DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Expansion of Countermine Lidar UAV-based System (CLUBS)

Joong Yong Park
Optech Inc.
7225 Stennis Airport Drive, Suite 300
Kiln, Mississippi 39556
phone: (228) 252-1004 fax: (228) 252-1007 email: joongyong.park@optech.com

Award Number: N00014-10-C-0085
http://www.optech.com

LONG-TERM GOALS

The long-term goal of this work is to examine the utility of commercial bathymetric lidar technology solely, and in combination with commercial passive imaging spectrometers, for measuring environmental information for military applications in the littoral zone. These findings will indicate how commercial systems might evolve to achieve improved performance for rapid environmental assessment, and for deployment in unmanned aerial vehicles.

OBJECTIVES

1. A prediction of the measurement accuracy of existing bathymetric lidar systems under a wide range of environmental conditions.

2. A recommendation of design parameters leading to a smaller, light-weight airborne bathymetric lidar capable of producing data similar to that produced by the Compact Hydrographic and Rapid Total Survey (CHARTS) or the Coastal Zone Mapping and Imaging Lidar (CZMIL).

APPROACH

The in-air segment of the optical path length is determined by the delay between the lidar transmit time (T0) and the sea surface detection on the lidar waveform. Likewise, the in-water segment is determined as the time delay between the sea surface and seafloor detections. The overall ranging accuracy, for any specific lidar system, is then the sum of these segments, and is a function of the parameters shown in Table 1. These parameters affect the shape of the lidar waveform. The ranging accuracy algorithms used in the lidar processing software identify the specific time bins associated with the two cardinal points on the waveforms. Therefore, it is understandable that ranging accuracy could vary with changes in waveform shape.

We proposed to use the Optech Waveform Simulator to generate a very large number of waveforms (millions) for the CHARTS and CZMIL systems using a wide range of environmental properties and a known depth. The simulated waveforms are processed with the actual waveform processor code used to measure depths in the CHARTS and CZMIL systems. We then make a direct comparison of the computed optical path lengths to the simulated optical path lengths. We will analyze the results for systematic changes in accuracy as caused by specific changes in the environment. Based on these findings, we will consider if changes to data processing algorithms can be implemented to improve accuracy of results.

To produce a conceptual design for a miniaturized, fusion-based coastal and benthic mapping system, we proposed 3 possibilities for starting the study:

(1) Miniaturizing the CZMIL lidar design using a circular scanner and segmented detector, with receivers based on PMT detectors operated in the logarithmic mode;

(2) Conversion of an Optech ALTM ORION or other topographic lidar to a green laser, with addition of a high speed digitizer, to produce a cross-track high repetition rate lidar;

(3) Adopting a data fusion approach using a simple, low spatial density lidar with a high spatial resolution imaging spectrometer, and spectral processing software developed in the CZMIL program, to function as an active-passive bathymeter.

Performance of bathymetric lidar systems declines rapidly as laser power and aperture decrease. Therefore, we immediately understand the requirement for a careful analysis of the trade space. To support this analysis, we use the Optech Waveform Simulator to vary the system parameters in Table 1, in order to generate synthetic waveforms for each of the concepts under study. This analysis leads to an understanding of the radiometric performance of the system, but a geometric simulator must be used to understand the spatial density of the measurements.

WORK COMPLETED

We verified the ability of the Optech Waveform Simulator by determining similarity with actual waveforms using Correlation Coefficient test, Spectral Angle Mapper (SAM) test and Kolmogorov-Simirnov Test (KS-test).

We investigated the class of aircraft to be used in order to understand the form factor, weight, and power available.

Table 1. Parameters that can be manipulated in the Optech Waveform Simulator.

Environmental parameters	Units	Systematic Parameters	Units
Meteorological visibility	km	Lidar altitude	m
Sun zenith angle	deg	Laser incident angle	deg
Sun azimuth angle	deg	Laser beam divergence	mr
Light conditions (day, night)	-	Laser pulse energy	J
Wind speed above the water surface	m/s	Receiver pupil radius	m
Bottom depth	m	Initial beam radius	m
Effective Fresnel reflectivity	-	FOV plane angles	mr
Diffuse attenuation coefficient (K_d)	1/m	System response function	ns
Backscattering coefficient ($\beta(\pi)$)	1/(m*sr)	Optical system transmittance	-
Bottom reflectance	-		
Effective forward scattering	1/m		
Volume scattering function	-		

RESULTS

1. Range accuracy assessment of in-water optical path length measured by CZMIL and CHARTS systems

The Optech waveform simulator is developed to predict waveforms for any lidar under different environmental conditions and deployment modality. Before generating milions of simulated waveforms, the first step with the waveform simulator is the verification of the ability to generate waveforms highly similar to those measured by the system.

A literature survey identified three potential metrics that determine "similarity" of two time-varying functions: Correlation coefficient test, SAM test and Kolmogorov-Simirnov Test (KS-test). Correlation coefficient is defined in eq. 1.

$$\rho_{xy} = \frac{E(X-\mu_x)(Y-\mu_y)}{\sigma_x \sigma_y} \qquad \text{(eq.1)}$$

where X and Y are sample sets, σ is the standard deviation and μ is the mean and E(.) is the expected value operator. The coefficient values range from 0 to 1, where 1 signifies highest correlation. The coefficient has no units. SAM is a popular tool for comparing hyperspectral signatures. This technique considers the given two functions as vectors and computes the angle between them. The angle ranges from 0 to 90 degrees. Similar functions have smaller angles. KS-test calculate cumulative distribution functions (CDFs) of the two sample sets. The maximum distance between the CDFs is estimated and this yields D_{stat}. This is also illustrated in Figure 1. D_{stat} within a critical region defines the similarity of the functions. The coefficient has no units.

We identified five regions that were previously surveyed using the SHOALS system for the analysis with environmental conditions, namely; Ft. Lauderdale, FL, Looe Key, FL, Alpena, MI, and Buttermilk Bay, MA (Figure 2). We adopt a Radiative Transfer Equation model (RTE) with small angle approximation for modeling Waveform Simulator. The physical model adopted is a multiple forward, single backscattering model. The details of the Waveform Simulator can be found in [1].

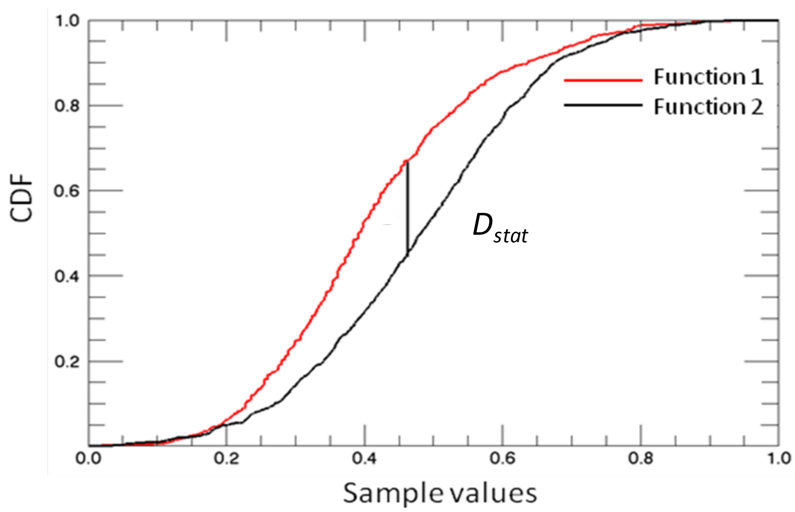

Figure 1. CDF plots of two functions and the estimated D_{stat}

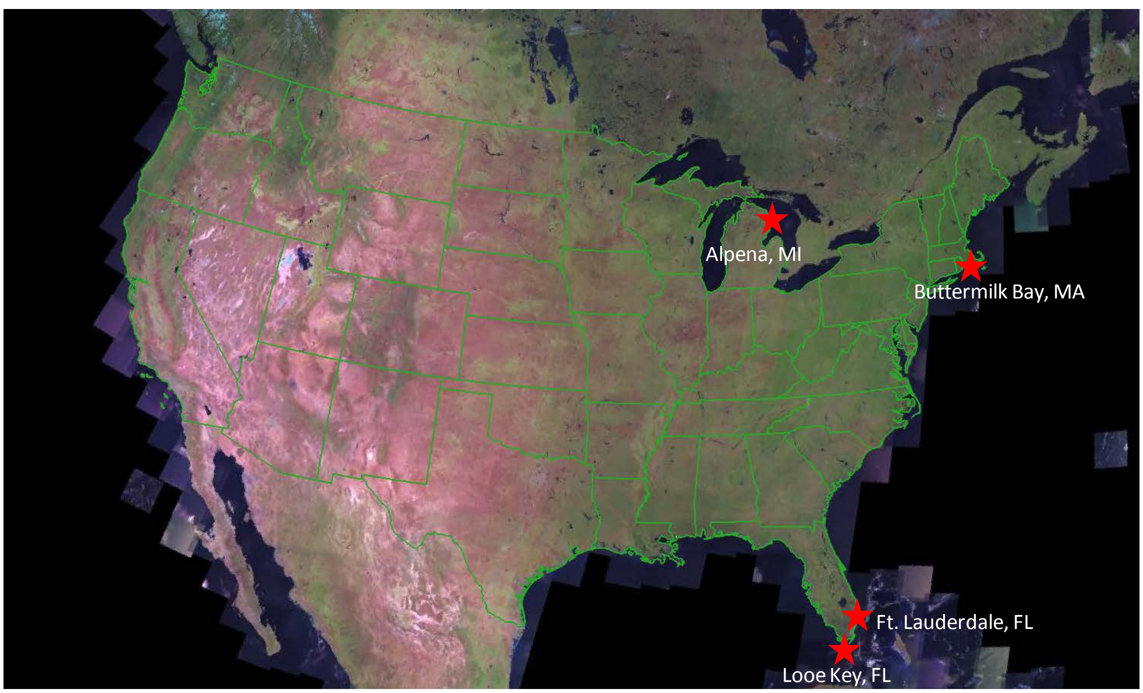

Figure 2. Regions of interests picked for the study to understand the environmental influence on ranging accuracy.

In this reporting period, we focus on validating the influence of water properties (specifically $a+b_b$) on the return waveforms. Therefore, we determined regions of interests where the actual SHOALS returns have reached or nearly reached extinction. In all further discussions in this report, bottom return is not present or is negligible in the real and simulated waveforms. Figures 3 and 4 show the comparison between the actual and simulated SHOALS waveforms for the different regions.

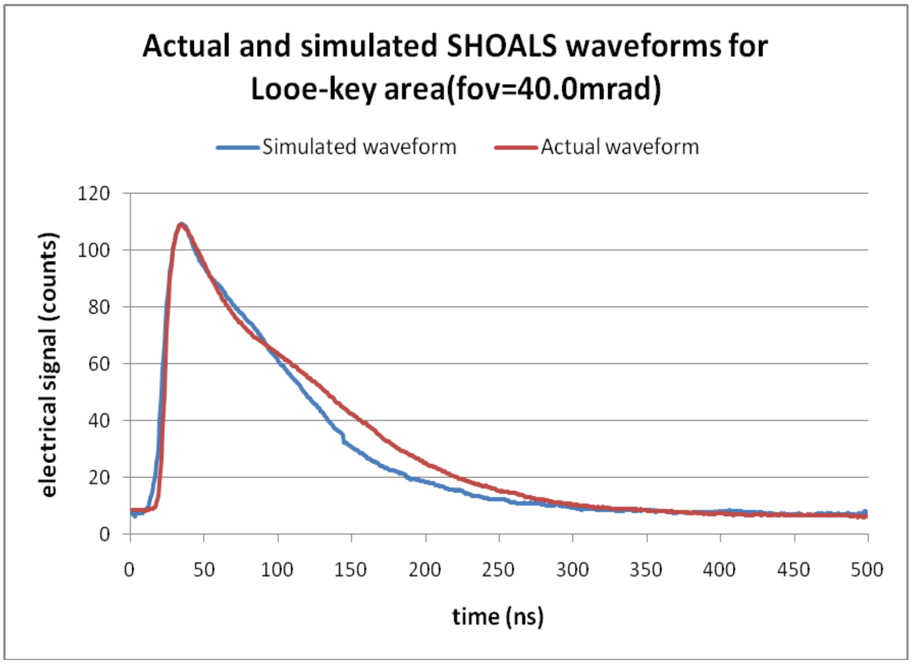

Figure 3. Comparison plot of simulated waveform and actual SHOALS for Looe Key, FL.

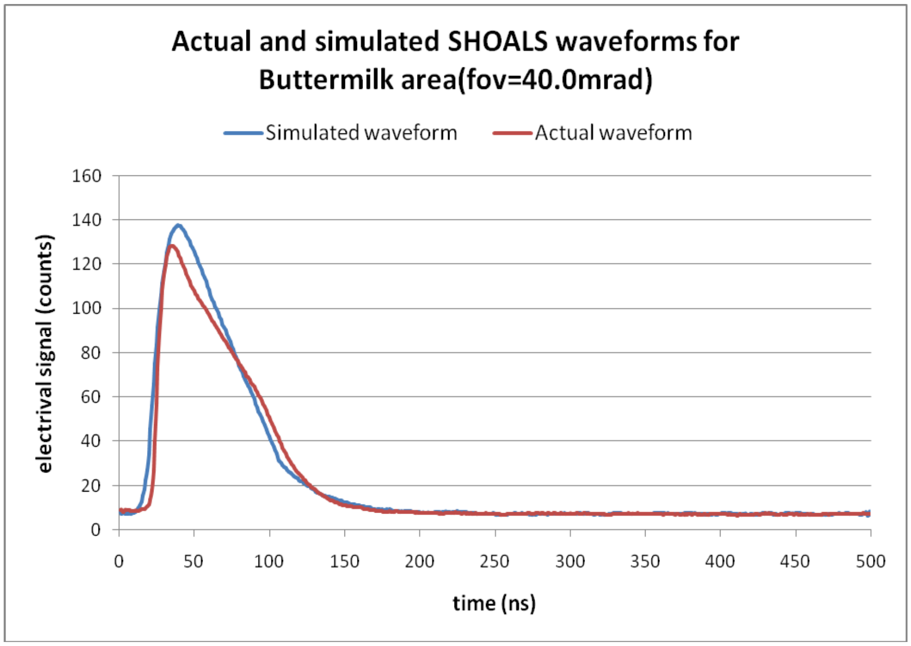

Figure 4. Comparison plot of simulated waveform and actual SHOALS for Buttermilk Bay, MA.

Table 2. Summary of similarity metric tests for the selected regions of interests

Region	**Looe Key, FL**	**Ft. Lauderdale, FL**	**Alpena, MI**	**Buttermilk Bay, MA**
Water properties				
Effective Fresnel reflectivity	0.002	0.0028	0.00144	0.0005
Diffuse attenuation constant	**0.064**	**0.068**	**0.079**	**0.17**
Backscattering coefficient	0.00073	0.00111	0.00055	0.00219
Bottom reflectance	0.05	0.05	0.015	0.05
Effective forward scattering coefficient	0.0854	0.009	0.009	0.1236
VSF parameter	6.9	7.1	7.3	7.9
Measured diffuse attenuation constant	**0.065**	**0.07**	**0.082**	**0.2**

The SHOALS datasets were processed using CZMIL DPS and environmental maps were generated. A small homogenous ROI was identified within each dataset (where depth, reflectance, $a+b_b$ were relatively constant). Environmental parameters estimated by CZMIL DPS were observed and real waveforms were extracted. Subsequently, the waveforms were averaged and a single waveform under the ROI was imported into the Waveform Simulator. The estimated environmental parameters from CZMIL DPS formed the initial inputs to the Waveform Simulator. These parameters were then iteratively adjusted using the Waveform Simulator until a visual close match was reached. We ensured that the manually adjusted parameters do not deviate from the estimated parameters. We then apply the similarity metric tests on 50 actual and simulation simulated SHOALS waveforms. We show the final parameters used in the simulations and resultant test metrics in Tables 2 and 3 respectively.

To quantify the results obtained we did the following. We applied the similarity metric tests for two cases:

1. Actual SHOALS waveforms extracted from the same neighborhood within a dataset;
2. Actual SHOALS waveforms extracted from two regions with different environmental characteristics.

Consequently, similarity test values thus obtained can be used as indicators to differentiate similar and dissimilar waveforms. These values are tabulated in Table 4. There are no hard and fast rules that define the similarity of two functions as it depends on the application. After applying similarity tests on several sample real SHOALS waveforms we conclude that two waveforms can be considered similar if the correlation coefficient, angle (SAM test), D_{stat} (KS-test) should be close to greater then 0.95, less than 10 degrees and less than 0.1 respectively.

Referring back to Table 3, the KS-test for simulated Buttermilk Bay region is on the borderline. However, the correlation coefficient and SAM angles are well within the required cut-off. We believe that the KS-test is very conservative test and therefore we relaxed the cut-off value for this test. Again the metric values in Table 3 indicate that all the simulated waveforms from the different regions are similar to real SHOALS waveforms.

Table 3. Summary of similarity metric tests for the selected regions of interests

Similarity test	**Correlation coefficient**	**SAM**	**KS-test**
Region			
Looe Key, FL	0.985725	7.307821	0.0856
Ft. Lauderdale, FL	0.994355	4.594308	0.10708
Alpena, MI	0.990218	5.950775	0.0704
Buttermilk Bay, MA	0.990884	6.421699	0.11132

Table 4. Similarity metric tests results on actual SHOALS waveforms

Similarity tests	Correlation coefficient	SAM	KS-test
Region			
Looe key region 1 waveform vs Looe key region 2 waveform	0.998217	2.262078	0.03316
Looe key region 1 waveform vs Buttermilk Bay region1 waveform	0.923897	20.4515	0.3984

2. Conceptual Design for a miniaturized, fusion-based coastal and benthic mapping system

The field of unmanned aerial vehicles (UAV) is expanding extremely rapidly. UAV's are now called UAS (Unmanned Aerial Systems) to incorporate the ground and communication equipment required for their operation. For the purpose of discussion UAS systems can be divided into 3 categories: Large, medium and small.

Large UAS typically have a wingspan of 8 meters or more, fly to the highest altitudes (up to 65,000 ft) and carry payloads for longer duration. The most well known in this category are the Predator series (current models are the Predator 1B and Predator 1C or Grey Hawk) and the Global Hawk (the Navy operates a version of the Global Hawk called the MQ-4C). Small UAS are designed for short range surveillance and targeting – these systems carry small payloads (less than 50 lbs) and fly for a short duration. A popular small UAS is the catapult -launched Scan Eagle and the Scan Eagle Dual Bay which both have a wingspan of approximately 3 meters and flying radius of 100 km. Scan Eagle UAS are equipped with day and night (thermal cameras) and can be outfitted with a NanoSAR system in a gyrostablized turret. The next generation Scan Eagle is called the Integrator which has a wingspan of 4.8 meters and can carry a payload of 37.5 lbs.

To decide the class of UAS to be used, we first determined the basic conceptual system requirements based on shown in table 5. In fact, producing a conceptual design for a new lidar requires an iterative process of considering the radiometric and geometric factors together, until a compromise is reached wherein most of the design objectives are achieved.

Table 5. Basic conceptual system requirements.

System power requirement	600W (with recording/processing system)
Laser power requirement (average)	3 Watts (green), 3 Watts (IR)
Laser repetition rate	3-10 kHz
Laser pulse length	1-3 ns
System weight	< 70 lbs
UAS survey speed	110-120 knots (56-62 meter/sec)
Volume	< 2 ft^3
KDmax	2.0 - 2.2
IHO 1a detection requirement	2 meter cube

To put a miniaturized lidar system on a UAV one must considering the following:

- Power and weight restrictions
- System stabilization
- Internal versus external mounting of the system
- Required power and repetition rate to meet IHO standards (1A or 1B)

For our altitude, speed and payload weight requirements we are looking at the medium size rotor-based VTOL (Vertical Take Off and Landing) UAS (see Table 6). VTOL systems do not require a runway for take off and landing and can operate from land or be ship-based. The Navy is currently using the Fire Scout (the platform for the optical COBRA system) but is currently developing a complementary system, the Fire-X system (Figure 5). Fire-X can carry more weight and fly faster and higher than the FireScout and is currently undergoing testing at the Yuma Proving Ground (YPG) in Arizona. The Fire-X turned a manned Bell 407 helicopter into a UAS by using the avionics developed for the Fire Scout. Because the airframe did not have to be developed from scratch the first test flight of the Fire-X took place less than a year after the program started.

The A160 system is attractive rotor-based system in that it has the highest altitude and endurance capabilities and several thousand hours of flight time but also has had a few crashes including 2 in 2010. A160 is unique in it has variable speed rotor RPM and its speed can be tailored to operating conditions. The A160 can be outfitted with an ultra high frequency foliage penetrating radar (the DARPA FORESTER system) tests of this system in Belize in 2010 resulted in a crash.

The K-Max is another rotor-based VTOL UAS in this category but it is primarily used for the movement of cargo to resupply troops.

Recently the Navy's Fire Scout program office has decided to recommend the NGC/Bell 407 Fire-X design over the Lockheed/Kaman K-MAX, or Boeing's A160 Hummingbird.

What all systems have in common is payload – they all have what is called "EO/IR" payloads, meaning a passive optical (daylight) video or frame camera(s) coupled with a thermal camera (3-5 microns is most common, sometimes a 8-12 micron camera is included). Most systems also incorporate laser rangefinder / laser pointer capabilities. Two COTS payload packages are common – the FLIR Brite Star II and the Raytheon MTSA and MTSB systems. Both packages are mounted in gyrostabilized externally mounted turrets.

We believe the FireScout and Fire-X are potential vehicles for CLUBS. We will continue define the physical constraints on the design for these vehicles. We will conduct market survey and discussions with laser manufacturers to determine availability of green lasers suitable for airborne deployment. We will discuss potential vehicles and define the physical constraints on the design.

Table 6. Medium sized, rotor-based VTOL UAS.

	FireScout	Fire-X	A160 Hummingbird (YMQ-18)	K-MAX
Length (m)	7.3	10.6	10.7	15.8
Rotor radius (m)	8.4	11.2	11	14.7
Payload (lbs)	600	2950	1000	6,000 (cargo hook)
Endurance (hrs)	5 - 8	16	18.7	12+
Altitude (ft)	20,000	20,000	20,000 – 30,000	15,000
Max speed (kts)	115	140	140	100
Operating radius (km)	200	na	4,000	1850
Manufacturer	Northrup Grumman	Northrup Grumman / Bell Helicopter	Boeing	Kaman Aerospace / Lockheed Martin

Figure 5. Fire-X UAS based on the Bell Helicopter 407 airframe and FireScout flight control system.

IMPACT/APPLICATIONS

This project has the potential to impact the operational Navy in two significant ways. First, the study is important to NAVO in their worldwide deployment of CHARTS, and second, it is of interest to agencies interested in deploying bathymetric lidar on smaller platforms. Both require expert knowledge as to how bathymetric lidar performance varies with electro-optical design, physical deployment, water column conditions, and seafloor characteristics, and how data processing algorithms function to produce the required bathymetric measurements.

RELATED PROJECTS

Coastal Zone Mapping and Imaging Lidar (CZMIL). CZMIL is a strategic partnership between Optech International and the Department of Marine Science at the University of Southern Mississippi. This effort is leading to the design and construction of a next generation bathymetric lidar to improve performance in shallow water and achieve water column and seafloor characterizations. The CZMIL project will also establish an industry/government/academic center of expertise for bathymetric lidar.

REFERENCES

[1] Ramnath, V., Feygels, V., Kopelicich, Y., Park, J.Y., Tuell, G., (2010), Predicted Bathymetric Lidar Performance of Coastal Zone Mapping and Imaging Lidar (CZMIL). Proceedings of SPIE on Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XVI, Vol. 7695