shows the two DTMs co-registered. In featureless areas, the two models intersect, showing general depth measurement agreement. However, the objects measured by multibeam consistently protrude above the Lidar surface.

By vertically shifting one DTM with respect to the other, areas of significant divergence can be highlighted. Figure 16 shows the same two DTMs, with the Lidar DTM shifted up (shoaler) by 1m. Numerous features from the multibeam penetrate the Lidar surface, indicating disagreement of more than 1m.

Discussion

One can look at the process of measuring the seafloor from a signal processing point of view. A fundamental theorem of signal processing, the Nyquist theorem, states that in order to recover the signal of interest one needs to sample at twice the frequency of the signal of interest. For example, compact discs are sampled at 44.1 kHz to be able to reproduce sound for the human ear, which is limited to about 20 kHz. If we apply this same theory to bathymetric measurement for object detection, and define our distance of interest to be 2m, we need to sample the seafloor at least at 1m intervals. Any coarser sampling will not yield a reliable reconstruction of the seafloor at the resolution required.

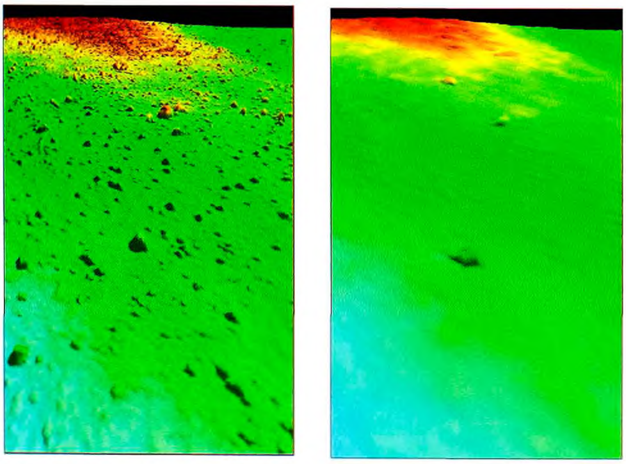

Figure 14 (a and b): Oblique view of best resolution DTMs for an approximately 500m x 500m area in Eastern Long Island Sound: a) multibeam (CUBE, 0.4m); b) Lidar (2m, interpolated).

Conclusions and Future Work

1) Lidar system-based surveys collected under the challenging conditions encountered in this survey are not sufficient for object detection as defined by IHO Order 1 (detection of a 2m cube). In addition, substantially larger objects are likely to go undetected.
2) Lidar object detection performance can be improved by using tighter spot spacing.
3) Further work needs to be done to predict the object detection performance of Lidar systems under a variety of conditions, including depth of water, spot spacing, type and relative reflectance of objects, turbidity, and sea state.

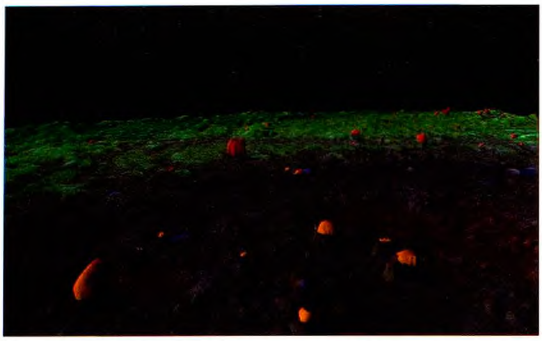

Figure 16: Dual DTM comparison with Lidar DTM shifted shoaler by 1m for the same area as depicted in Figure 15. Again, multibeam is shown in warm colours.

4) The International Hydrographic Organisation should consider specifying a confidence interval for object detection, both in S-44 (accuracy requirements) and in the product specifications for charting, such as the CATZOC A descriptions.

The results of this study were presented at the Shallow Survey 2005 conference in Plymouth, UK in September, 2005. After this conference, a study was undertaken by Tenix LADS, Inc. using the detailed data from this study. Tenix LADS, Inc. plans to use this ground truth information to both improve object detection performance, and predict the circumstances under which object detection is possible.

This is a challenging environment for survey systems with respect to object detection. Any parties wishing to use this area to test the object detection capability of their systems are encouraged to contact the author for the bounds of the 'postage stamp' areas, information on water-level stations, and high resolution DTMs for comparison.

References

Calder, B. (2003). Automatic Statistical Processing of Multibeam Echosounder Data, *International Hydrographic Review* 4.

Guenther, G.C., T.J. Eisler, J.L. Riley, and S.W. Perez (1996). Obstruction Detection and Data Decimation for Airborne Laser Hydrography. Proc. 1996 Canadian Hydro. Conference, June 3-5, 1996, Halifax, N.S., Tuesday 51-63.

International Hydrographic Organisation (1998). Special Publication No. 44, IHO Standards for Hydrographic Surveys. 4th edition.

Riley, J.L. (1995). Evaluating SHOALS bathymetry using NOAA hydrographic survey data. Proc. 24th Joint Mtg. of UJNR Sea-Bottom Surveys Panel, Nov. 13-17.

Sinclair, M. (2005). Hydrographic Lidar Survey – Experiences from Long Island Sound. US Hydrographic Conference.

Biography of the Author

LCDR Shepard Smith is a NOAA Corps Officer currently assigned to NOAA's hydrographic program, specializing in hydrographic processing technology. He is a 2003 graduate of the Cat A ocean mapping program at the University of New Hampshire and a 1993 graduate of Cornell University's mechanical engineering program. He recently served as Executive Officer of the NOAA Ship THOMAS JEFFERSON.

E-mail: shep.smith@noaa.gov