Littoral Environmental Nowcasting System (LENS)

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Abstract- **Recent advances in electro-optical sensors, environmental characterization algorithms and nearshore circulation models will soon allow near-real-time, high-resolution characterization of littoral regions using unmanned aerial vehicles (UAVs). The fundamental objective of a new program at the Naval Research Laboratory is to develop a UAV-based system that couples remotely acquired imagery with advanced data analysis and state-of-the-art numerical models to provide a nowcast of littoral environmental conditions. The conceptual use of this system includes the estimation of waves, currents, and bathymetry to support expeditionary warfare operations particularly with respect to very shallow water and surf zone regions. The system is envisioned to operate organically in that no external sources of information are required. The framework of this system is described and the issues pertaining to operational deployment are discussed.**

I. INTRODUCTION

The littoral region (especially the surf zone) has been identified as an area of great importance for successful Naval operations largely due to the wide range of variability in littoral processes encountered worldwide [1]. Knowledge of the spatial and temporal variation of the littoral environment is critical for expeditionary warfare, specifically with respect to amphibious landings, in-stride neutralization of mines, and prediction of mine burial [2]. Unfortunately, environmental measurements in many littoral regions are difficult to obtain because of harsh conditions and/or locations that are inaccessible to conventional collection platforms. Also the dynamic nature of the littoral requires frequent, high-resolution samples. For example, a prior determination of bathymetric features and contours may not provide an accurate characterization of the littoral environment at the time of the planned operation because vertical changes in bathymetry of more than 1 m over time spans as short as a few hours are possible. Wave conditions can change even more rapidly.

The Naval Research Laboratory has started a program to develop capabilities for rapid environmental assessment of coastal regions, particularly with respect to surf zone characterization. This program, known as LENS, for Littoral Environmental Nowcasting System, utilizes motion imagery from Unmanned Aerial Vehicles (UAVs) to quantify bathymetry and wave conditions such that littoral processes can be estimated under operational scenarios. In addition, this capability greatly extends the data collection possibilities during scientific research experiments in terms of both scale and accuracy.

The program objective is to develop a system that couples remotely acquired, temporally and spatially variant information within the littoral zone with a state-of-the-art numerical circulation model to support naval operations in littoral regions. This system uses automated processing of electro-optical motion imagery (a video-like product consistent with imagery derived from current and planned tactical reconnaissance platforms) to drive numerical modeling software to provide nowcasts of waves, currents, and bathymetry. The primary region of interest is in very shallow water and through the surf zone to the shoreline, although the system will have targeting and analysis capabilities that will be relevant to areas landward of the beach (e.g. the dune line position) and offshore (e.g. directional wave spectra). The major advantage of this approach is that an environmental characterization of the present conditions can be made rapidly and at high resolution.

Many of these image processing algorithms were derived from academic and government research conducted using fixed cameras under the Argus program directed by Oregon State University and as part of ONR supported research on using airborne electro-optical sensors [3, 4]. Parameters that can be estimated using these methods include shoreline location, surf zone width, bar morphology, bathymetric profiles, wave height, wave period, wave direction, and alongshore currents. The significance of these data are that they are sufficient to drive existing numerical circulation models for simulating hydrodynamic and morphological processes in the littoral environment and thus to provide the near real time characterization without other inputs. In essence, the envisioned military application will be an organic system, although, other regional-based products such as wave forecasts or climatologies could also be incorporated if desired. Application and validation of the prototype system (particularly with respect to the circulation model) is proposed during the upcoming, ONR-supported, Nearshore Canyon Experiment (NCEX) in 2003, with demonstration and preliminary transition of the complete system as part of future military exercises.

Even though recent software and hardware advances in technology make integration of the data collection and modeling systems possible, the development of LENS will be complex. In this publication, we describe the LENS approach, present examples of existing functionality, and

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discuss the necessary improvements required to allow operational application. Critical aspects of this effort include defining an optimal modulation transfer function to relate directional intensity spectra to directional wave spectra, adapting the numerical model to integrate multi-scale inputs, and implementing robust and advanced methods for using wave phase and linear dispersion to infer three-dimensional bathymetry.

II. LITTORAL CHARACTERIZATION METHODLOGY

I. Electro-Optical Motion Imagery from Fixed and Airborne Platforms

A variety of remote sensing approaches have been used to monitor the environmental characteristics of littoral regions [3, 5-10]. These include electro-optical (E-O), multispectral, and radar based sensors that estimate currents and wave features such as wave amplitude and phase. The usefulness of the various approaches ranges greatly because the imaged signature of a wave is nonlinearly related to sea surface elevation, and modulation transfer functions for radar and multispectral imagery are often complex. However, measurement of wave breaking patterns and wave phase using visible-band, electro-optical imagery (Fig. 1) is generally viewed as a reliable and accurate approach. Fortunately, a large number of littoral parameters can be directly estimated using E-O image intensity including wave period, breaker angle, surf zone width, mean currents, shoreline location, and sandbar position [11-13]. Other characteristics such as wave height, energy spectra, nearshore currents, and bathymetry can be inferred for E-O images using either more complicated time series analyses or theoretical relationships [14, 15].

Fig. 1. Snapshot image of complex nearshore waves from the Duck, NC Argus station on November 3, 1999.

Although the choices of motion imagery sensors have greatly increased in recent years given the explosion of the consumer video market, there are a few important requirements. One fundamental requirement for these techniques is that multiple frames of imagery be collected to allow statistical confidence limits to be established and to determine the range of variability over significantly long time intervals. This requirement distinguishes what is known as motion imagery from individual images (which we refer to as snapshots) in that patterns of behavior are often obvious in motion imagery (as in motion pictures) when compared to single frames. It is our experience that sampling should occur at a frequency of no less than 2 Hz for a duration typically ranging on the order of tens of minutes to several hours. Another prerequisite is that the imager has a ground plane resolution of approximately 1 m. A final requirement separating electro-optical motion imagery from traditional video is that the imagery is digital to allow for computer based analysis.

The methodology for converting between E-O imagery and geophysical information is well established as it largely relies upon the principles of photogrammetry. Holland et al. [9] present a thorough description of the rectification process for translating between image plane and ground coordinates using digital imagery from standard video cameras deployed during field experiments. In addition, a variety of applications for motion imagery data have been presented including the use of time exposures, timestacks, and pixel arrays [12, 16]. Once rectified, imagery is easily quantified in terms of distances and speeds rather than pixel-based coordinates such that motion imagery can be used in a manner similar to traditional instrumentation.

There have been two alternative approaches for deploying systems for littoral characterization using E-O sensors. Fixed platform installations, such as in towers, light houses, or on hilltops offer the advantages of long-term sampling with minimal difficulties relating to system size, power or data storage. Additionally, the viewing geometry generally remains fixed allowing repeated pixel based analyses to be highly automated. One of the premier collections of this type data is maintained by the Coastal Imaging Laboratory at Oregon State University (http://cil-www.oce.orst.edu:8080/). In contrast, imagery collected from airborne platforms, such as UAVs, typically has a much higher viewing angle resulting in a more consistent pixel footprint through the coverage area, can be rapidly collected at a number of spatial locations, and is generally more suitable for covert military operations. One disadvantage of airborne imagery is that the geometric transformation between image and ground coordinates has to be recalculated for each image frame, but that process has been automated [17]. Collections using airborne vehicles are generally preferable to space-based platforms given the often lower pixel resolution and shorter temporal dwell of the satellites.

II. Examples of Motion Imagery Analyses

In the following sub-sections, we present examples that indicate the types of littoral parameters that can be obtained using E-O motion imagery. These data are from the Argus camera system deployed at the US Army Corps of Engineers' Field Research Facility in Duck, North Carolina, USA. Although more than a decade of imagery is available from this site, for these examples automated analysis were performed on imagery collected from

November 3-4, 1999. During this time period, narrow-banded waves with low heights (approximately 0.8 m in 8 m depth) and a wave period of around 9 s were observed.

III. Shoreline and sandbar position

Wave breaking patterns can be used to reveal the location of shorelines and submerged sandbars based on the assumption that waves preferentially break in regions that are relatively shallow. Intensity patterns from a single frame are often insufficient to differentiate longer term breaking patterns due to submerged bathymetric features from short-scale variations in wave forcing, therefore, a temporal average of multiple frames is used to quantify the cross-shore and alongshore locations of the nearshore morphologic features. Temporal variations over a tidal cycle in the locations of these patterns can also be used to estimate foreshore slope [18, 19].

Fig. 2 shows a time exposure average of pixel intensity at Duck that has been rectified to ground coordinates using a combination of imagery from six cameras. The underlying bathymetry strongly mimics the wave breaking patterns such that a linear sand bar is readily apparent at the cross-shore position approximately 100 m offshore of the shoreline.

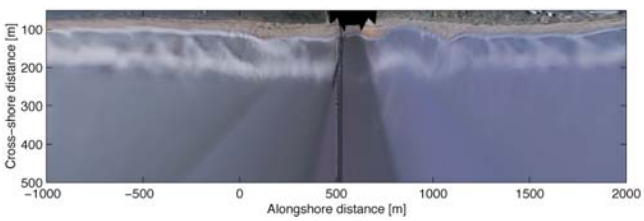

Fig. 2. Rectified, time exposure image of nearshore wave dissipation patterns from the Duck, NC Argus station on November 3, 1999.

IV. Wave characterization

Outside the breaking region, image intensity is representative of the amount of incident light scattered off of the slope of the wave surface. Steeper portions of waves appear darker than flatter portions such that E-O based motion imagery provides a good proxy for wave phase near the fundamental frequency of the wave. Inside the surf zone, contrast changes are largely governed by energy dissipation and advected foam rather than sea surface slope; however, the passage of bores past a given location is still readily quantifiable. For example, estimation of wave period can be obtained from the peak in the energy spectrum in a single pixel intensity time series. Given that pixels can be considered equivalent to fixed instruments through use of the rectification process, cross-spectral analysis of time series from pixel arrays can be used to determine dominant wave angle, wavelength, and even frequency-directional spectra (Fig. 3). The relationships involved in these computations extend from the spectral estimation of a wavenumber component using two closely spaced sensors following

$$k_x(f)=\frac{\phi(f)}{\Delta x} \tag{2.1}$$

where k_x is the cross-shore component of wavenumber, f is frequency, Δx is the separation distance, and ϕ is the phase difference between sensors given by the arctangent of the ratio between quadrature spectra and co-spectra. Although approaches for converting from intensity to sea surface elevation are possible, in practice it is simpler to constrain the energy density magnitude at the peak frequency to a known value obtained using external measurements or other approaches (including breaker height estimation using motion imagery).

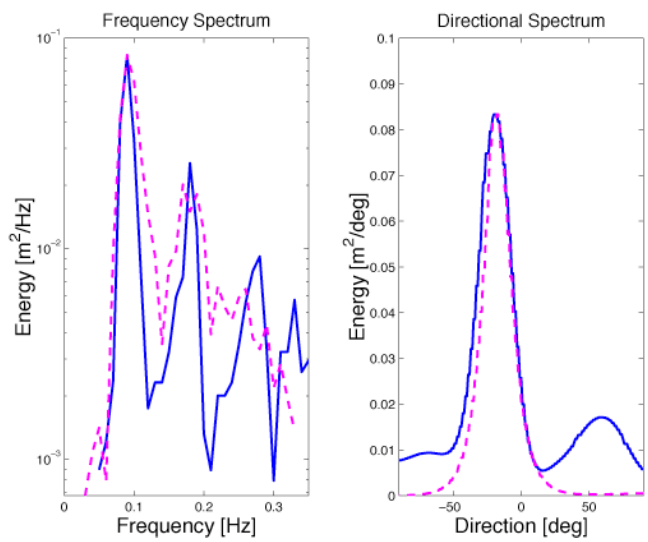

Fig. 3. Frequency and directional spectra calculated using arrays of pixel intensity time series (solid) and from in-situ pressure gages (dashed) for November 3, 1999. Intensity spectra have been adjusted to the pressure gage energy peak.

V. Nearshore currents

Other more sophisticated methods for quantifying littoral processes are also possible. A motion imagery based approach that has recently been proven extremely useful is particle image velocimetry or PIV. Holland et al. [20] describe the application of this laboratory method to field data to allow the detection of nearshore currents. PIV yields current estimates similar to radar based measurements and at lower cost, higher spatial resolution, and larger spatial coverage than in-situ sensors [20, 21]. The largest disadvantage of the method is that it is computationally intense with typical study regions on the order of 200 m^2 requiring processing times on the order of 5 seconds per frame.

Fig. 4 shows one example of how this approach can be used to obtain extremely high-resolution measurements of surf zone current magnitudes and directions. The example was obtained from a prior experiment specifically designed for PIV. In general, a large signal to noise ratio in the advected foam pattern is required to produce accurate PIV estimates. Related, but less processor intensive methods using tracers to quantify flow patterns are also being investigated.

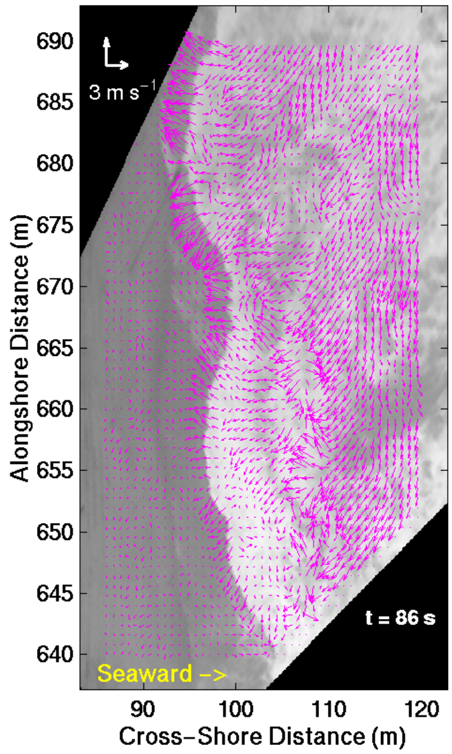

Fig. 4. PIV estimates of inner surf zone currents (from a prior experiment). Vectors are spaced every 0.8 m and a vector scale is located in the upper left-hand corner of the image.

VI. Bathymetry estimation

Water depth in littoral regions can be inferred from motion imagery by estimating the shortening and slowing of waves as they shoal [15, 22]. Although this technique has been practiced since WWII, only recently have data quality and time series analyses been sufficiently improved to allow robust estimation of littoral bathymetry. The general approach has been described by Holland [14] and suggests that depth estimation errors on the order of 3-9% of the observed depth are possible. The technique is based upon a simple, theoretical relationship between wavelength (*L*), wave period (*T*), and water depth (*h*) known as the linear dispersion equation for surface gravity waves. For the case of no mean currents in the direction of wave propagation, this equation is given as:

$$\sigma = \sqrt{gk \tanh kh} \qquad (2.2)$$

where $\sigma = 2\pi / T$, $k = 2\pi / L$, and g is the gravitational constant. For values of σ and k estimated using the methods described in the above section, solution for depth is obtained by inverting (2.2).

Fig. 5 shows bathymetry profiles measured using GPS-based surveying instrumentation and estimated using motion imagery based inversion. The two curves are extremely similar with only slight over prediction of the depth apparent on the landward flank of the inner bar. This error can be attributed to wave height effects that are not included in (2.2), but can be corrected using other approaches [14].

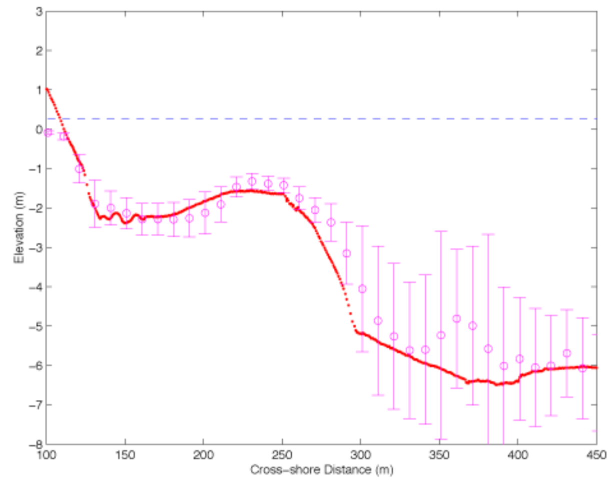

Fig. 5. Measured cross-shore bathymetry profile (solid) versus motion imagery based bathymetry inversion (circles) for November 4, 1999. The vertical lines indicate confidence limits for the inversion estimates. The tidal elevation is shown as the dashed line.

VII. Numerical Models of Nearshore Circulation

Numerical models of nearshore processes (waves, currents) have reached an advanced stage of sophistication and accuracy to make their use as prediction tools tenable. For the simulation of nearshore wave and current fields, typical input includes bathymetry (at a resolution sufficient to include major features such as bars) and offshore wave conditions (spectral parameters or actual directional spectra). Generally, a coupled wave and hydrodynamic model system is used, with the wave field calculated from the initial condition and the resulting forcing information provided to the circulation model. The bathymetric resolution requirements are usually similar between the two models. Assumptions for the lateral boundary conditions are usually made (either closed or periodic), though velocities can be input if available.

Fig. 6 shows the prediction of littoral conditions for November 3, 1999 using coupled numerical models with known bathymetry over the prediction domain and observed forcing conditions at the offshore boundary. The wave diffraction model REFDIF-S [23, 24] was initiated with frequency-directional spectra measured in 8-m depth. These results served as forcing for the SHORECIRC model of nearshore waves and currents [25, 26]. This characterization shows a complex circulation pattern with an interesting focusing of waves in the upper portion of the prediction domain that matches the enhanced dissipation patterns shown for that location in Fig. 2. The maximum predicted depth-averaged currents are approximately 0.3 m/s and show a weak rip centered at y = 750 m. This characterization exemplifies the type of nowcast that would be made available using LENS operationally.

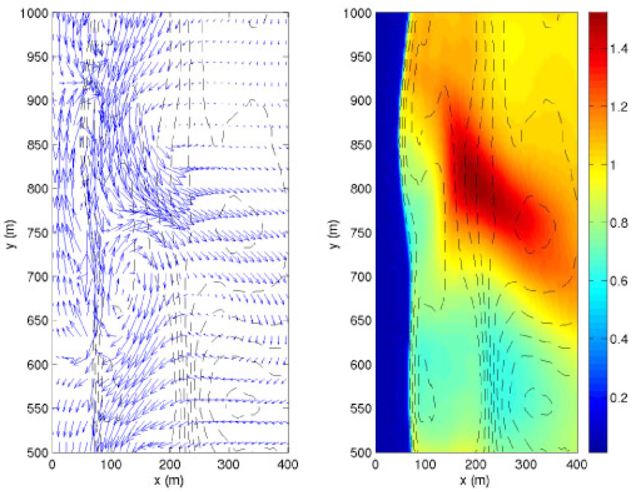

Fig. 6. Predicted current field (left) and wave heights (right) for November 3, 1999. Bathymetry contours are shown (dashed).

VIII. UAV-based Application

Conversion from research to military applications requires the use of re-locatable and potentially covert sensing systems. Although placement of a fixed platform camera on a natural vantage point might be conceptually feasible for special operations, a variety of UAV-based sensing systems planned for use in military operations can be readily adapted. For example, a digital E-O system known as AROSS [27] has been proven to provide imagery of similar or superior quality to fixed platform Argus imagery. One of the unique capabilities of AROSS that is desirable for use in future operational sensors is the ground coordinate spotlight capability that allows the camera to locate and point at a fixed spatial coordinate using on-board GPS and inertial hardware.

Rectification of individual images to a common ground plane is not significantly more time consuming than fixed platform image rectification although airborne results with equivalent mapping errors require some user intervention to exclude outliers. Once rectified, however, the algorithms described above can be applied in a nearly identical fashion with no loss in accuracy for the estimated littoral parameters. Therefore the only major obstacle to using UAV-based imagery is that the size of the imagery files at sufficient resolution to meet littoral nowcasting requirements is large, often on the order of hundreds of megabytes. We envision that over the next few years advances in communications protocols, on-board processing systems, and image compression algorithms will make this constraint less severe.

III. LENS FRAMEWORK

Because expeditionary warfare in the littoral is so difficult, we propose that the LENS approach to environmental characterization will greatly enhance Naval capabilities in military operations. In contrast to a generalized climatology of past conditions or a qualitative forecast of future conditions, our nowcasting product will accurately extend the observations of present conditions to higher resolution and to include additional parameters such as subsurface currents. The nowcast wave conditions would be expected to be relevant over the next 2-6 hours while the estimated bathymetry would be representative for several days or until the onset of a storm. An emphasis is placed on automation such that little or no user intervention is required. Also LENS will leverage imagery that is already being collected on-scene for other purposes. Our approach is diagrammed in the Fig. 7.

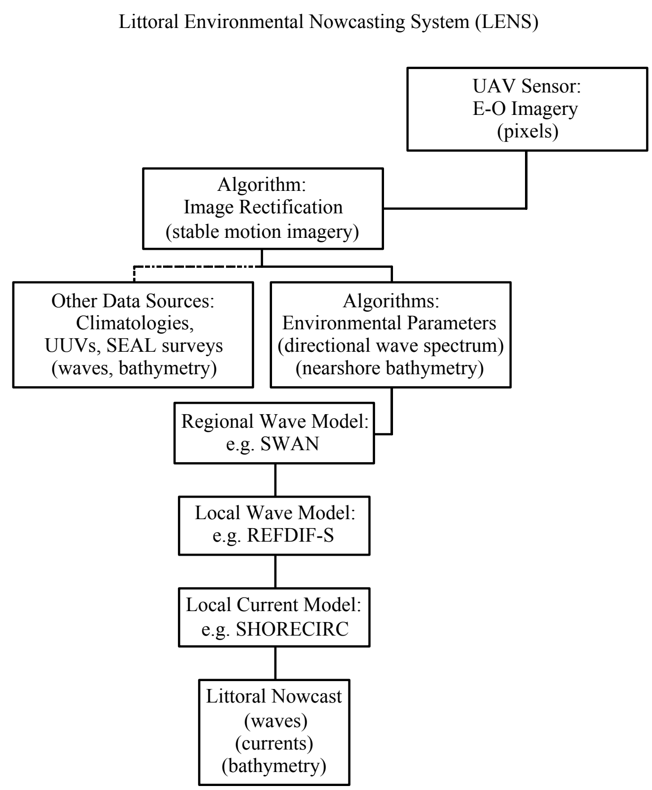

Fig. 7. Diagram showing conceptual framework for LENS prototype to be demonstrated in military exercises.

Under this scenario, between 24 and 72 hours prior to an littoral operation, a generalized depiction of the battlespace environment could be obtained at multiple locations using covert reconnaissance imagery by coupling LENS estimates with other data sources, as needed. This step will allow the production of a superior nowcast both in terms of accuracy and resolution to assist in landing site selection, particularly with respect to identifying any recent changes in bathymetry. For example, identification of rip channels or sand bars may influence the selection of assault routes with lower mine densities or more deeply buried mines. Nearer to the assault, a more continuous characterization of environmental conditions would then be made during any mine countermeasures operations using imagery collected for those purposes. This suggested framework would positively impact the implementation of in-stride mine clearance operations as wave and current effects to countermeasures systems would be known. In addition, the LENS approach is amenable to tracking errors throughout the analysis such that confidence in predictions can also be relayed.

Before operational demonstration is achieved, however, further work on integrating the predictions over multiple scales is required. For example, it is unclear what minimum resolution for bathymetry or offshore forcing is necessary for accurate surf zone wave and current prediction. Also a better understanding of the relationship between pixel intensity and wave amplitude is being investigated to allow direct determination of wave energy spectra from imagery. Good progress has been made in taking these approaches to routine and robust application under operational scenarios as part of the Video Imaging System of Surfzone Environmental Reconnaissance (see for http:/visser.nrlssc.navy.mil for more information) and AROSS efforts, so we expect successful demonstration using UAV platforms in the near future [28].

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