Multi-sensor Remote Sensing in the Nearshore

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LONG-TERM GOALS

The proposed program directly supports the Navy goal of predicting the 4D nearshore environment for amphibious operations that involve surf zone breaching. Our effort specifically involves improving our understanding of the fundamental relationships between nearshore hydrodynamic processes and remote sensing observations of these processes from multiple remote sensors. We utilize this understanding to improve our ability to numerically simulate and, hence, predict the time and space variability of the nearshore environment. The Navy also makes considerable use of remote sensing techniques for littoral mine and obstacle detection, and breaking-induced foam and whitewater can be a significant source of signal clutter for relevant sensing systems. In this regard, the proposed work will also explore the presence of foam and whitewater bubbles as revealed by optical and microwave systems, with the potential to aid in the design and tactical deployment of aerial reconnaissance imaging systems.

OBJECTIVES

The objectives of this project are as follows:

1. Conduct a radar system calibration through a collaborative field deployment with Dr. Bill Plant (Applied Physics Lab, UW-APL)..

2. Develop and test a deterministic radar scattering model that is applicable to the nearshore.

3. Continued analysis of remote sensing observations from Duck site and assessment of wave parameter extraction algorithms.

4. Collaborate in related efforts a) surf zone bubble modeling (Dr. Jim Kirby, U. Delaware) and b) polarimetric remote sensing (AROSS-MSP, Arete Associates). Collaborations will include participation in model testing and incorporation of bubble model results into radar scattering model, as appropriate. In addition, related optical polarimetry project results will be included in a comparative study of nearshore sensors.

5. Investigate potential model parameterizations for predicting the coverage of whitewater and foam that will generate clutter at optical wavelengths.

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APPROACH

Our main thrust has involved a nearshore remote sensing experiment (Multi Remote SENSor Observations; MR-SENSO) conducted in the spring of 2008 at the USACE Field Research Facility (Duck, NC). Data was collected using three remote sensors: 1) X-band, HH-pol, marine radar imager, 2) X-band, coherent, dual-pol radar (RiverRad, UW-APL), and 3) the on-site Argus camera station. This is a unique data set. The RiverRad system operates in staring mode, but allows calibration of the synoptic marine radar images. The suite of systems allows us to compare the remote signals from breaking and non-breaking waves in both the microwave and optical bands over a large synoptic area of the nearshore zone.

The key individuals in this effort have been the PI along with Patricio Catalan (PhD Candidate, Coastal & Ocean Engineering, OSU). Bill Plant and Gene Chatham from University of Washington Applied Physics Lab were the owners and operators of the RiverRad system. We have also worked with the Coastal Imaging Lab (Rob Holman and John Stanley) in the collection and processing of the optical data.

Our synoptic combination of both marine radar and video observing systems allows direct comparisons between the two imaging mechanisms and will lead to a better understanding of the strengths and weaknesses of both for nearshore research and observational remote sensing. The main analysis approach has been to develop the joint pdf of the radar and optical signals and to use the joint pdf to clearly identify wave breaking events. The radar signals (from both systems) from these identified events are then analyzed in detail in order to quantify the signals from breaking waves.

Another key aspect of our approach has been the development of a nearshore scattering model for X-band radar. The purpose of developing a radar scattering model for the nearshore is that such a model is necessary in order to extract wave height estimates, the directional wave energy spectrum, and the fraction of breaking waves from radar data. Extracting these products will also lead to better bathymetric data products via incorporation of measured wave nonlinearity into depth inversion algorithms.

In our scattering formulation the wave roller is modeled as a single layer of water droplets above the underlying wave surface. The backscatter coefficient for this collection of scatterers is determined using the First Order Dense Media Radiative Transfer (DMRT) theory. Under this approach, scattering and absorption of the incident electromagnetic fields are accounted for including coherent and non coherent interactions between particles and also interactions with the media boundaries, in this case, the water surface. Collective scattering effects are included by means of the quasi-crystalline approximation (QCA) to account for the extinction coefficient of the dense media. The method requires a few physical input parameters such as the single particle size; total volume fraction; a stickiness parameter to account for clustering and the relative electric permittivity and operating microwave frequency. This approach is based on previous work regarding microwave scattering from snow.

Finally, our effort also includes collaboration with Drs. Jim Kirby and Fengyan Shi of the University of Delaware. Under their current ONR project, their objectives are to “develop a model for bubble injection, interaction, and evolution, transport and fate in a complex surfzone environment”. This process is intimately related to the remote sensing observations and the scattering of incident EM energy from the surf zone. We have supplied our optical data from previous laboratory experiments and are working with them on model/data comparisons.

WORK COMPLETED

- Conducted field experiment (MR-SENSO) involving three remote sensors: one Optical (ARGUS III) and two microwave (Marine Radar, X-band, HH,PPI, non-calibrated and RiverRad, X-band, HH/VV/Doppler, calibrated, staring)
- Calibration of marine radar using RiverRad.
- Analysis of MR-SENSO data
    - Characterization of the Probability Density Functions and Joint Probability Density Function associated with optical and marine radar data.
    - Qualitative assessment of the microwave scattering sources associated to different stages of the wave phase (non-breaking, steepening, active breaking, remnant foam)
    - Development and application of a detection method for individual wave breaking events based in the combined constant false alarm provided by both marine radar and optical imagery.
    - Quantification of the backscattered parameters associated to different stages of the wave phase. Relevant parameters under study are the normalized radar cross section and Doppler spectra at both polarizations (HH, VV) and the polarization ratio HH/VV.
    - Comparison of Doppler velocities against celerity estimates.

    (Much of the above work is summarized in Catalán, P.A, M.C. Haller, W.J. Plant, and R.A. Holman, Surf zone breaking wave identification using marine radar, *Proceedings of Coastal Engineering*: *31st Intl. Conf.*, ASCE, 2008. [in press])
- Development of nearshore scattering model
    - Actively testing our volumetric scattering model applicable to X-band scattering from the wave breaking roller in the surf zone.
    - Comparison of the volumetric scattering model predictions (cross-sections and polarization ratios) against field data.

RESULTS

Figure 1 shows the footprint of the different sensors along with the resolution of a single trigger for both active sensors. While both active sensors cover a significantly larger area than that of the video system, the analysis is focusing on the overlapping regions.

In order to calibrate the system, intensities from targets of known cross-section need to be calculated at different ranges to solve for the unknown constants in the radar equation. For the present case, a cross-calibration was performed in which the NRCS values of the ocean surface as measured at HH by RiverRad where linked to their synchronous intensity values as obtained by the marine radar system. Care was taken to remove from the calibration instances where the marine radar record showed zero intensity. Those points are associated with either backscattered power below the sensitivity of the system, or shadowed regions. In either case, those points would be uncorrelated with the RiverRad signal and would bias the calibration results. A set of 5 consecutive RiverRad runs (aggregate length of 10 minutes) at azimuthal angles Φ=18.0, 28.5, 36.5, 46.2, 55.0 degrees were used as reference and compared against a single marine radar run. Constants for the calibration equation were determined using a linear least squares fit. A sample of the result is shown in Figure 2.

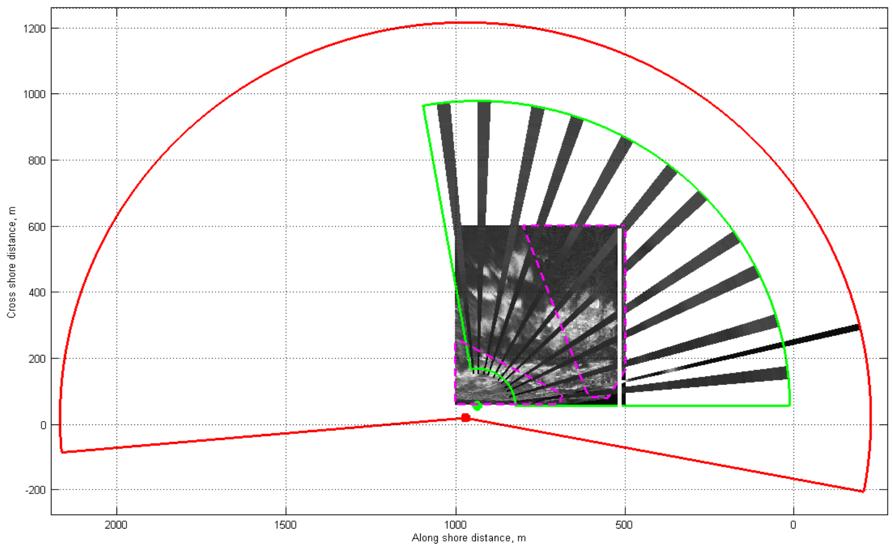

Figure 1: Field of view of the sensors, Red and green lines denote the swath covered by the marine radar and RiverRad, respectively. Ten sectors of the RiverRad scan are shown and also a single trigger from the marine radar. Merged ARGUS images are shown as background. Beach is located along bottom of the figure. Vertical white line is the FRF pier.

As can be seen, the overall trend is well recovered, showing good agreement in terms of dynamic range and overall response. However, there are some noticeable point-to-point differences between the calibrated signals. This can be related in part to the implicit assumption that the whole radar footprint would be covered by distributed scatterers, and that both systems will be reacting in the same way to those scatterers. It is known that some scattering mechanisms are sensitive to incidence and azimuthal angles, thus the slight differences in alignment, grazing angle, reported could explain part of the difference in NRCS values outside of the surf zone. The difference in elevation could also mean that waves shadowed for RiverRad might not be shadowed for the marine radar. As waves progress onshore and begin to break, the contribution of other scattering mechanisms could depend on their fractional area coverage of the radar footprint and therefore the difference in radar footprints could be also a factor.

For the rest of the analysis we focus on three different runs characterized by different degrees of surf zone “foamy-ness” as shown in Figure 3. JPDFs are estimated with a simple histogram method, by counting the frequency of occurrence of a given intensity (in the case of video) or NRCS pair in the ensemble of samples collected on a given zone throughout the run.

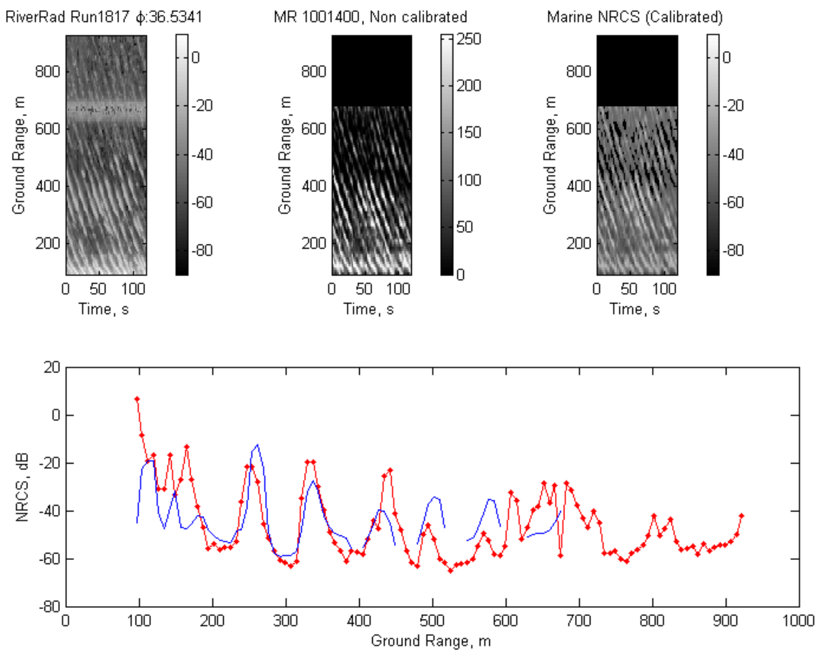

Figure 2: Example of the marine radar calibration. Upper row shows (left) NRCS (dB) timestack of RiverRad Run 1817; (center) the corresponding grayscale intensity from marine radar; (right) the resulting NRCS values of the marine radar run. Lower panel shows a time transect of the calibrated NRCS compared against the synchronous RiverRad measurement.}

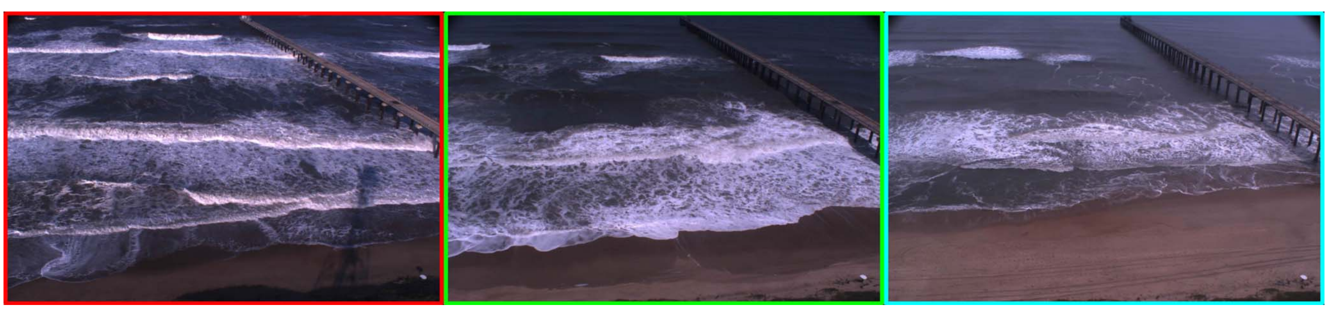

Figure 3: Video snapshots taken from Camera 1 for each of the three selected runs. Frame colors differentiate the runs 9 (red); 13 (blue); 18(cyan)}

The minimum number of usable samples (after removal of marine radar data with zero intensity) thus counted was of the order of 535000 (Camera 1, Surf zone, Run 18), whereas the minimum fraction of usable samples was 18% (Camera 1, Offshore zone, Run13), although values typically exceeded 60%. The joint and individual histograms were constructed using predefined 25 bins 11 intensity values-wide for video and 3 dB-wide for the case of marine radar. In the case of the latter, the variable of interest the cross-calibrated NRCS (σ_0) in order to minimize possible range dependencies. For simplicity, results are presented in terms of the field of view of Camera 1 for both sensors. Results from the other cameras show similar behavior unless noted otherwise.

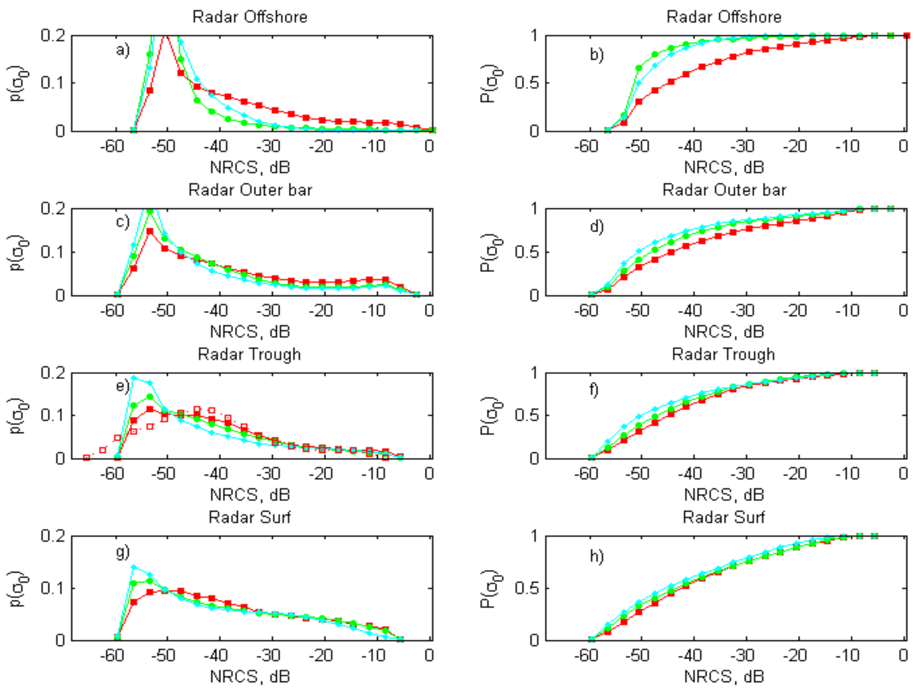

Figure 4: Probability (left) and Cumulative (right) Density Functions for the video data taken from Camera 1. Top to bottom correspond to measurements taken in the Offshore, Outer Bar, Bar trough and Surf zone boxes, respectively.(□) Run 09; (o) Run 13; (◊) Run 18.

Figure 4 shows the probability distributions obtained for the video data, the left column showing the PDFs and the right column showing the corresponding CPDFs. It is possible to notice that, in general, the PDF's come in three shapes. The first type shows the expected peak at low intensity values, which accounts for a large fraction of the data, for instance, the offshore series for run 18 (cyan series in Figure 4a). This corresponds to non-breaking waves, which modulate the incident radiance on the sensor as a function of the wave slope. The resulting signal has a relatively narrow dynamic range that spans a few bins of the histogram thus explaining the spikiness of the PDF. It can be noticed as well that though the shape of the is preserved, the curves are offset between runs owing to changes in the camera settings such as shutter speed and aperture, which were allowed to be adjusted freely between runs depending on the illumination conditions. Additionally, the color of the sea surface will change depending on ambient conditions. However, these differences between runs are not considered relevant because we are interested primarily in a qualitative assessment of the signal.

A second type of shape can be identified as a low magnitude spike followed by an exponentially decaying tail. This kind of behavior would be expected of zones where breaking takes place with some degree of foam persistency. This can be seen for instance in the trough (see Figure 4e), most notably for runs 13 and 18 when foam showed less persistency according to the snapshots (see Figure 3). It is of note that for some cases both the PDF the CPDF are characterized by steep increases in value at low intensities, suggestive that a large fraction of the time the signal falls back to the level of non-breaking waves, suggesting either intermittent breaking or low foam persistence. As foam persistence becomes more pronounced, the tail of the distribution begins to contribute to a larger fraction of the PDF and the low intensity portion of the PDF and CPDF curve becomes less steep. The reason for this is the simultaneous presence within the field of view of patches of remnant foam persisting between waves and patches of dark water associated with non-breaking waves. An extreme case of this behavior occurs for Run 18 in the surf zone, where the PDF exhibit a bimodal distribution, with a clear peak at low intensities and a secondary peak at somewhat larger intensities. This is further exemplified in Figure 5, where it can be seen that the PDFSs obtained from single point time series do not deviate significantly from the ensemble PDF for Run 9 and Run 13. Run 18 seems to indicate that the ensemble PDF could be the result of averaging time series showing a larger variability.

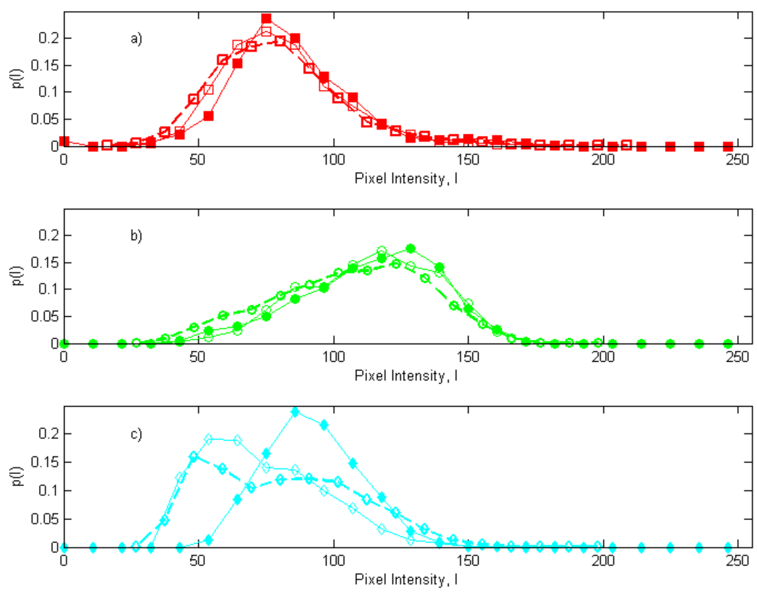

Figure 5: Comparison of single-point and ensemble PDFs for the video data taken from Camera 1 in the surf zone. Top to bottom correspond to different runs. Solid lines are histograms obtained from the time series at two random points within the field of view. Dashed lines correspond to the PDF of the ensemble of data within the field of view.

Up to this point the analysis of the scattering sources has relied on prior understanding of the video PDF, which enabled us to characterize the presence of foam but not necessarily distinguish it from active breaking. The same analysis is less conclusive for the radar PDF although there are some strong indications that the presence of breaking and/or foam have a clearly defined signature in the PDF, namely an inflexion point followed by secondary peak at NRCS values larger than -30 dB. In order to overcome the apparent limitations of using both sensors independently, it is possible to combine the information in the joint probability density function. This procedure enables the characterization of the scattering sources as seen by the radar sensor based on their optical signature, under the hypothesis that the brightest optical signals ought to be associated with active breaking.

Figure 6 shows the JPDFs for all the zones and runs considered. It can be seen that for almost all cases the peak of the JPDF occurs at relatively low video intensities and low backscattered power. This is consistent with the notion of scattering from unbroken waves occurring for a large fraction of the wave phase thus accounting for a larger fraction of the JPDF. When only non breaking waves are present (thus darker video intensities), it is found that the JPDF is concentrated over an axis spanning a relatively narrow range of video intensity bins but spread over a wide range of radar NRCS bins (e.g. Figure 6 b) and c)). This can be explained in terms of a modulation of the signal by the wave slope, which induces a relatively large dynamic range for the NRCS in accordance with the CST. One interesting detail present in for instance in Figure 6 (c) is the presence of events that are very dark (in a video intensity sense) but associated with relatively large scattered power (larger than -30 dB). This means that strong scattering occurs for dark video faces which are caused by the front of steep unbroken waves, another indication of scattering in accordance to CST. A similar behavior can be seen in the trough for decaying wave heights(Figure 6h and 6i), but the signal shows a somewhat broader video range making the conclusion less obvious. A secondary axis is also apparent in other cases (e.g. Figure 6a, 6e, 6f). This vertical axis spans a wide range of video intensity bins but a relatively narrow range of backscattered power. This pattern could be explained as remnant foam (which induces a wide video intensity dynamic range) not scattering strongly from microwaves.

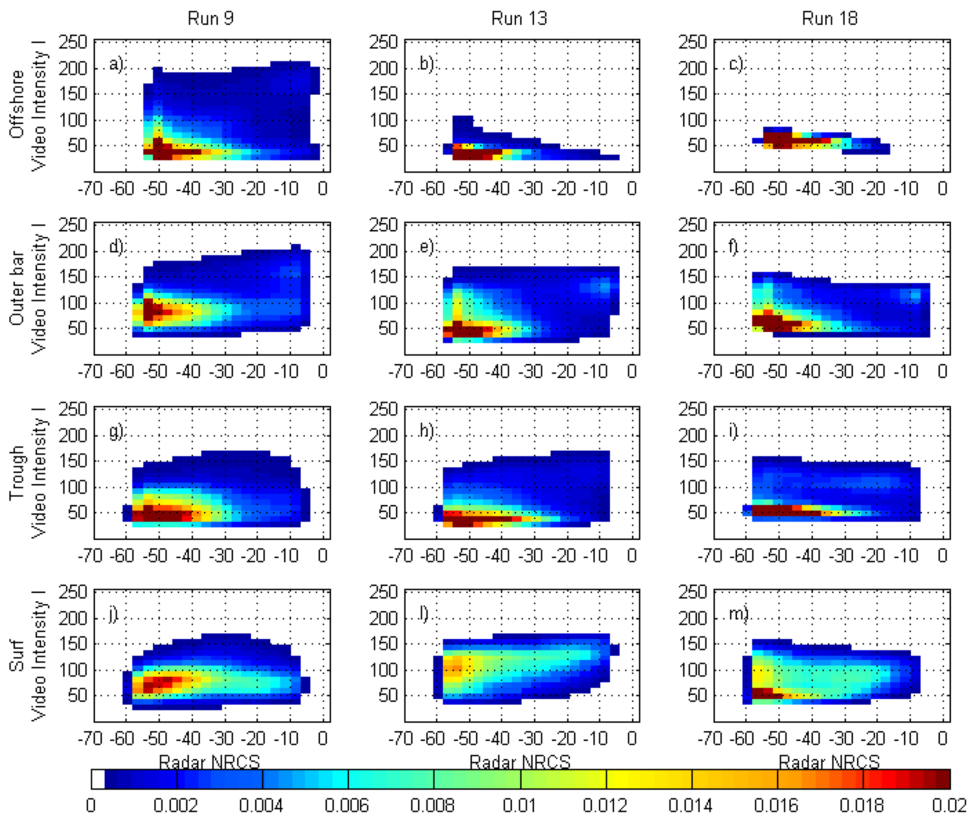

Figure 6: Joint Probability Density function for video (Camera 1) and Marine radar. Columns correspond to Runs 9, 13 and 18, respectively. Rows correspond to zones within the surf.

With the identification of these two axis in the JPDF it is possible to identify unbroken waves, very steep waves and to some degree, foam. The presence of active breaking in turn could be associated with large video intensity indices and large radar backscattering. Accordingly we can see that many of the zones exhibit a local peak in this region of the JPDF (e.g. Figure 6 a, d, e, f, h, and i). The presence of this peak suggests a clear separation between foam and active breaking for both sensors, apparently validating the assumption that foam is the source of less intense optical returns than active breaking.

Consequently, the results are consistent with intermittent breaking taking place in the offshore zone and outer bar for Run 9, when wave height was the maximum; or in the outer bar for the other two environmental conditions. It is of note as well that for these zones and conditions, the axis previously identified are clearly defined suggesting a clear separation between the signals.

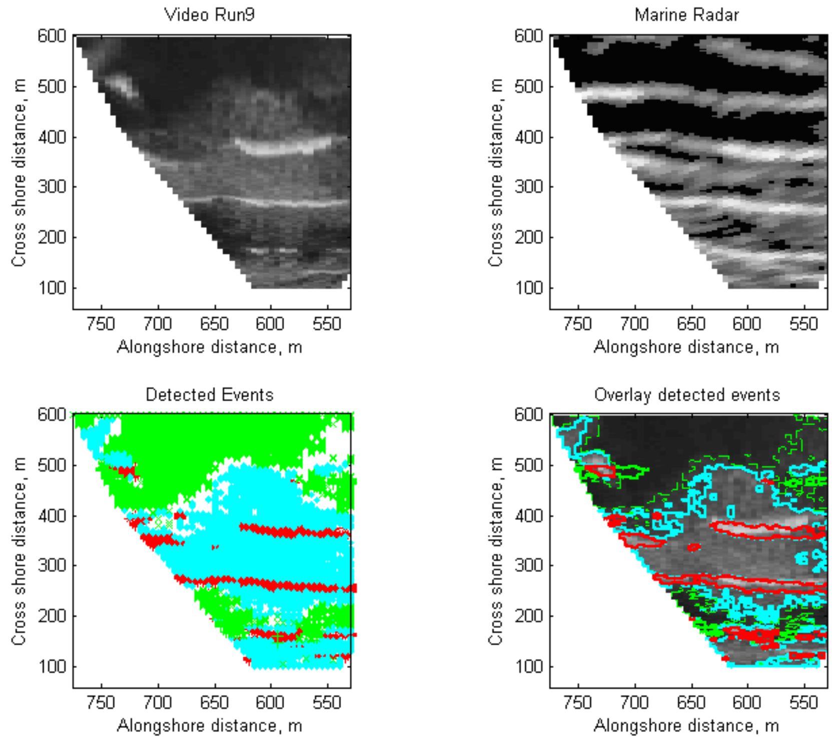

Figure 7: Combined breaking detection (Run 9). Red markers denote breaking; cyan denote remnant foam; thin green lines denote dark video patches and thick green lines denote steep waves.

Figure 7 demonstates the identified breaking events using the combined results from both optical and microwave sensors.

IMPACT/APPLICATIONS

This research program directly supports the Navy goal of predicting the 4D nearshore environment for amphibious operations that involve surf zone breaching. Our effort specifically involves improving our understanding of the fundamental relationships between nearshore hydrodynamic processes and remote sensing observations of these processes from multiple remote sensors. We utilize this understanding to improve our ability to numerically simulate and, hence, predict the time and space variability of the nearshore environment. In addition, the initial results from this project suggest that marine radar is an effective tool for filling in the gaps between very nearshore observing systems (video) and larger scale observing systems (such as HF radar, satellites).

RELATED PROJECTS

- *Kirby and Shi, ONR-CG core program* – development of a model for bubble injection, interaction, and evolution, transport and fate in a complex surf zone environment. Their work will inform our bubble distribution model and both efforts can eventually be coupled to form an overall sensor performance model.
- *Arete Associates ("Mud Flats"), ONR-STTR* – our ongoing work under subcontract to Arete involves the polarimetry of light reflected from the ocean surface. This work will better inform the scattering matrix at the air/water interface.
- R. Holman/Coastal Imaging Lab (Coastal Geosciences funding)—we are active collaborators in remote sensing data analysis and interpretation.
- Nathaniel Plant, USGS—we are actively collaborating on wavenumber estimation methods (see Plant et al., 2008) and on incorporating regular radar data products into ongoing Beach Wizard runs at Duck, NC.

PUBLICATIONS

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HONORS/AWARDS/PRIZES

2007 Editors' Citation for Excellence in Refereeing, *JGR-Oceans*