

MEETING HYDROGRAPHIC CHARTING SPECIFICATIONS WITH THE SHOALS-1000T AIRBORNE LIDAR BATHYMETER

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1.0 ABSTRACT

In August and September of 2004, Fugro Pelagos became the first survey contractor to combine vessel-based multibeam echosounder and airborne-based lidar bathymetry technologies on a single hydrographic charting task order for NOAA. This project also represented the first time that NOAA utilized the SHOALS-1000T Airborne Lidar Bathymeter on a survey for hydrographic charting purposes. Because of this, system performance had to be verified through a series of tests before mobilizing to Alaska. This paper will present the results of those tests and demonstrate that the SHOALS-1000T meets IHO Order 1 standards.

Fugro Pelagos and NOAA jointly developed a comprehensive system acceptance test, which was executed through a series of flights at NOAA's test area at Shilshole Bay in Puget Sound near Seattle, Washington in August 2004. NOAA had surveyed the "ground truth" in this area previously using a Reson SeaBat 8101 Multibeam Echosounder. Fugro Pelagos had also conducted similar acceptance tests at Shilshole with the LADS MkII system in 2001 and the SHOALS-400 system in 2002.

In the testing that occurred in 2004, Fugro Pelagos flew the SHOALS-1000T in bathymetric mode at four alternative sounding densities. Two hundred percent coverage was achieved at 2m x 2m, 3m x 3m, 4m x 4m and 5m x 3.8m sounding densities. With these data, average surface differences and associated standard deviations were computed for each of the four sounding densities. In addition, target detection could also be analyzed at each sounding density.

2.0 INTRODUCTION

In order to evaluate the performance of the SHOALS-1000T LIDAR system, bathymetric data were acquired over an established test area in Shilshole Bay, Seattle. The test area had previously been surveyed by NOAA early in 2001, using a Reson SeaBat 8101 multibeam echosounder (MBES). The site was selected for the number of different sized objects that could be used for target detection, allowing a general ground truth to be performed.

This paper summarizes the results of tests that were carried out to compare the SHOALS-1000T LIDAR data with the multibeam "ground truth" survey data. For additional information on the specific data acquisition and processing methods that were used on this project, as well as a more comprehensive presentation of the analysis and results, the reader is referred to the comparison report entitled, "SHOALS-1000T Hydrographic LIDAR Comparison," which was produced and delivered to NOAA under Contract DG133C-03-CQ-0011, Task Order T0017.

3.0 DATA ACQUISITION AND PROCESSING

The survey in Shilshole Bay was designed to cover the multibeam survey test area and the surrounding area. The area surveyed is indicated in Figure 1.

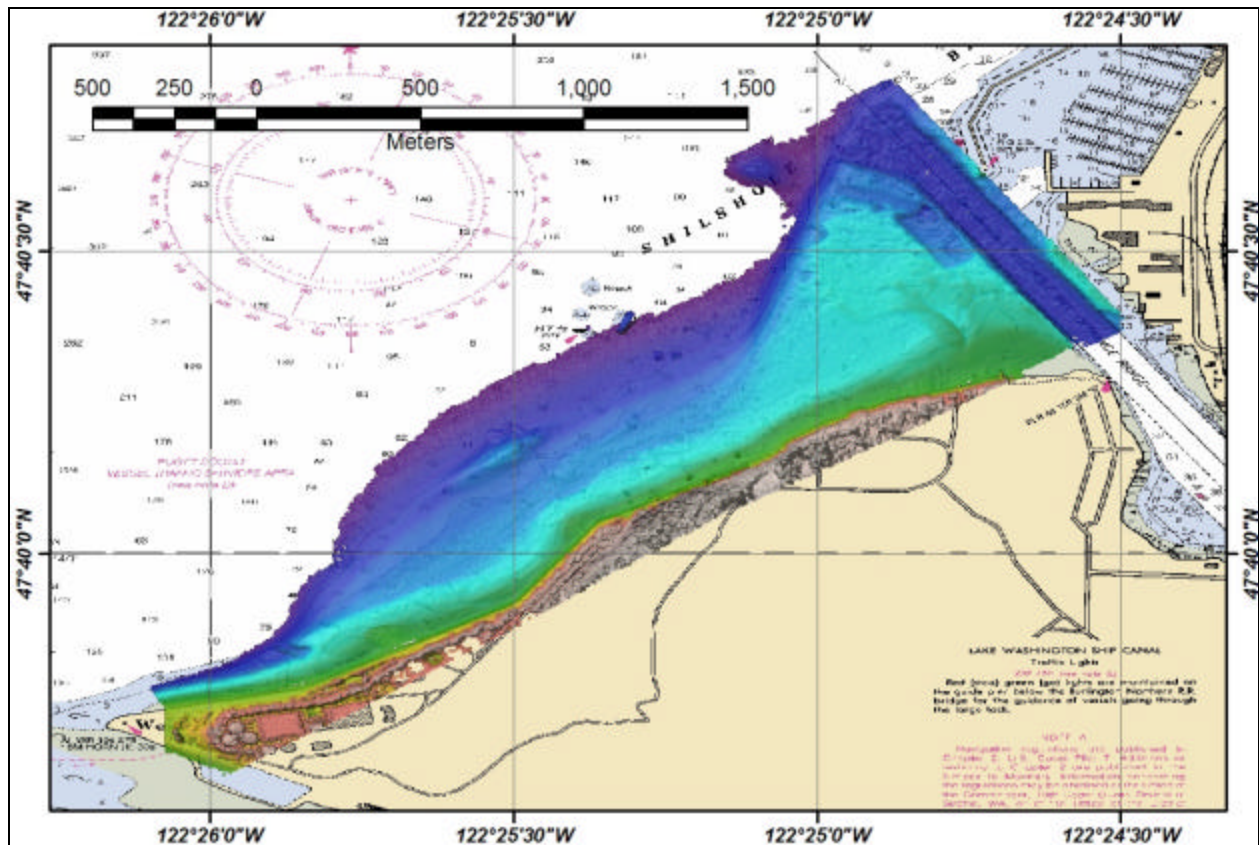


Figure 1. Survey Location

The survey took place from August 12 - 14 and August 28, 2004. Bathymetric data were collected at the laser spot spacings shown in Table 1. Each spot spacing was flown twice, yielding 200% coverage.

Table 1. Laser Configurations Flown

Laser Spot Spacing (m)	Altitude (m)	Speed (knots)	Swath	Planned % Overlap
2 x 2	300	124	60	20
3 x 3	300	128	125	20
4 x 4	300	162	165	20
5.0 x 3.8	300	180	174	20

Cross lines, flown perpendicular to the main scheme survey lines, were flown across the multibeam reference surface and also up the channel at 2m X 2m and 4m x 4m spot spacings.

The survey area was flown multiple times on multiple days in an effort to obtain good overlap with the multibeam reference surface. The multibeam reference area was flown and covered by the SHOALS-1000T in its entirety. Consistently, maximum depths reached by the SHOALS-1000T were around 18m during the survey period. This fact resulted in only partial effective coverage of the multibeam reference area. It is understood that this is not the optimum time of year to survey in the Shilshole Bay area, and deeper penetration would be expected earlier in the year.

Each dataset acquired was processed in the following two ways:

- Using the real-time DGPS navigation in WGS84 and applying observed preliminary tides from NOS Gauge No. 9447130, Seattle
- Using post-processed Kinematic GPS (KGPS) in NAD83, using Geoid03 to transform elevations to NAVD88 and then applying an offset of 0.715m to reduce the data to MLLW (*This is the offset between NAVD88 and MLLW published for NOS Tide Gauge 9447130.*)

In order that a post-processed KGPS solution could be used for positioning and refinement of the inertial solution, dual frequency GPS data were acquired on the ground at one second intervals for every flight. These data were uploaded to the National Geodetic Survey (NGS) Online Positioning User Service (OPUS) for static post-processing.

All data were processed using the Optech SHOALS-1000T Ground Control System (GCS) on Windows XP workstations. The GCS includes links to Applanix POSPac software for GPS and inertial processing, and IVS Fledermaus software for data visualization, 3D editing and quality control.

4.0 IHO TESTS AND RESULTS

Several tests were conducted to evaluate the SHOALS-1000T LIDAR data and establish whether they met IHO standards for hydrographic survey, as defined in Special Publication No. 44 (SP44). The following tests were conducted:

- SHOALS cross line compared to a DTM of all SHOALS-1000T survey lines
- SHOALS cross line compared to a DTM of the multibeam reference surface
- All SHOALS soundings compared to a DTM of the multibeam reference surface

Details on each test are presented in the following sections.

The CrossCheck Utility from IVS was used exclusively during these tests to produce statistics, based on the depth accuracy specification given in SP44:

$$\pm \sqrt{a^2 + (b * d)^2}$$

where d is water depth, and values for a and b vary according to the order of the survey. For Order 1 and 2 surveys in shallow water, values are given in Table 2.

Table 2. Coefficients for IHO Order 1 & 2

IHO Order	a	b
1	0.5	0.013
2	1.0	0.023

4.1 SHOALS CROSS LINE VERSUS DTM OF ALL SHOALS SURVEY LINES

For each dataset, a DTM was made using all survey lines. This was then compared to soundings from the cross lines using the CrossCheck utility. For example, for each 2m x 2m dataset, all 2m x 2m cross lines were used for comparison. In each case, however, cross lines, which ran perpendicular to the multibeam reference surface, were examined separately from those, which ran up the channel.

A summary of results is presented in Table 3 and Table 4 below.

Table 3. Summary of Results for Cross Lines Perpendicular to MBES Reference Surface

Positioning	Survey Spot Spacing (m)	DTM Grid Size (m)	Cross Line Spot Spacing (m)	QC Results			
				No. of Samples	Mean Diff (m)	St Dev of Diff	% Pass IHO Order 1
KGPS	2x2	2	2x2	15007	-0.006	0.128	100%
KGPS	3x3	3	2x2	12297	0.080	0.119	100%
KGPS	4x4	4	4x4	9487	0.017	0.125	99%
KGPS	5x5	5	4x4	8794	-0.011	0.126	99%
DGPS & Tides	2x2	2	2x2	13104	-0.031	0.112	100%
DGPS & Tides	3x3	3	2x2	10805	0.019	0.115	99%
DGPS & Tides	4x4	4	4x4	6541	-0.032	0.117	99%
DGPS & Tides	5x5	5	4x4	6360	-0.085	0.120	99%

Table 4. Summary of Results for Cross Lines Running Along the Channel

Positioning	Survey Spot Spacing (m)	DTM Grid Size (m)	Cross Line Spot Spacing (m)	QC Results			
				No. of Samples	Mean Diff (m)	St Dev of Diff	% Pass IHO Order 1
KGPS	2x2	2	2x2	30922	-0.099	0.193	97%
KGPS	3x3	3	2x2	27895	-0.083	0.227	95%
KGPS	4x4	4	4x4	20484	-0.043	0.449	83%
KGPS	5x5	5	4x4	17334	-0.057	0.547	78%
DGPS & Tides	2x2	2	2x2	31617	-0.014	0.179	98%
DGPS & Tides	3x3	3	2x2	29991	-0.077	0.232	95%
DGPS & Tides	4x4	4	4x4	23188	-0.030	0.373	86%
DGPS & Tides	5x5	5	4x4	18140	-0.044	0.499	79%

From Table 3, it can be seen that all data in both KGPS and DGPS mode meet IHO Order 1 above the required 95% confidence level, at all spot spacings. These comparisons are carried out over relatively flat ground, with only a few small targets. When the cross lines along the channel are examined, however, the pass rate is reduced as the DTM grid size is increased. The increased DTM size has the effect of smoothing the steep sides of the channel, causing an apparent error. However the errors only occur at the channel sides, as can be seen in Figure 2. This is also indicated by the comparatively low mean difference and high standard deviation.

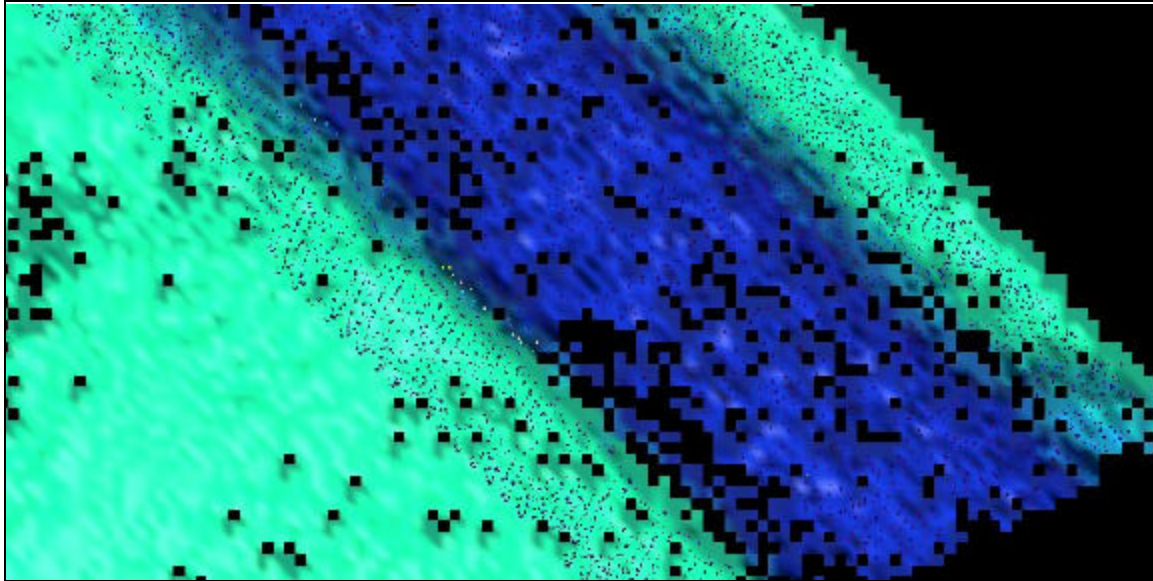


Figure 2. Error on Channel Edges (Large Change in Sounding Color indicates Larger Error)

4.2 SHOALS CROSS LINE VERSUS DTM OF MBES REFERENCE SURFACE

A DTM of the multibeam reference data was made in Fledermaus at 1m grid size, using a weighting diameter of 1. This surface was then compared to soundings from the cross lines using Fledermaus Cross Check utility. Analysis was carried out for data processed using KGPS, and data processed using DGPS and tides. No significant differences were apparent between the two processing methods.

When first compared, mean differences were high as shown in Table 5. This was caused by the comparison occurring over the wreck. LIDAR soundings with small acceptable errors in position provided large vertical errors. This is common for many datasets collected over steep slopes. The wreck was removed from the cross lines and analysis repeated. Once removed, data easily met IHO Order 1 standards at the 95% confidence level, with an average difference of less than 4cm from the multibeam surface.

Table 5. Summary of Cross Lines v Multibeam Reference Surface

	No. of Samples	Mean Difference (m)	St Dev of Difference	% Pass IHO Order 1
KGPS with Wreck	4125	0.663	2.063	88%
KGPS without Wreck	3624	0.036	0.193	98%
DGPS & Tides with Wreck	3712	0.658	2.228	89%
DGPS & Tides without Wreck	3302	0.004	0.339	98%

4.3 All SHOALS DATA VERSUS DTM OF MBES REFERENCE SURFACE

A DTM of the multibeam reference data made in Fledermaus at 1m grid size, using a weighting diameter of 1, was compared to soundings from the SHOALS-1000T survey lines using the Fledermaus Cross Check utility.

It should be noted that for the purposes of these tests, the multibeam reference surface from NOAA was deemed a perfect representation of the seabed. Some further error allowance could be made for this.

Again, analysis was carried out with and without the inclusion of soundings over the wreck. As seen previously, data over the wreck increases the mean difference observed and standard deviation of the dataset. With the wreck excluded from the analysis, data easily meets IHO Order 1 depth accuracy standards, with a mean difference of 7cm from the multibeam surface. The LIDAR data in this case is shallower than the multibeam data. No significant variations are seen between different spot spacings or KGPS versus DGPS processing methods. Mean differences have been presented in Table 6 below.

Table 6. All SHOALS Data v MBES Reference Surface

	No. of Samples	Mean Difference (m)	St Dev of Difference	# Fail IHO Order 1	% Pass IHO Order 1
KGPS with Wreck	24169	0.362	1.431	1714	93%
KGPS without Wreck	22635	0.078	0.202	471	98%
DGPS & Tides with Wreck	28000	0.352	1.486	1724	94%
DGPS & Tides without Wreck	26459	0.070	0.189	447	98%

5.0 TARGET DETECTION

The multibeam reference area (Figure 3) has a minimum water depth of 12.6 meters and a maximum of 30.1 meters. Seafloor slope is oriented NW with a general 3.1° gradient. Clearly depicted are three wrecks and some other significant bottom features.

Due to water clarity issues, only the targets at the shallower end of the MBES reference surface are seen with the LIDAR datasets. Targets seen include A, D, H, I, L, M, N. Targets were inspected using the KGPS processed dataset with 4m x 4m spot spacing and 2m x 2m spot spacing. It is unlikely that target detection results would vary considerably using the DGPS processed datasets, given the results in Section 3.

A summary of the results is presented in Table 7.

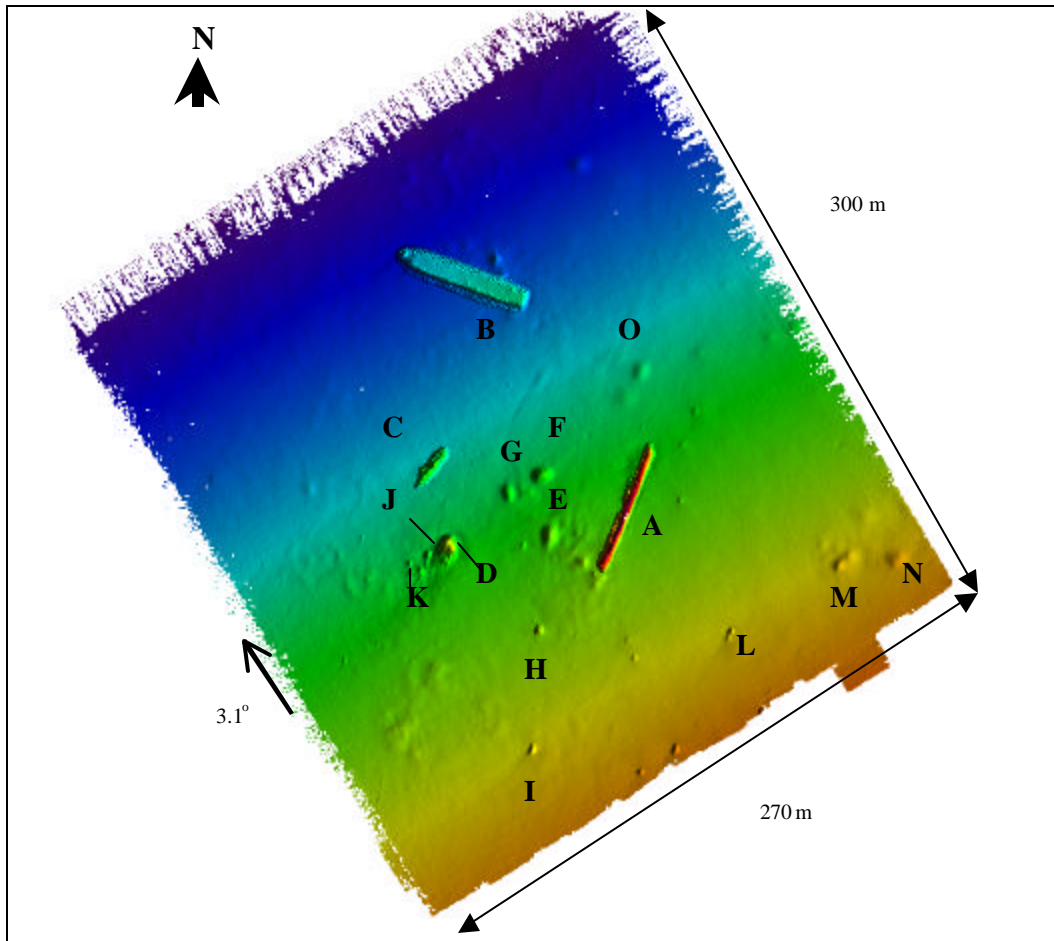


Figure 3. Multibeam Reference Surface DTM showing Targets

Table 7. Summary of LIDAR Target Detection

Targets	Multibeam				LIDAR - 4x4 ALL			LIDAR - 2x2 ALL		
	Size in meters (length x width, or diameter)	Depth (m)	Height Above Seafloor (m)	Surrounding Water Depth (m)	Depth (m)	Height Above Seafloor (m)	Surrounding Water Depth (m)	Depth (m)	Height Above Seafloor (m)	Surrounding Water Depth (m)
A	56 x 4	9.0	8.9	17.9	8.4	9.7	18.1	8.2	9.6	17.8
D	7.6	16.8	3.2	20.0	Too Deep for Dataset			15.8	Too Deep for Dataset	
H	4.2	16.8	0.8	17.6	17.2	0.6	17.8	16.9	0.9	17.7
I	2.2	14.7	1.0	15.7	14.6	1.0	15.6	14.8	0.7	15.5
L	2.8	15.0	0.3	15.3	15.1	0.5	15.5	14.6	0.5	15.1
M	10.2	14.6	0.7	15.3	14.4	0.8	15.2	14.4	0.8	15.2
N	6.6	14.0	0.7	14.7	13.7	0.7	14.5	13.7	0.8	14.5

The least depth for each target, whether for multibeam or LIDAR, was measured by looking at the individual soundings. In general, data review indicated that the LIDAR system was able to detect the targets but had difficulty with some of the least depths because of the footprint size. If the top of the object is flat, the system can get a more accurate least depth than if it comes to a sharp peak. Objects D,

M and N are more rounded than the other targets. Figure 4 shows object D. Blue soundings represent multibeam soundings, while the green soundings represent soundings from one 2m x 2m LIDAR dataset.

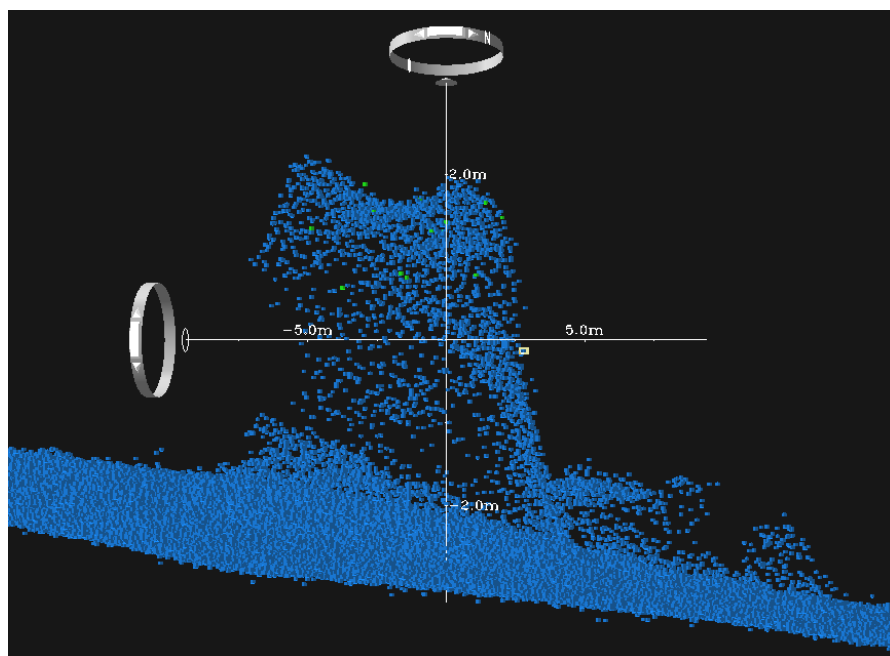


Figure 4. Object D (MBES = Blue, 2x2m LIDAR = Green)

While targets were found in the LIDAR data it should be noted that often these are detected by only one sounding. This is particularly the case when using a dataset flown at 4m x 4m.

Due to the small amount of overlap with the MBES reference surface, this data did not provide for extensive analysis of target detection probability.

6.0 CONCLUSIONS

The purpose of this survey was to verify that Fugro Pelagos, Inc., operating the SHOALS-1000T, could provide hydrographic quality bathymetry data that meets all of the IHO requirements within LIDAR technology capabilities. It was not intended or necessary to prove LIDAR technology in general, since this, has been proven in the past.

The depth sounding measurements achieve IHO depth accuracy specifications above a 95% confidence level over relatively smooth bottom. The LIDAR collection and processing system was capable of detecting all targets within the abilities of LIDAR data with 4m x 4m spot spacing. LIDAR technology does not have the same accuracy as multibeam when it comes to finding least depths on sharp targets. This is almost solely due to footprint size. Generally, the LIDAR system reports depths on such hard targets as deeper than reality. The results of the IHO tests show that Fugro Pelagos, Inc., operating the SHOALS-1000T, is able to reach all required IHO standards for hydrographic surveys within the abilities of LIDAR technology.