Letter to the Editor

Sir,

I would like to make some comments on the paper "Empirical object detection performance of lidar and multibeam sonar systems in Long Island Sound" [IHR 7, 2, (August 2006), 19-27] by LCDR (NOAA) Shepard M. Smith, because it makes use of text and a graphic from an earlier paper of mine (Guenther et al., 1996). To provide the necessary background, I need to first discuss the general subject of small-object detection capabilities in airborne lidar bathymetry surveys. This is presently a topic of great interest to the hydrographic survey community in the United States, and also one in which there seems to be some confusion. I would like to try to help clarify the situation.

First of all, there is no question that the newer high-resolution multi-beam sonars have superior object detection performance compared to lidar. That is not the point. Both sonar and lidar have their areas of optimum utility based on survey requirements, safety, cost, and speed of coverage considerations. The question is which survey system will meet the requirements of a desired survey or a fraction of a survey. Sonar and lidar are complementary for near-shore bathymetric and hydrographic surveys, and a wise surveyor will know how to make appropriate use of both (Graham et al., 1999). In this letter, I will discuss lidar.

For the case of lidar, the relationship between small-object detection capabilities and survey requirements is a complex question which has not been fully resolved to date, and a series of tests and studies are currently being planned jointly by NOAA's Office of Coast Survey, the U.S. Navy, and the U.S. Army Corps of Engineers to help quantify and clarify the issue and perhaps set some standards. A fact that needs to be clearly understood for survey planning and execution is that the depths to which small-objects can be detected are less than the corresponding depths to which the sea bottom can be accurately surveyed. The problem for the surveyor is to be able to determine how much less. Unfortunately, this depends on a large number of system, survey, and environmental parameters. This is an extremely complex problem that has not, as yet, been satisfactorily solved, but will be a focus of the above-mentioned studies.

It should be stated unambiguously that properly designed and operated lidar systems can detect objects as small as a 1-m cube, sitting on the sea floor, under ideal circumstances (Tulldahl et al., 2000) – but the probability of detection depends strongly on factors such as object height, object surface area and reflectivity, laser-spot spacing, water depth, water clarity, laser-beam nadir angle, solar background, etc. For hydrographic surveys, however, the required probability of detection must be extremely high (perhaps 95%). For current-generation lidar systems, these high probabilities can be obtained, to depth limits dictated by water clarity, for 2-m cubes (Heslin, 2007), but it is difficult to obtain such a very high probability of detection for objects much smaller than a 2-m cube, except for limited circumstances such as a very high-density survey in relatively shallow, clean water. For these reasons, it is possible for lidar hydrography systems to meet current IHO S-44 Order-1 specifications (with associated 2m cube requirements) under appropriate circumstances, *but, not for all circumstances and, again, importantly, not to the maximum survey depth of the system for standard bottom returns. The survey manager is responsible for making the correct choices of systems for each unique survey and for limiting surveys in the field to the requisite conditions. It should be noted that the IHO Order 1 and Special Order system detection requirements of 2m and 1m cubes, respectively, are minimum requirements. In certain situations, it may be deemed necessary by the charting authority to detect smaller features to minimize the risk of undetected hazards to surface navigation.*

To determine whether a given system is appropriate for a given survey, it is a matter of knowing how well that system will perform under expected environmental conditions compared to the stated survey requirements (Engstrom and Axelsson, 2001). Lidar hydrographic surveys, in which object detection is a requirement, are conducted differently from general lidar bathymetric surveys and are much more expensive due to greater costs for flying, processing, and verification. For example, sampling densities are typically higher, algorithms must be tuned for weak returns on the leading edges of the stronger bottom returns, and outliers cannot be discarded but must be verified by reflying. Consequently, lidar surveys are conducted in a manner to optimize small-object detection only when required. For typical bathymetric surveys, this may not be necessary. What we are discussing now is hydrographic surveys which have inherent small-object detection requirements.

Now, regarding the Smith IHR paper:

As pointed out in the first column of the Smith paper, our 1996 study included analysis of the two very different survey geometries - characteristic of the Optech SHOALS and CHARTS (Wozencraft and Lillycrop, 2006) and Tenix LADS MkII (Spurling and Perry, 1997) systems. [To avoid confusion, it should be noted that the current CHARTS system is technically a SHOALS-3000, and falls under the "SHOALS" umbrella. In this letter, I will use "LADS" as shorthand for the LADS MkII instrument, but comments related to scan pattern and nadir-angle effects are true for the original RAN LADS, as well.] One of the important conclusions of that earlier paper is that the beam nadir angle is a very important factor and that the predicted performance of a system such as LADS, in terms of small-object detection, may be somewhat compromised (at least for the studied case of a limited survey data density) due to its use of near-nadir laser-beam incidence angles for a fraction of the survey swath. Smith then goes on to indicate that in his paper he is going to lump the performance of all lidars together because "No studies which compare object detection performance of Lidar (sic) systems have been published..." This may be true for field data, but our paper, which he references heavily, does provide such modeled results.

Smith continues "There are more differences between classes (i.e., sonar and lidar) than within each class,..." and "Therefore, throughout this paper the generic descriptions (Lidar (sic) and multi-beam) for these systems are used." He thereby asserts that, for his purposes, the LADS results which he presents for small-object detection performance are representative of all lidar systems, including SHOALS. I respectfully disagree. The results of our paper say otherwise for the analysed cases of object heights less than two metres and 4-m spot spacing. Indeed, for many reasons, I do not believe it is appropriate to imply the performance of a SHOALS system based on results from a LADS survey. The systems actually share very little in terms of design philosophy, hardware, software, procedures, and operating scenarios.

On page 21 (second col.), Smith reports of the LADS survey, whose small-object detection data are used as the basis for the entire remainder of the paper, that "...object detection was not a performance requirement in the contract." On one hand, given the intent of this paper, this is a surprising statement. On the other hand, IHO accuracy requirements do require small-object detection, and, perhaps that should be enough. An increase in survey density alone, however, as indicated in his paper, is unlikely to be sufficient. Based on the disappointing results reported, it appears that object detection may not have been a strong enough focus for the survey in question, or that there may have been a misunderstanding of limitations and required procedures by the sponsor and/or the contractor. The performance of LADS may improve if new software or procedures are invoked. The point I wish to make, however, is that I must respectfully question the relevance of the remainder of this paper as it pertains to generic "lidar", under these circumstances. In my experience, lidar surveys must be optimized in many respects for small-object detection if small-object detection is a survey requirement (Guenther, 2007: p.270). SHOALS surveys have employed such specialized software and techniques since 1995. As noted above, if this is not done during *survey design and execution, it should not be surprising if the results are disappointing. Said results would not necessarily be characteristic of true system potential capabilities.*

The only mention of SHOALS in the Smith paper (p. 20, second col.) was, unfortunately, in a negative light. It would be easy for a reader to draw the unintended but false impression from this statement that SHOALS may not have good object-detection capabilities. The opposite is true – it is excellent. The included quote was based on one of the very early missions of the original SHOALS-200 system, before the ad hoc object-detection software and procedures had been developed. Indeed, they were developed in 1995 as a direct response to the results of that survey (for which object detection was not a specific requirement), and they have been in active use ever since. Figure 1 in Smith's paper, copied from our 1996 paper, is for SHOALS parameters, and it predicts a high detection probability for 2-m cubes in clear water.

In the 2003 acceptance tests of the SHOALS-1000T system (LaRocque et al., 2004), ten 2-m cubes were constructed and placed on the sea bottom in two lines (six in one and four in the other) at depths ranging from 5m to 28m. The data processors were not told where they were. A successful object detection was defined as at least two hits on a target for a given pass, because, for a real survey, a single hit could be an outlier and generates an expensive refly flag in the SHOALS production protocols. The lines were flown many times with spot spacings of 2x2m, 3x3m, and 4x4m. The water was quite clear; diffuse attenuation coefficients were typically around 0.08/m. The results were outstanding (Heslin, 2007). For 42 passes flown at 2x2m spacing, over one line or the other, the detection probabilities on all targets were 100% for every pass. For 20 passes flown at 3x3 spacing, over one line or the other, the detection probabilities on all targets were 100% for every pass. For 10 passes at 4x4 spacing, the probabilities dropped off in a manner qualitatively consistent with predictions of our 1996 paper, with lower probabilities at smaller and deeper depths and higher probabilities at middle depths. In summary, in a clean water situation, SHOALS-1000T had 100% detection probability, with at least two hits per target, for 314 target opportunities (without a single miss) on each of ten 2m cubes at depths between 5m and 28m on each of 62 passes, for spot spacings of 2x2 and 3x3 metres. I consider this performance to be both surprising and remarkable. For dirtier water, performance will, of course, be reduced at deeper depths, as it will for smaller objects. It is for these often more common cases that better survey-planning and evaluation guidelines need to be developed.

The question of the optimization of the reported LADS survey for object detection aside, when regarding the question of whether all lidars can be considered to all be the same regarding small-object detection probabilities, it must be noted that LADS utilises a push-broom-style laser scan that has a variable nadir angle and goes near nadir, while SHOALS generates an arc in which a constant 20-degree nadir angle is maintained. For LADS, a significant fraction of the pulses are closer to nadir than they are to the maximum scan angle at the edges of the swath. According to predictions in our 1996 paper for a 4x4m survey density, for objects smaller than 2m high off the sea bed, a near-nadir beam-incidence angle should lead to a reduction of small-object detection capability – i.e., down the center of the swath, much as side-scan sonar has a loss of signal in the same location. For example, for 4x4m density, our Figure 5 predicts performance at nadir compared to Figure 4a's performance at a 20-degree nadir angle. For the 1.0 m^2 object surface area common to those figures, the 20-degree case has moderate object-detection probability for 1.3-m high objects and small probability for 1.0m high objects, while the nadir case shows a smaller detection probabilities by a factor of two for a 1.3m high object and no detection of a 1.0m high object.

I certainly acknowledge, in the paper and now, that these results are predictions from a complex mathematical model, and quantitative performance for real systems will differ to some extent, but I am confident that the qualitative or relative differences are valid. For SHOALS, with its use of a constant nadir angle for scanning the survey swath, the probability of small-object detection is constant across the swath, and the primary object-detection region within the beam spot, for targets under 2m high, is on the side of the bottom spot closer to the aircraft (in the so-called "undercutting" region). For LADS, with its highly variable beam nadir angle, the primary object-detection region varies between the edge and the center of the beam spot as the beam nadir angle varies, and the probability of small-object detection, for a limited data density such as 4x4m, will be variable across their survey swath. For both systems, very high data density surveys (1x1m or 2x2m) will significantly improve object-detection performance over lower dens-

ities (in a complex manner, different for each system) and are highly desirable. Practically speaking, such higher densities will provide greater accuracy but will be more costly, and some may not be physically possible due to constraints of the lidar hardware or aircraft flight characteristics.

Smith includes a short "Discussion" paragraph at the end of the paper in which he states that spatial sampling (intended to imply laser-spot spacing) should be done according to the Nyquist criterion – i.e., that 1m spacing is required to resolve 2m objects. He asserts that "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." I do not agree that this is either the goal of the surveys we are conducting or appropriate mathematics for this technology. I believe the purpose of a hydrographic survey is not to micro-profile the shape of every rock and coral head but rather to detect such features and to determine their least depth. Furthermore, Nyquist criterion sampling implies the use of a probe whose resolution is smaller than features of interest. That is clearly not the case for lidar surveys, in terms of small objects. The laser beam is purposefully expanded so that the diameter of the footprint on the surface is on the order of two meters, both for eye-safety considerations and to ensure sufficient surface-detection probability. The lidar beam expands further in the water column, often significantly, due to scattering from entrained particulate materials. At depth, the laser footprint may be significantly larger than a 2m feature. That does not stop the feature from being detected by properly-designed pulse-detection software, as has been well proven, as noted above. Indeed, this very beam spreading actually increases the feature detection probability in shallow water, for the case of limited spot spacing. In the SHOALS acceptance tests noted above, 98 2m cube target opportunities with depths as great as 28m were detected at a 100% rate with 3x3m spot spacing. One-meter spot spacing is most definitely not required to meet IHO Order-1 survey requirements (with the associated 2m cubes) under these conditions. On the other hand, it may be noted that decreased spacing would be a benefit in dirtier waters (and would result in slightly greater accuracy in measured object elevations), and 2x2m spacing is strongly preferred operationally if small-object detection is a survey requirement.

In conclusion:
Small-object detection is a tricky and difficult situation for both sonar and lidar because the object return is typically merged with, and, perhaps, partially buried under the associated sea-bottom return. I cannot speak for sonar, but certainly for lidar, not only are hardware design and implementation important, but software, operator training, and field procedures are critical.

There is a butterfly effect here. Very small changes in signal processing algorithms and field procedures can result in large changes in small-object detection performance. These must be carefully designed, developed, tested, tuned, operated, and maintained for each system. For this reason, it is not appropriate to imply the performance of one lidar system from that of another, and it is not fair to judge system performance on results from an un optimized survey. Higher survey densities, within system capabilities and cost constraints, will provide superior results for both systems.

Based on my 31 years of experience in the field of airborne lidar bathymetry, I can say for certain that the results and conclusions of the Smith paper are not for "lidar", because there is no such single generic entity when it comes to small-object detection performance. His results and conclusions are not for SHOALS, and they may not be for future LADS surveys for which small-object detection is a stated requirement, particularly if the capabilities of the latter are improved as a result of Smith's report. Airborne lidar hydrography data can and do meet IHO Order-1 accuracy standards, including small-object detection, within limits of depth and water clarity. The task which lies ahead is for the survey community to better understand and define those limits. Stay tuned; we will be hearing more about this as progress is made.

As a small editorial comment, I would like to note that the word 'lidar' is not capitalised. It may be written in all capital letters as an acronym, but the preferred usage is "lidar", just like 'sonar' and 'radar'.

Thank you for reading.

Sincerely,

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