Forecasting the Ocean Optical Environment in Support of Navy Mine Warfare Operations

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ABSTRACT

A 3D ocean optical forecast system called TODS (Tactical Ocean Data System) has been developed to determine the performance of underwater LIDAR detection/identification systems. TODS fuses optical measurements from gliders, surface satellite optical properties, and 3D ocean forecast circulation models to extend the 2-dimensional surface satellite optics into a 3-dimensional optical volume including subsurface optical layers of beam attenuation coefficient (c) and diver visibility. Optical 3D nowcast and forecasts are combined with electro-optical identification (EOID) models to determine the underwater LIDAR imaging performance field used to identify subsurface mine threats in rapidly changing coastal regions. TODS was validated during a recent mine warfare exercise with Helicopter Mine Countermeasures Squadron (HM-14). Results include the uncertainties in the optical forecast and lidar performance and sensor tow height predictions that are based on visual detection and identification metrics using actual mine target images from the EOID system. TODS is a new capability of coupling the 3D optical environment and EOID system performance and is proving important for the MIW community as both a tactical decision aid and for use in operational planning, improving timeliness and efficiency in clearance operations.

Keywords: Ocean, Optics, Forecast, MCM, Mine Warfare, System Performance, Glider

1. INTRODUCTION

Current United States Navy Mine Counter Measure (MCM) operations often use EOID sensors to identify underwater targets after detection via acoustic sensors. These EOID sensors, which are based on laser underwater imaging by design, work best in "clear" waters and are limited in coastal waters especially with strong subsurface optical layers. Knowledge of the spatial distribution of optical properties, in particular scattering and absorption, is important for these systems to be successful. Information regarding surface optical properties is obtained from satellite, providing only marginal assessments to determine how well a system will perform due to the existence of optical layers. Knowing the spatial and temporal characteristics of the 3D optical variability of the coastal waters along with strength and location of subsurface optical layers maximizes chances of identifying underwater targets by exploiting optimum sensor deployment[1]. TODS is a 3D optical forecasting system developed to fuse the optical measurements from gliders, surface satellite optical properties, and 3D ocean forecast circulation models to extend the 2D nowcast/forecast surface satellite optics into a 3D optical volume of the beam attenuation coefficient (c) with subsurface optical layers, yielding a 3D optical forecast capability. Modifications were made to an EOID performance prediction and image simulation model, Electro-Optical Detection Simulator (EODES)[2] to integrate a nowcast/forecast 3-D optical volume covering an entire Region of Interest (ROI) as input and to derive a system performance field in support of the AQS-24 EOID system. These enhancements extend present capability based on glider optics and EOID sensor models to estimate the system's "image quality." Prior to producing regional system performance information, a single glider optical profile was used in a very large operational region. This location is not usually located where actual targets are detected yielding different optical properties than the single location / point measured by the glider. Characterization of the 3D optical environment of the entire ROI / operational area can be a force-multiplier for tactical decision making and operational planning during MCM detection, identification, and clearance operations.

Ocean optical properties are highly variable on small spatial and temporal scales in the coastal ocean, where most MCM operations take place. Remote sensing from satellite offers limited sampling of the optical environment close to these

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space and time scales. Limitations include (1) the satellite can see only the upper portion of the ocean's water column and cannot resolve the optical properties of the entire water column (it is important to know the strength and location of optical layers if present); (2) consistent cloud cover can be an issue for real-time operations: and (3) repeat coverage of an area of interest may happen only once a day. Nowcast surface optical properties alone are not adequate in support of these operations. Real-time measurements of the vertical optical properties of the water column from gliders or packages deployed by the helicopter are often used for operations in predicting how well an EOID sensor will perform. These measurements are limited spatially, and the data may not represent the surrounding environment. By knowing the limitations of both surface satellite observations and insitu measurements during MCM operations and being able to forecast the 2D surface optics from satellite, and extending the 2D satellite image forecasts into a 3D optical volume, we can better predict EOID sensor performance. This capability would allow tactical decision makers in the MCM community to estimate EOID sensor performance for a given day's environmental conditions and provide forecasts at hourly resolution over a 48-hour period.

The work presented here is the result of a collaborative effort between the Naval Research Laboratory (NRLSSC) and Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center in Mississippi and the Naval Surface Warfare Center, Naval Support Activity, and AMCM Weapons Systems Training School in Panama City, FL. The Vulcanex 11-1 exercise provided an excellent opportunity for an end-to-end testing and evaluation of the TODS system components (2D surface optical forecast – OpCast, 3D Optical Generator – 3DOG, and the MIW system performance surfaces for the AQS24 – EODES). We participated in and supported the HM-14 squadron during the Vulcanex 11-1 training exercise that took place off the coast of Panama City, FL, during April 2011 for mine clearance operations using the AQS-24 sonar with underwater laser imaging systems. We provided real-time assessments and forecasts of the surface and subsurface ocean optical conditions for EOID. We obtained image snippets from the EOID system along with Battle Space Profiler (BSP) or Airborne Environmental Profiler (AEP) data from the HM-14 squadron for validation of the 3D optical volume and system performance predictions. The data-flow and fusion effort presented here is a step forward in providing the warfighter an optical 2D/3D nowcast/forecast and EOID system performance prediction capability. We demonstrate a new capability that provides critical 3D optical information not only for EOID system performance but also subsurface visibility for diving operations. Errors in the 3D optical volume, optical forecasts, lidar performance, and predicted sensor tow heights will be assessed. The TODS system is currently being tested and evaluated for transition into operations at NAVOCEANO.

2. METHODS

Performance estimates in support of mine clearance operations in support of the HM-14 squadron during the mine warfare training exercise Vulcanex 11-1 were generated by fusing nowcast/forecast satellite surface optical properties, modeled 3D physical parameters of temperature, salinity, and currents, and glider optical measurements of the entire water column. The fusion of these data sets was used to generate the 3D optical environment for input into the EODES software to produce EOID system performance estimates in support of the AQS-24 target imaging system (Figure 3).

2.1 Surface Satellite Optical Properties

Imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua) ocean color satellite at 250m resolution[3] was processed daily at NRLSSC using the Automated Processing System (APS)[4] to generate optical properties. The Vulcanex 11-1 operational area (Figure 2) was predominantly clear at surface. Multiple fronts passed through the region during the exercise causing the circulation and optics patterns to change very quickly while increasing the optical properties (more turbid/less visibility). Beam attenuation (c) at 531nm and horizontal and vertical diver visibility were the APS-derived products used for the 2D/3D optical forecasting to support this exercise. The beam-c product/3D volume was the only input for the EOID performance model. The optical algorithm of choice was the quasi-analytical algorithm (QAA)[5]. Standard algorithms relating the remote sensing reflectance to backscattering and absorption were used to derive the beam-c and diver visibility products. (Figure 1)

2.2 Ocean Circulation Model

Ocean currents, temperature, and salinity were modeled and forecasted using a high resolution regional/relocatable version of the Navy Coastal Ocean Model (RELO-NCOM) and obtained from NAVOCEANO in real-time. The high resolution RELO-NCOM is nested within the Global NCOM and offers 3D forecasts of ocean temperature, salinity, and currents[6]. NCOM is atmospherically forced by the Navy Coupled Ocean and Atmospheric Mesoscale Prediction System

(COAMPS). The NCOM model has 40 sigma depth layers. Physical data from satellite and insitu measurements are assimilated through the NRL Coupled Ocean Data Assimilation System (NCODA) with an automated quality assessment[7]. The resolution of the model is approximately 1.7nm (3km). The modeled forecasts provided by NAVOCEANO were at 3-hour time steps out to 96 hours. (Figure 1)

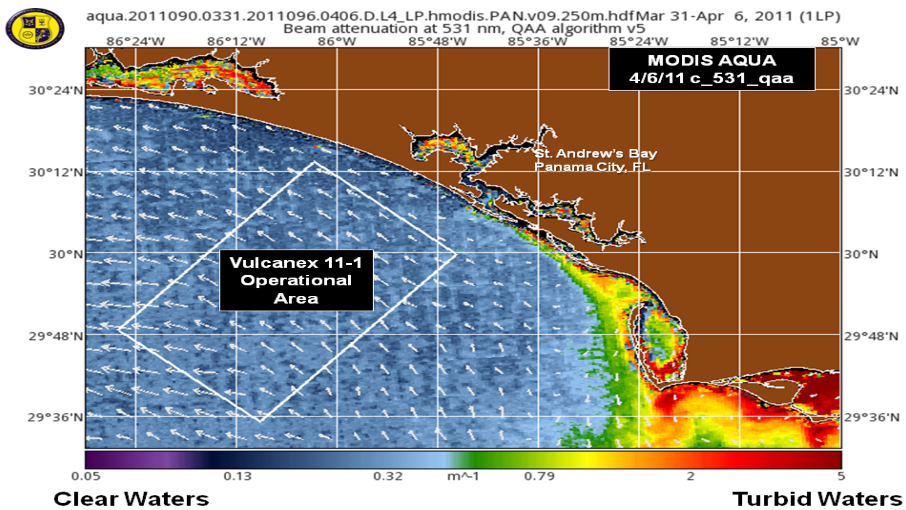


Figure 1. MODIS Aqua surface beam attenuation (c) image at 531nm at 250m resolution for the Vulcanex 11-1 operational area collected on April 6, 2011. Surface waters represented in blue colors are clear and yellows and reds more turbid/coastal. White vectors represent surface flow direction and magnitude from the RELO-NCOM model.

2.3 Unmanned Underwater Vehicle (UUV)

In collaboration with NSWC and U.S. Coast Guard in Panama City, a NAVOCEANO Slocum glider equipped with NRLSSC optical and physical sensors was deployed and provided real-time ocean environmental data (Figure 3). The glider collected optical and physical data from March 21, 2011 through April 12, 2011. These data were combined with real-time satellite-derived optical properties and circulation models to provide the next day's optical and system performance predictions, optimal towing altitude for the laser and subsurface horizontal visibility, both derived from the measured beam attenuation coefficient (c). The glider operated 23 days covering over 384 kilometers while collecting 5,868 profiles. All exercise support including satellite processing, model runs, and glider control was done remotely from NRLSSC. The NRLSSC sensors included a Sea-Bird Electronics 41 CTD, WetLabs BAM measuring beam-c @ 532nm, WetLabs scattering meter measuring backscattering at 470, 532, and 660nm, WetLabs ECO chlorophyll fluorometer, WetLabs ECO Colored Dissolved Organic Matter (CDOM) fluorometer, and WetLabs ECO Phycoerythrin Fluorometer.

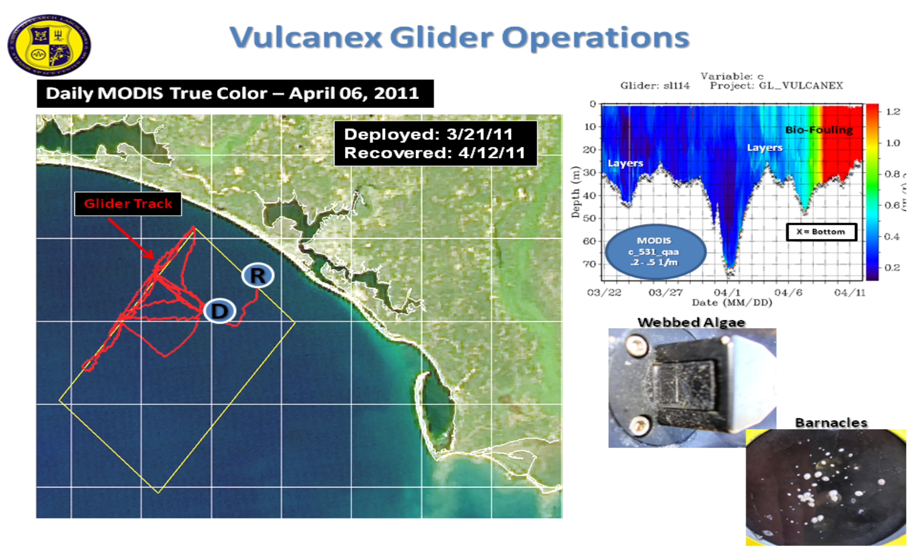


Figure 2. MODIS Aqua true color image with operational area and glider track overlaid (red). Plot represents a cross-section of beam attenuation (c) at 531nm for the entire deployment (March 21 – April 12, 2011). Note in the cross-section plot in upper right corner that near the end of the exercise, bio-fouling of the optical sensors occurred. Sensor pictures of BAM (beam-c meter) represent causes of bio-fouling due to webbed algae and barnacles.

2.4 Generation of 2D Satellite Surface Forecasts

Surface optical forecasts support was done using a 2D Eulerian advection model called OpCast[8]. OpCast is designed to forecast coastal ocean properties by fusing the RELO-NCOM modeled forecasts and a nowcast "seed" satellite optical image (Figure 4). The daily MODIS Aqua "seed" image of beam-c @531nm at 250m resolution was created using a 7-day latest pixel composite satellite image for the day. The 7-day latest pixel composite beam-c image was generated by using the most recent satellite pixel for the last seven days to fill in for invalid data due to clouds, atmospheric correction and algorithm failures, and glint. Next an attempt to fill in pixels that have remained invalid for the entire 7-day period using a triangular interpolation is made[9]. Pixels that are still invalid are then filled in with yesterday's forecast. Once the daily beam-c "seed" image and the forecast ocean circulation model currents were available, they were ingested into a 2D forecast model producing hourly surface optical forecasts out to 48 hours. The forecasts do not account for biological and optical processes at the ocean surface. However, for short-term forecasting (48 hours) in the coastal ocean, this assumption appears valid.

2.5 Generation of 3D Optical Volume

The 3D Optical Generator (3DOG) component of TODS was developed to provide a real-time optical characterization of the optical environment. This software uses the following inputs: glider optical and physical profiles, satellite surface nowcast/forecast (OpCast) of beam-c and 1% light level and the RELO-NCOM model nowcast/forecasts of vertical density and temperature fields for determining the location and intensity of the Mixed Layer Depth (MLD) at each grid location. The MLD is determined using the Brunt-Vaisala Frequency (BVF) and temperature thresholds. The procedure starts by using today's glider profiles, which are optimized using a Gaussian model and optics/physics relationship to generate coefficients for generation of a 3D optical volume (beam-c)[8]. This coupling of the measured beam-c from the glider and physical properties (temperature, salinity, and density) yielded a relationship (Gaussian) between the optics and physics (Figure 4). The nowcast/forecasts surface MODIS Aqua beam-c images at 250m resolution were coupled with the 3D ocean circulation RELO-NCOM model nowcast/forecasts and 3D Gaussian model coefficients to extend the surface optical properties vertically generating the nowcast/forecast optical 3D volume of beam-c at 250m resolution for the entire operational area. The modeling of the subsurface optics is tied to surface optical property, which is considered truth. The vertical estimation of the optical property is constrained over the first attenuation length and does not extend below the 1% light level. The vertical resolution of the 3D optical volume contains 29 layers.

2.6 Generation of the EOID Performance Surfaces

The nowcast/forecast 3D optical volumes from 3DOG are input into an EOID system performance model (EODES) to produce go-no-go and optimal tow altitude performance surfaces. EODES predicts the EOID system performance expected under a specific set of optical conditions[2]. System performance estimates from EODES are used to support Navy MCM operations for underwater target detection and identification. EODES provides sophisticated physical models for better performance prediction[2]. These models take into account the details of the system configuration and operation, the influence of optical properties of the water column, presence of ambient light, and the correlation between system resolution, optical blurring, and signal-to-noise. Inputs for this code include sensor type, laser power, vehicle towing altitude above bottom, information on the vertical optical environment (which is obtained from the 3D optical volume (3DOG)), and bottom depth. Outputs include the system Image Quality Rating (IQR) of a target at specified towing altitude for a go-no-go performance surface (IQR > 7 for detection/identification, IQR > 5 and < 7 for detection only, and IQR < 5 for no detection or identification) along with optimal towing altitude for identification (Figure 4) for the AQS-24 target imaging system. The EODES model provides a measure of relative performance, IQR, using a simplified rating scale patterned after a General Image Quality Equation (GIQE). The performance measure of the IQR is based on a predefined scale using a simple traffic light decision aid of red (no go), yellow (questionable), and green (go) that supplies a level of confidence that a particular EOID sensor, in this case the AQS-24[2], will work in the operational area under a specific set of optical conditions. The IQR rating is a function of Ground Sampled Distance (GSD), Relative Edge Response (RER), and Signal-to-Noise Ration (SNR). The EODES IQR metric is a measure of image degradation due to limited resolution (GSD), blurring (RER), and contrast loss and noise (SNR)[10]. Target identification is dependent on system towing altitude, target depth, and the location and strength of the optical layers. Optical properties of absorption and scattering are most important, and surface optical properties from satellite are not adequate to predict system performance. Using the 3D optical volume to predict system performance for an entire image/region/op-area gives better spatial coverage than using insitu optical and physical profiles at a certain location.

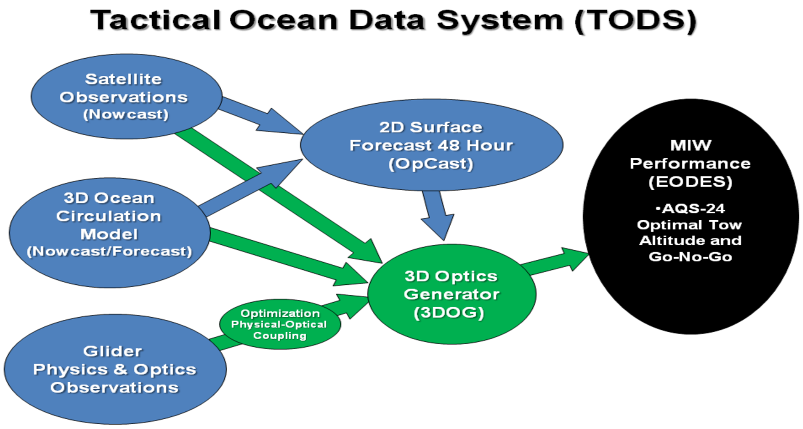


Figure 3. Tactical Ocean Data System (TODS) component and operational flow chart. MIW EOID performance surfaces generated by fusing nowcast/forecast satellite surface optical properties, modeled 3D physical parameters of temperature, salinity, and currents, and glider optical measurements of the entire water column.

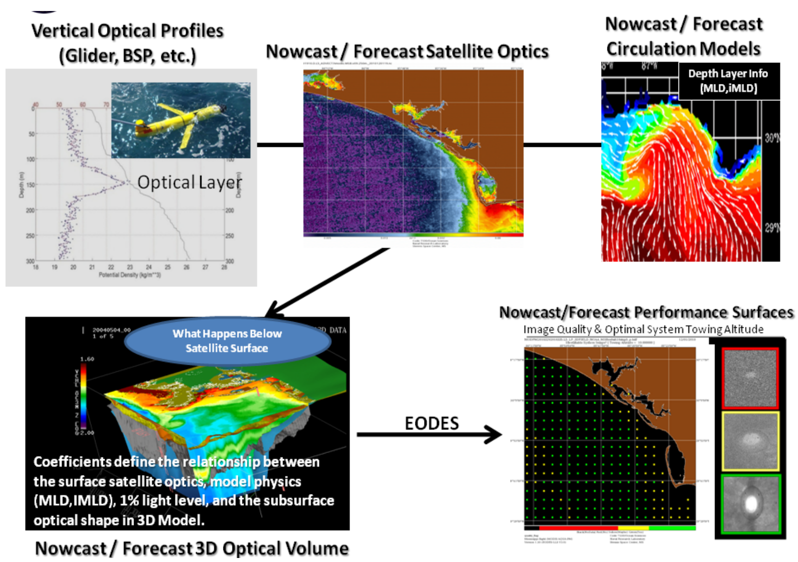


Figure 4. Flow diagram showing the method of fusing glider optics, physical models, and satellite surface optical properties resulting in a 3D optical volume that can be used to estimate system performance in support of the AQS-24 EOID sensor[8]. In the go-no-go performance surface, based on the IQR metric, green represents that optical conditions are favorable for target detection and identification, yellow represents detection only, and red represents no detection and identification of bottom target.

3. RESULTS

We participated in Vulcanex 11-1, a training exercise that took place off the coast of Panama City, FL, supporting the HM-14 in its mine clearance operations using the AQS-24 sonar with underwater laser imaging systems. The sonar system was used initially to locate targets of interest, which were then flown again with the imaging system for reacquisition and identification. Note these targets consist of mines, tires, rocks, concrete boulders, mattress springs, etc. We provided real-time assessments and forecasts of the surface and subsurface ocean optical conditions for EOID. The data-flow and fusion effort presented here is a step forward in providing the warfighter with (1) an optical 2D/3D nowcast/forecast and EOID system performance prediction capability and (2) a way for tactical decision makers to evaluate the performance of the EOID system being used in operations. Optical properties in the operational environment can be highly variable and possibly the most critical factor in the EOID system performance. The accuracy of the system performance in the operational environment is significant in tactical planning to meet MCM mission objectives. Figures 5, 7a, 7b, and 8 show results and accuracy of surface satellite, 3D optical volume, and system performance products provided to the HM-14 squadron during the Vulcanex 11-1 exercise. Figure 6 is an example real-time daily support product provided to the fleet (nowcast). This same figure was also provided for the 24- and 48- hour forecasts.

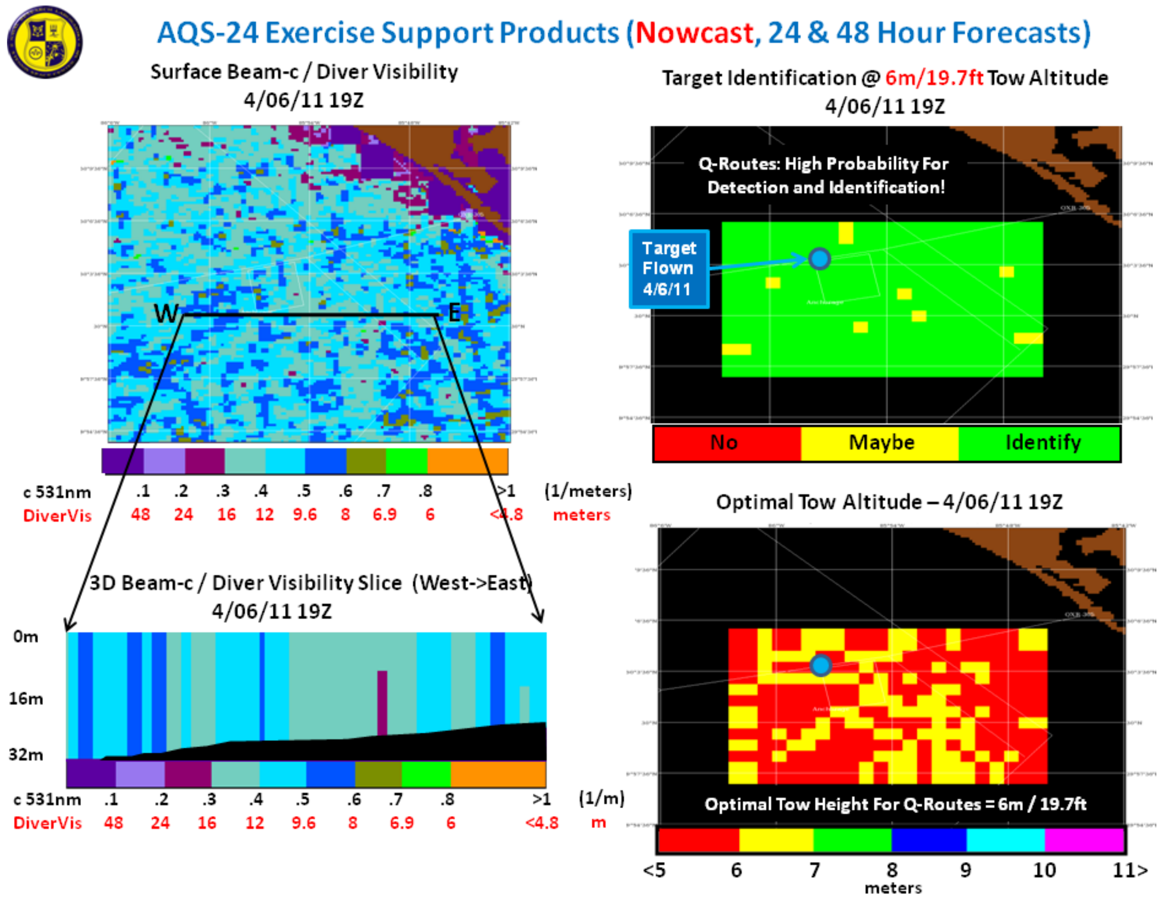


Figure 6. Real-time daily support product provided to the fleet (HM-14) during the Vulcanex 11-1 exercise for April 6, 2011. Top left image represents the surface (nowcast) of beam-c @531nm in inverse meters and diver visibility in meters. Surface beam-c ranged from 0.3 – 0.6 inverse meters on the average, while diver visibility ranged from 8 – 16 meters. Bottom left image represents a subsurface slice from west to east across image (black line in top left image) of beam-c and diver visibility. Range in subsurface beam-c also ranged from 0.3 – 0.6 inverse meters on the average, while diver visibility ranged from 8 – 16 meters. The subsurface was overall homogeneous (same as surface). The top right image represents a target ID go-no-go performance surface based on the IQR at a tow altitude of 6m/19.7ft (green/identify IQR > 7, yellow/maybe 5 < IQR < 7, red/no identify IQR < 5). The bottom right image represents the optimal tow height for the entire operational area. For this day, the predicted optimal tow altitude between 6 and 7 meters.

Image snippets from the AQS-24 (EOID) system and BSP/AEP profiles of beam-c at 532nm were obtained from the HM-squadron to validate predicted system performance and the 3D optical environment. Results from the fleet also included the clearance and target identification results which contained data of system tow, target type, system tow altitude, and whether or not the target was detected and identified. The mine target of interest were pre-laid and of known type.

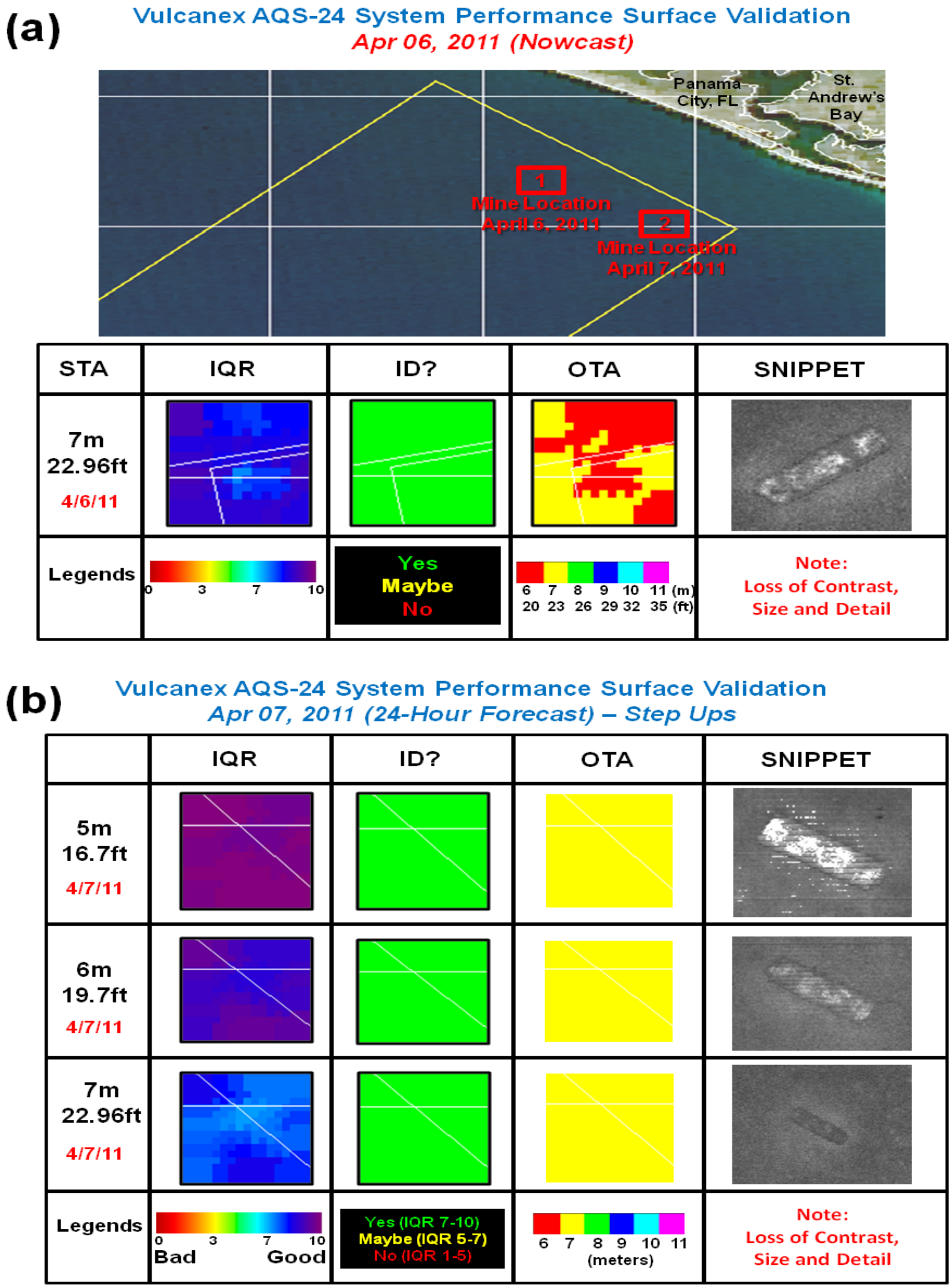
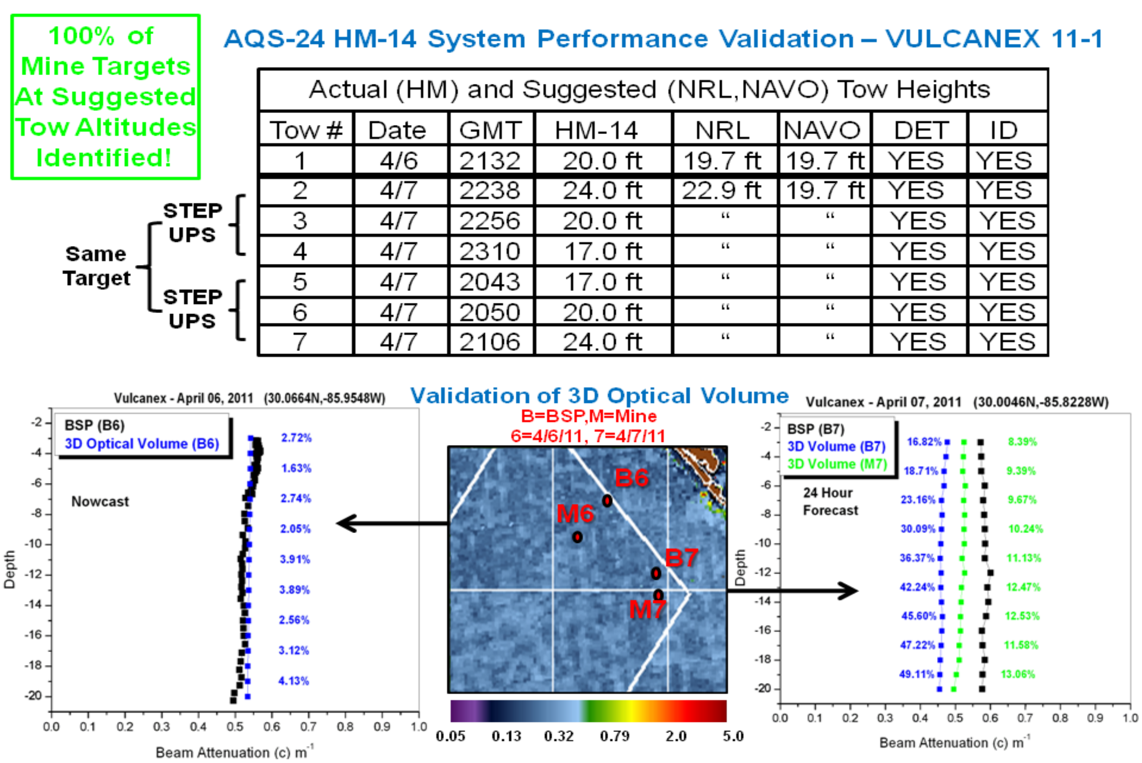

(a)
Vulcanex AQS-24 System Performance Surface Validation
Apr 06, 2011 (Nowcast)
Panama City, FL
St. Andrew's Bay
1
Mine Location April 6, 2011
2
Mine Location April 7, 2011
STA
IQR
ID?
OTA
SNIPPET
7m
22.96ft
4/6/11
Legends
0 3 7 10
Yes
Maybe
No
6 7 8 9 10 11 (m)
20 23 26 29 32 35 (ft)
Note:
Loss of Contrast,
Size and Detail
(b)
Vulcanex AQS-24 System Performance Surface Validation
Apr 07, 2011 (24-Hour Forecast) – Step Ups
IQR
ID?
OTA
SNIPPET
5m
16.7ft
4/7/11
6m
19.7ft
4/7/11
7m
22.96ft
4/7/11
Legends
0 3 7 10
Bad Good
Yes (IQR 7-10)
Maybe (IQR 5-7)
No (IQR 1-5)
6 7 8 9 10 11
(meters)
Note:
Loss of Contrast,
Size and Detail

Figure 7.

(a) This figure illustrates the results and validation of the system performance prediction for April 6, 2011 using the nowcast 3D optical environment predicted by the TODS system components (Surface optical nowcast/forecast – OpCast, 3D optical nowcast/forecast volume – 3DOG, and AQS-24 EOID system performance predictions - EODES). For this day, the predicted system performance was derived using the nowcast (clear satellite image). In the top image note the location (red box) labeled with 1. This is the location were the first mine target was located and flown with the AQS-24 EOID system. The results of the system performance (EODES) software are shown in the table at the bottom of figure for area defined by the red box only. Column 1 is the System Tow Altitude (STA), which was towed 7m/22.96 feet off the bottom. Column 2 is the Image Quality Rating (IQR), which ranged from 8 to 10. Column 3 is the go-no-go for target identification (ID?) showing green for the entire box region 1, meaning that the target should be identified for the system altitude flown. Column 4 is the Optimal Tow Altitude (OTA) for the box labeled 1, which ranged from 6m/20ft to 7m/23ft. Column 5 is the system target image flown which was identified by the HM-14 squadron.

(b) This figure illustrates the results and validation of the system performance prediction for April 7, 2011 using the nowcast 3D optical environment predicted by the TODS system components. For this day, the predicted sytem performance was derived using the 24 forecast derived from April 6, 2011 (April 7, 2011 image was cloudy). In the top image in Figure 7a, note the location (red box) labeled 2. This is the location where the second mine targets was located and flown with the AQS-24 EOID system. The results of the system performance (EODES) software are shown in the table at the bottom of this figure for the area defined by the red box labeled 2 only. Step-ups were performed on this day, meaning the target was flown at multiple tow altitudes of 5m/16.7ft, 6m/18.7ft, and 7m/22.96ft. Column 1 is the STA. Column 2 is the IQR which ranged from 7 to 10. Note that the IQR degrades as the system moves up in the water column (top to bottom row). Column 3 is the go-no-go for target identification (ID?) showing green for the entire box 2 (labeled in true color image in Figure 7a) or all three tow altitudes, meaning that the target should be identified for the system altitude flown. Column 4 is the OTA for the box 2, which remained constant for all three tow altitudes at 7m/23ft. Column 5 is the system target image flown at each altitude which was identified by the HM-14 squadron. Note the loss in size (resolution) and contrast as the system moves farther away from the target (top to bottom row).


AQS-24 HM-14 System Performance Validation – VULCANEX 11-1

Actual (HM) and Suggested (NRL,NAVO) Tow Heights							
Tow #	Date	GMT	HM-14	NRL	NAVO	DET	ID
1	4/6	2132	20.0 ft	19.7 ft	19.7 ft	YES	YES
2	4/7	2238	24.0 ft	22.9 ft	19.7 ft	YES	YES
3	4/7	2256	20.0 ft	"	"	YES	YES
4	4/7	2310	17.0 ft	"	"	YES	YES
5	4/7	2043	17.0 ft	"	"	YES	YES
6	4/7	2050	20.0 ft	"	"	YES	YES
7	4/7	2106	24.0 ft	"	"	YES	YES

Figure 8. This figure illustrates the validation of the system performance prediction and 3D optical volume at the target location for both days (April 6-7, 2011). These two days were the only days that mine targets were found and imaged by the AQS-24 EOID system. The table at the top of figure shows the tow information gathered from the HM-14 squadron. For "tow #1" on April 6, 2011 (Figure 7a), the TODS system (NRL) predicted a tow altitude of 19.7ft. The squadron flew the system at 20ft, resulting in the detection and identification of the mine target at location/box 1 (Figure 7a). For tow #'s 2 through 4 (Step-Ups) on April 7, 2011 (Figure 7b), the TODS system (NRL) predicted a tow altitude of 22.9ft. The squadron flew the system at multiple altitudes off the bottom (24ft, 20ft, and 17ft), resulting in the detection and identification of the mine target at location/box #2 (Figure 7a). This was repeated a second time for tow #'s 5-7 with the same outcome. The plot in the bottom left of figure shows the beam-c profile extracted from the nowcast optical volume generated by TODS/3DOG (blue) plotted with the actual insitu beam-c collected by the HM-14 squadron's BSP/AEP (black) on April 6, 2011 at location B6 on the image between the two plots. Note errors throughout the entire water column range from 1% to 4% error. The actual mine target was at location M6. The plot in the bottom right of figure shows the beam-c profile extracted from the 24-hour forecast optical volume generated by TODS/3DOG (blue) plotted with the actual insitu beam-c collected by the HM-14 squadron's BSP/AEP (black) on April 7, 2011 at location B7 on the image between the two plots. Note errors throughout the entire water column range from 16% to 49% error (B7). The actual mine target was at location M7. The profile extracted from the 24-hour forecast optical volume generated by TODS/3DOG at the mine target location (M7) was also plotted (green), showing a decrease in error in relation to the BSP for all depths (8% - 13%) due to spatial and temporal variability and suggesting the need for characterizing the 3D optical environment of the entire operational area for the prediction of EOID system performance versus using the BSP/AEP for operational support only a few kilometers away from target.

4. SUMMARY

As a proof-of-concept, satellite data merged with glider profiles and numerical models to derive a 3D optical volume can be used to derive tactically relevant products in support of EOID mine warfare missions. The ability to predict when and where EOID sensors will/will not perform effectively reduces the timeline of MCM missions. Methods used for this study represent a fusion satellite optical properties, glider optical profiles, and physical models to characterize the optical battle space environment. Knowing that a target can be detected and identified at a specific EOID sensor towing altitude or the optimal towing altitude over a large spatial region is critical for mine warfare mission planning and decision making. We present a method that extends the capability provided by point measurements from gliders and the satellite surface optics to create a real-time nowcast and forecast of the optical battle space. With increased data from gliders and satellites, uncertainties of the optical environment and system performance can be reduced.

A daily brief of the environmental nowcast and forecast was provided to the Naval Oceanography Mine Warfare Command and the HM-14 squadron during the Vulcanex 11-1 exercise in Panama City, FL in April 2011 in support of mine clearance operations using the AQS-24 laser imaging system. System performance predictions from the TODS system yielded 100% identification of mine targets at predicted tow altitudes. Positive feedback was received that the predicted optical environment and system performance (tow altitudes) for the AQS-24 laser imaging system was consistent with observations in the field and those products were crucial for mission planning and support. This was the first time an ocean's optical forecast was delivered on a routine basis to an operational exercise. We will continue the end-to-end evaluation of the TODS components with the final goal of transitioning capability into operations at NAVOCEANO.

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