A Comprehensive Model for Performance Prediction of Electro-Optical Systems

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LONG-TERM GOALS

The long-term goals of this effort are to provide reliable performance prediction and accurate system simulation capabilities for underwater electro-optic identification (EOID) systems. The Electro-Optical Detection Simulator (EODES) suite of numerical models developed under this program will predict the impact of environmental conditions, system parameters (e.g., apertures and PMT gains), and operational settings (e.g., platform speed and altitude) on system performance. Once fully validated, the models are anticipated to support mine countermeasures (MCM) mission planning and operator training. The two most prominent sensor technologies in this area are Laser Line Scan (LLS) and Streak Tube Imaging Lidar (STIL). Examples of systems using these technologies are the AN/AQS-24 (using LLS) and a variant of the AN/AQS-20 (using STIL) mine-hunting systems. The ALMDS (Airborne Laser Mine Detection System) also uses a STIL sensor to image underwater objects from an airborne platform. High-fidelity models for all these systems have been incorporated into the EODES software.

OBJECTIVES

Our objectives are to develop and validate EOID models to compute reliable metrics for the prediction of system/operator performance, and for generating synthetic images of bottom scenes under given environmental conditions and operational settings. These models will be validated, certified and incorporated into the Navy Standard Oceanographic and Atmospheric Master Library (OAML). The models will also be integrated into Tactical Decision Aids (TDAs), specifically the Mine Warfare Environmental Decision Aid Library (MEDAL). The code base is being developed in ANSI C/C++ to ensure portability across computer platforms and to facilitate incorporation within fleet TDAs.

APPROACH

Performance predictions for electro-optical systems are predicated on accurate modeling of light propagation in water. EODES contains a validated radiative transfer solver for ocean environments, which is used as the common basis for all system models. The modular nature of the EODES software framework enables new models to be implemented easily, rapidly, and independently. The investment in the current models and their software code base can be leveraged to accelerate development of other system models through code reuse and sharing of common interfaces for model inputs and outputs. The code base is developed in ANSI C/C++ to provide portability across computer platforms. The EODES model libraries can also be imported into the high-level Python language to facilitate the

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development of graphical user interfaces (GUIs) and visual decision aids. Models for the Laser Line Scan (LLS), the Streak Tube Imaging Lidar (STIL) and the Airborne Laser Mine Detection System (ALMDS) are currently implemented.

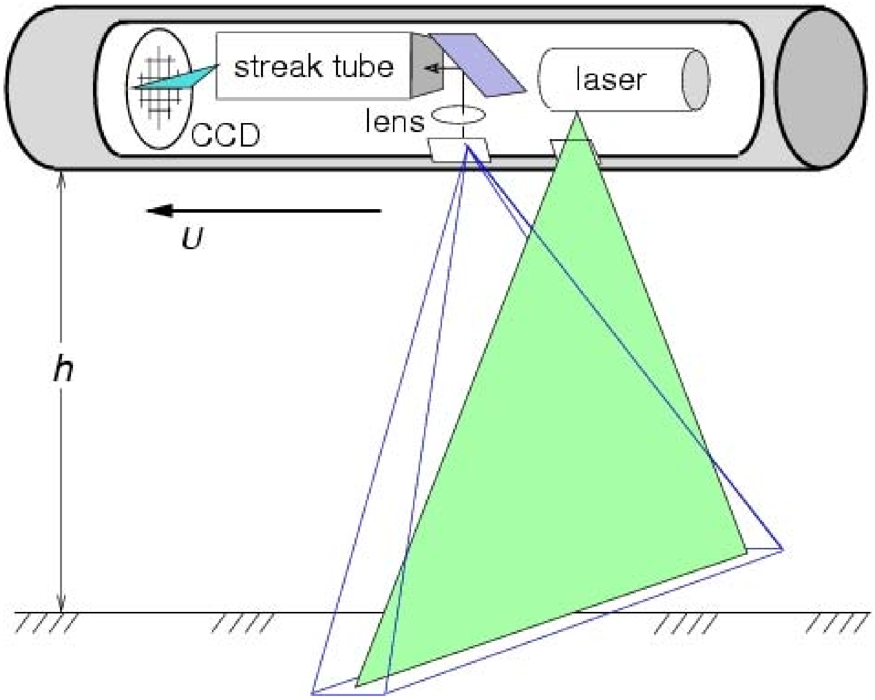

Figure 1: Schematic of the Streak Tube Imaging Lidar (STIL) system.

A STIL system uses a pulsed fan-beam to illuminate an entire cross-track line with each laser pulse, as depicted in Figure 1. In addition to a contrast map of the bottom, a pulsed laser provides range data determined from the signal's time of return. Consequently, radiative transfer for a STIL system is inherently time-dependent, and the system is subject to temporal blurring (sometimes referred to as pulse stretching or temporal dispersion). The image formation process of the STIL sensor employs a CCD array, which has its own characteristics, including the potential for saturation. A detailed model of the STIL system was implemented in EODES in the previous year as part of the overall effort. The STIL model is a fundamental component of the ALMDS model.

The ALMDS system is conceptually similar to the underwater STIL system, except that the platform is airborne at a typical altitude of 300 feet above the ocean, as sketched in Figure 2. Light is assumed to propagate in air without attenuation or scattering, but reflection and refraction at the air/water interface present significant complications for modeling this system. Glint (or glitter), the specular reflection of the laser beam from the ocean surface, is very important because it can saturate the CCD array and significantly degrade the ability of the sensor to detect an object near the surface. However, glint is very difficult to compute accurately because of the complicated structure and stochastic nature of the surface waves. Refraction across the air/water interface also complicates the imaging process. In air the laser beam is well collimated, but refraction across the wavy surface steers the beam in random directions within the water and destroys the collimation. To account for this, the fan beam is discretized into a large number of well-collimated beams. Each sub-beam is reflected and refracted at the air/water interface according to Snell's Law and the local slope of the wave surface. Within the water the beam is subject to attenuation and scattering, depending on the environmental conditions. The light scattered in the backward direction undergoes further attenuation and scattering as it propagates to the surface, where it is refracted and transmitted into air. The total return is obtained from superposition of the sub-beams.

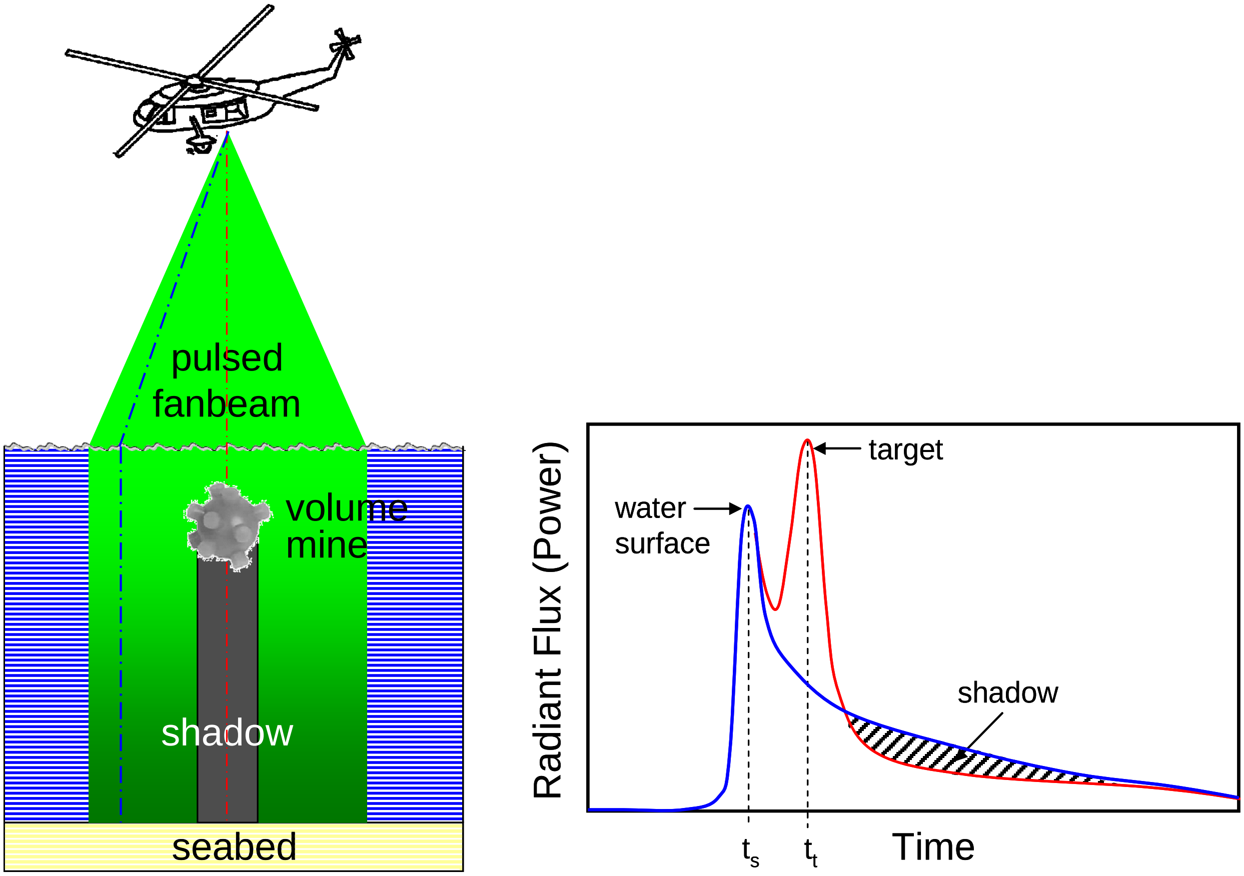

Figure 2: Schematic of the Airborne Laser Mine Detection System (ALMDS) on left; return signal from water surface and target in water column (if present) on right.

On the right of Figure 2 is a sketch of the power in the return signal as a function of time for the cases of a target present and not present. There is a large initial peak in the return due to reflection from the ocean surface (glint). With no target present, the remaining return is from volume backscatter that attenuates exponentially with depth and, therefore, time. With a target present, there is a secondary peak in the return due to scattering from the target, and the difference in time between these peaks is directly related to the depth of the target. The tail end of the return differs from the no-target case due to the shadow region created by the target. Together, the presence of a secondary peak from specular scattering and a suppressed return due to a shadow region form the basis for target detection.

WORK COMPLETED

A complete model for the ALMDS system has been implemented. It first computes a realization of a portion of a random ocean wave surface, as shown in Figure 3. The wave surface is a superposition of waves of different wavelengths λ and amplitudes. Gravity waves (λ > 1.7 cm) contain most of the wave energy. The energy of waves shorter than capillary waves (1.7 cm > λ > 4 mm) is effectively dissipated by viscous effects. Full details of the surface wave spectrum we have implemented can be found in Apel (1994).

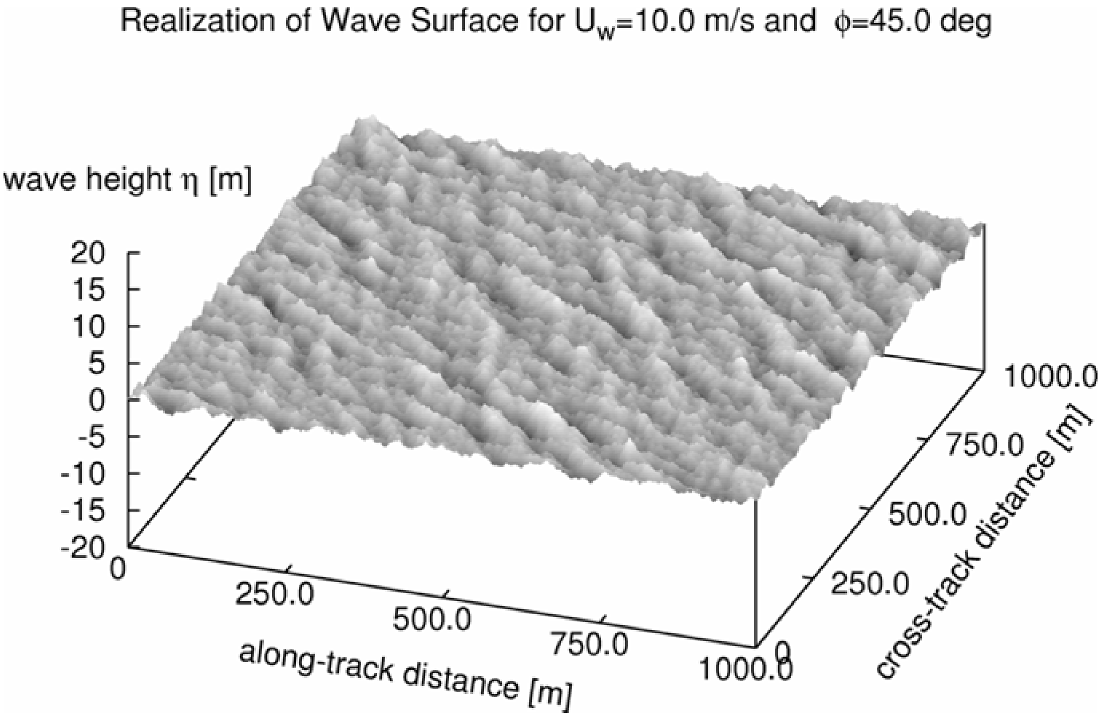

Figure 3: Realization of random sea surface generated by filtering a white noise process using semi-empirical model for wind-driven wave spectrum.

To compute the (time-dependent) signal received by the ALMDS sensor, we must first propagate the radiance distribution from the fan-beam laser through air down to the ocean surface. This is done without attenuation or scattering, and the result is that the laser illuminates a thin strip at the ocean surface with light that is well collimated. The illuminated area is discretized into small cells, with the light incident on each cell treated independently. In each cell, the normal to the wave surface is computed and the incident light is split into a reflected and refracted component according to Snell's Law. The reflected light (glint) is computed based on the incident radiance and a Bidirectional Reflectance Distribution Function (BRDF) that includes the effects of subscale wave surface roughness. The reflected light is then propagated back to the sensor without attenuation or scattering.

The refracted light is propagated to depth under the small-angle approximation for radiative transfer. The water is conceptually partitioned into thin, vertically stratified "slabs." The reflectivity of the slab is taken as β_π (the volume scattering coefficient in the backward direction) except when the target intersects the slab, in which case the target reflectivity is used. For slabs below the target the reflectivity in the shadow region is zero. The light scattered from each slab is computed and propagated back to the wavy ocean surface, again under the small-angle scattering assumption. The light is then refracted into the air and propagated back to the receiver. In this way, it is possible to construct the complete time history of the return signal.

Actual computations are carried out efficiently using a Fourier optics approach. Figure 4 is a collection of synthetic images generated from a mine-like target at depths of 2 and 4 meters. The wave surfaces are computed for wind speeds of 2, 4, and 6 m/s. For these images the water is clear (no absorption or scattering) to illustrate the effects of refraction alone on image distortion.

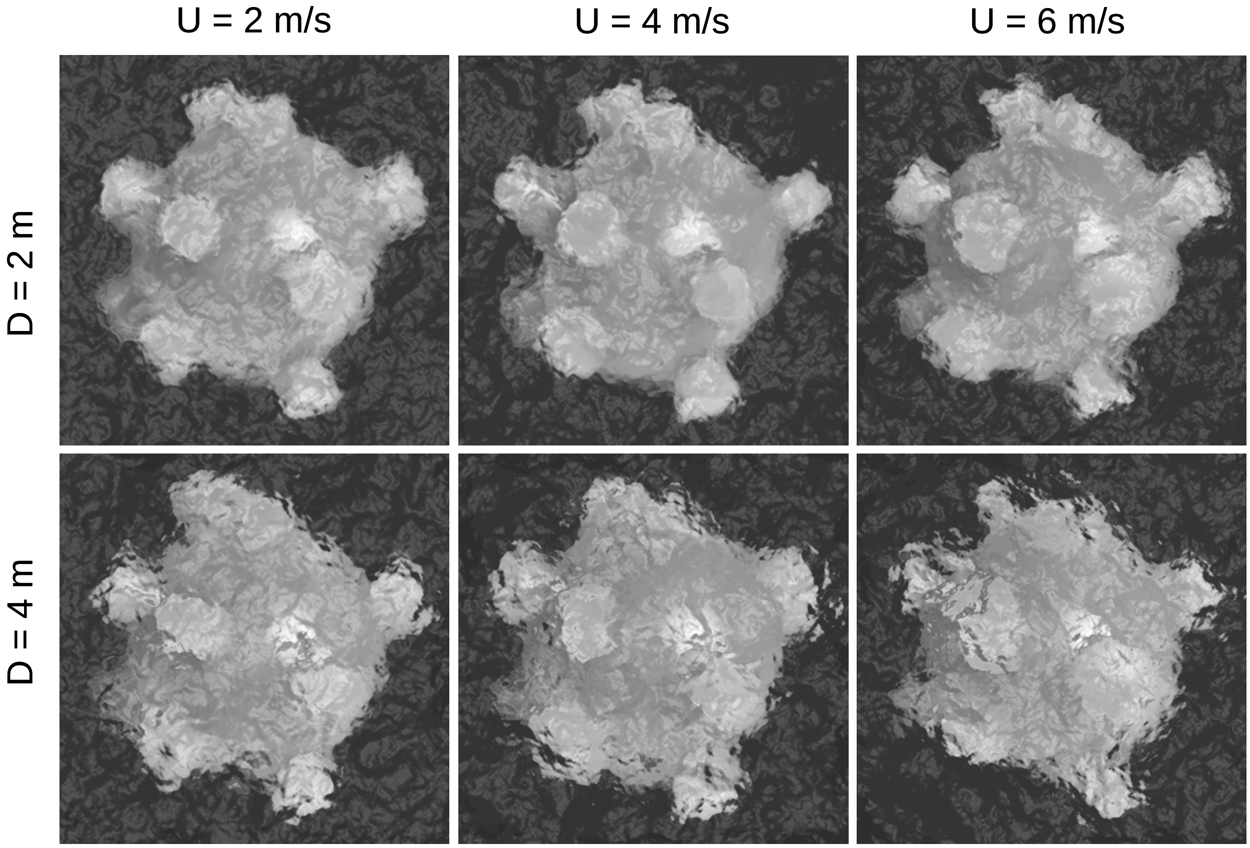

Figure 4: Synthetic images for clear water (without beam attenuation or scattering) demonstrate the effects of reflection and refraction through the water surface at various wind speeds (U) and target depths (D).

IMPACT/APPLICATION

When completed and validated, the performance prediction models for LLS, STIL and ALMD systems will be available for distribution and incorporation into Fleet Tactical Decision Aids, where they will facilitate effective MCM mission planning. The EODES model suite can also generate synthetic images which are valuable for training human operators, and can be useful in the development and validation of automatic target recognition algorithms. The system models and radiative transfer solvers within EODES will become useful design and analysis tools for prospective electro-optical systems.

TRANSITIONS

The models and metrics developed and validated by this work have been used to support MIREM exercises in 2003 and 2005 and the RIMPAC exercise in 2006 in testing of the AQS-24 minehunting system. The EODES models are currently in the process of obtaining OAML certification, in preparation for transition to the Naval Oceanographic Office and integration into the MEDAL tactical decision aid.

RELATED PROJECTS

Airborne Laser Mine Detection System (ALMDS).

Rapid Airborne Mine Clearance System (RAMICS)

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