

Hydrodynamics and Roughness of Irregular Boundaries

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Award Numbers: N00014-10-1-0414, N00014-11-1-0440
<http://www.soest.hawaii.edu/OE/pawlak/>

LONG-TERM GOALS

The research goals of the work target accurate parameterization and modeling of nearshore waves, currents and turbulence in complex reef environments. A central theme of this work is the response of steady and oscillating flow to highly irregular, broad-banded roughness. Previous ONR supported study by the PI's group have quantified reef roughness, examined the hydrodynamic response to a variable roughness at small scales and explored the relationship between hydrodynamic and physical roughness.

OBJECTIVES

Specifically, the work aims to examine methods for quantifying physical roughness scales in reef environments using an autonomous underwater vehicle (AUV) and to determine the hydrodynamically relevant roughness scales for wave and current flow.

The work underway is also enabling development of a series of practical applications including examination of the relationship between measured roughness and sidescan imagery, exploration of AUV-based ADCP observations for resolution of steady flow boundary layer dynamics, and implementation of new tools for measurement of turbulent stresses in wavy environments. In addition high-resolution reef morphology data will enable further study on the correlation between roughness and other measurable reef characteristics including coral color, health and species.

APPROACH

To achieve the objectives detailed above, we have been conducting a series of focused field experiments targeting resolution of flow hydrodynamics over a range of reef environments in varying wave and current conditions, with concurrent high resolution roughness mapping. Additional observations have also been carried out that leverages funding from the Army Corps of Engineers in collaboration with Mark Merrifield (UH Oceanography).

Observations have focused primarily on forereef regions at each site, where roughness height is small relative to the depth and wave breaking can typically be neglected. Results from these simpler

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE 30 SEP 2011		2. REPORT TYPE		3. DATES COVERED 00-00-2011 to 00-00-2011	
4. TITLE AND SUBTITLE Hydrodynamics and Roughness of Irregular Boundaries				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Hawaii at Manoa, Department of Ocean and Resources Engineering, 2540 Dole St., Holmes Hall 402, Honolulu, HI, 96822				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

domains can then provide a foundation for examining more complex roughness environments. The field experimental plan for each site features one or two bottom-mounted instrument packages, each with an upward looking 1200 KHz ADCP with 3 ADVs deployed on a nearby vertical spar, alongshore from each other and separated by roughly 200m, at depth of between 10 and 20 m. These packages target resolution of velocity profiles and Reynolds stresses. Instruments were deployed at each site for a period of about two weeks to resolve a range of wave and current conditions.

In order to quantify the relationship between the hydrodynamic response and the physical characteristics of the reef, we have carried out high-resolution roughness surveys at each site using a REMUS AUV equipped with a narrow beam acoustic altimeter and sidescan sonar. Surveys consist of dense 'mow' patterns in both along- and cross-shore directions with the vehicle operating at altitudes of 3-5 meters above the bed at depths ranging from 5 to 30 m (see figure 1). For the Kilo Nalu site, this covers an area of roughly 0.5 km².

We have also carried out AUV 'hydrodynamics' surveys at each site targeting the spatial evolution of current BL structure in response to the variable reef roughness. Our earlier work has shown that the REMUS ADCP can be effective in resolving steady BL structure with spatial averaging of 50-100m (Jaramillo & Pawlak, 2010). Analysis of along-track velocities has shown evidence of weak velocity bias in the direction of platform motion (figure 2) in agreement with other observations from vessel and AUV-mounted ADCPs (Fong & Monismith, 2004; Fong & Jones, 2006). In Jaramillo & Pawlak (2010), we further characterize the variability in this bias with sampling. Cross-track velocities have not shown any evidence of bias, however. Surveys thus focus on repeated cross-shore transects over the course of a tidal cycle to enable resolution of along-shore velocity profiles.

One postdoctoral researcher, Sergio Jaramillo, has been supported in part by this ONR project. The project has also provide partial support for research technicians, Kimball Millikan and Chris Colgrove, who have participated in field operations and experiment design.

WORK COMPLETED

The first year of project focused on quantitative characterization of substrates and corresponding roughness in coral reef environments along with investigation of AUV capabilities for detailed hydrodynamic measurements. The UH REMUS AUV was also outfitted with a narrow-beam (2.5° beam width) altimeter with a sampling frequency of up to 18Hz, which enables resolution of small-scale bed roughness over hydrodynamically relevant scales. In the second year of the original project (N00014-10-1-0414), we have completed analysis of substrate characterization (Jaramillo & Pawlak, 2011) and are continuing analysis of new roughness data. A follow-up project (N00014-11-1-0440) has funded new observations with analysis ongoing.

The first series of AUV surveys were carried out at the Kilo Nalu Observatory on the south shore of Oahu (Pawlak et al, 2009) in 2010. A full set of AUV surveys, with fixed-point turbulence measurements at 10m depth and cross-shore wave observations, was obtained in Dec. 2010 on the north shore of Oahu (figure 1). The observational period featured wave heights over 4m. Field observations were carried out at multiple sites around the island system of Palau in March 2011, in collaboration with researchers at UCSD SIO and Cal Poly (Terrill, Moline). The AUV and fixed-point observations focused on two sites: a current dominated lagoon patch reef and a wave-dominated reef pass. In addition a number of joint AUV surveys were carried out over a range of environments

including river mouths, reef flat and fore-reef sites. Further AUV surveys and bottom turbulence measurements were carried out along the eastern Guam coast in August 2011.

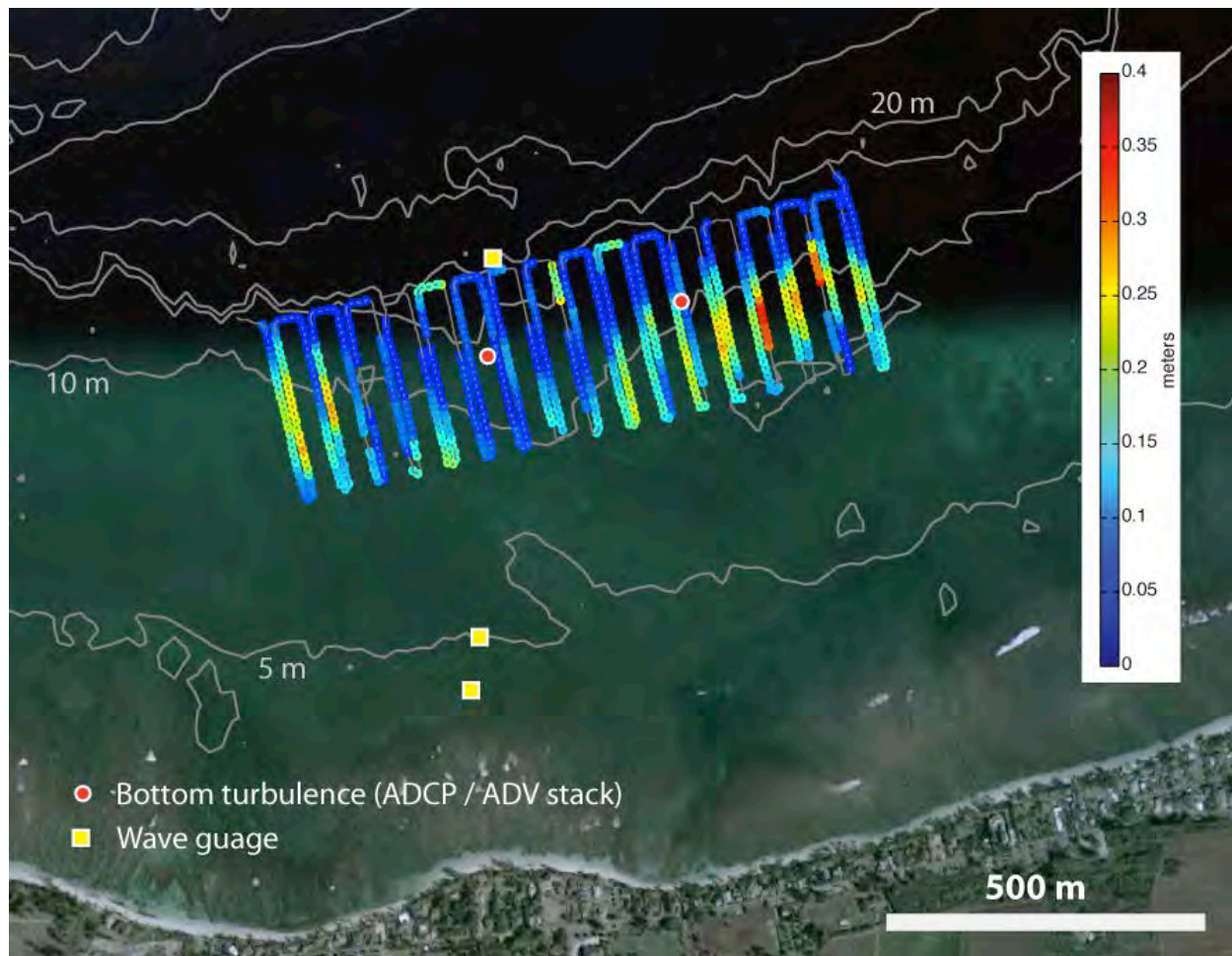


Figure 1) Aerial image of North Shore Oahu study site (Mokuleia). Roughness data from one survey is overlaid with LIDAR bathymetry.

RESULTS

The AUV resolves bed features at a horizontal resolution of ~ 5 cm for sidescan backscatter data, and ~ 10 cm for altimeter data. Compared to boat-derived roughness measurements (Nunes & Pawlak 2008), the use of an AUV for this task improves the quality and resolution of the data obtained by increasing platform stability and by maintaining a near-constant acoustic footprint for the altimeter-based roughness measurements. Methodologies for substrate characterization along with roughness characteristics for the Kilo Nalu reef are detailed in Jaramillo & Pawlak (2011). Given general substrate classifications from sidescan data, physical bed roughness is assigned for rough reef, bare reef and sand. For the Kilo Nalu surveys, rms roughness over wavelengths between 0.2 and 0.6 ranged from 3.3 cm for bare reef to 7.3 cm for rough reef areas. Roughness data from north shore Oahu surveys, shown in figure 1, show higher roughness values (0.2-0.3 m) that correlate well with the 10m

isobath over the region shown. Further analysis of additional survey data from this site and others is presently underway. Ongoing efforts are being directed to the identification of hydrodynamically relevant length scales for flow over coral reefs. The RMS roughness values measured during this study are an initial step in that direction.

Observations at each site have also included a series of AUV surveys targeting the spatial structure of the flow field and water properties at each site. Observations of currents have been complicated by bias in DVL data in the direction of vehicle motion, as mentioned above. Each survey, therefore, includes legs in opposite directions, centered on fixed-point current measurements to assess DVL performance. Profiles of bias velocities (figure 2) can then be determined and analyzed. Observations reveal a bias that typically shows a decaying profile near the vehicle with an increase with distance beyond some threshold range. Preliminary analysis indicates that the bias is dependent on acoustic backscatter levels.

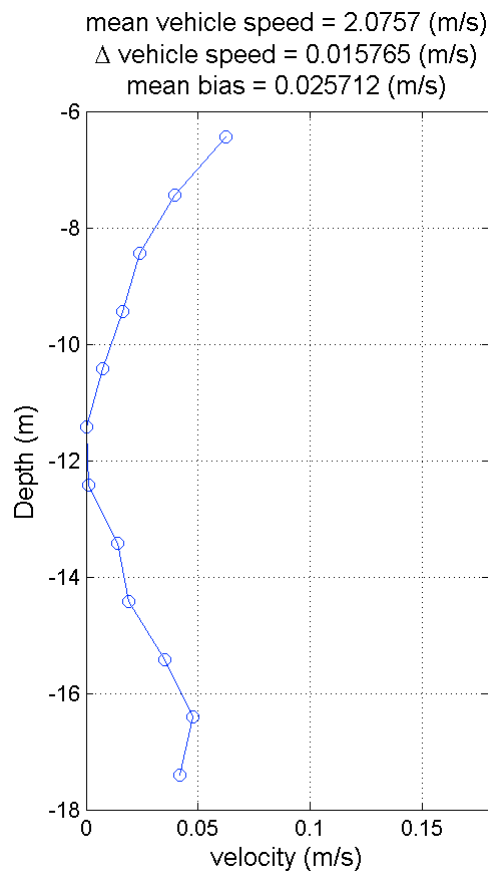


Figure 2) Sample profile of DVL velocity bias from AUV surveys at Kilo Nalu.

IMPACT/APPLICATIONS

Coral reefs are a dominant feature of coastal environments at low latitudes. Effective littoral operations in reef environments require accurate prediction and modeling of wave and current dynamics over complex boundaries as well as characterization of acoustic and optical processes. Turbulent processes

at the seabed are at the foundation of littoral hydrodynamics with the bed shear stress as a key parameter affecting dissipative and dispersive mechanisms.

In addition to direct effects on nearshore hydrodynamics, turbulence over rough beds influences optical and acoustic properties. Bed roughness also directly affects acoustic propagation in the coastal zone. The observations described here will enable more general characterization of bed morphologies in reef zones and will establish foundation for remote sensing of bed characteristics from aerial and satellite imagery. Beyond applications in coral reefs, the research is extending understanding of hydrodynamics of flow over complex boundaries in general.

The work described above has enabled new research applications focusing on benthic roughness mapping and classification, which have implications for nearshore wave and current modeling. Combined with direct measurements of roughness from a narrow-beam altimeter recently added to the UH AUV, sidescan imagery can provide valuable 2D context, enabling substrate identification and classification in complex reef environments. These observations can potentially be correlated with remote sensing methods to provide benthic classification with more extensive spatial coverage.

The detailed analysis of AUV DVL performance, underway as part of the ongoing work, is critical for development of AUV-based spatial hydrodynamic sampling. AUV spatial surveys can, in turn, provide a key tool for assessment and characterization of nearshore processes on complex coastlines.

RELATED PROJECTS

The work discussed here has been directly motivated by results from earlier ONR funded projects including a Young Investigator grant that focused on wave boundary layer dynamics and led to the establishment of the Kilo Nalu Observatory. Further ONR support has focused on internal tide effects on currents at Kilo Nalu. The REMUS AUV was acquired via an ONR DURIP. S. Jaramillo was also supported as a postdoc via an ONR grant to develop AUV capabilities at Kilo Nalu. Ongoing NSF-funded projects at Kilo Nalu are focused on wave and current boundary layer turbulence in the context of benthic geochemical exchange and stratified turbulence.

A USACE funded project (PI: Merrifield) targeting wave transformation and coastal flooding for island shorelines includes AUV-based roughness surveys at Guam, is enabling extension of the work described here providing an additional data set for analysis.

A newly funded NOAA Sea Grant project (2012-2014) will include collection of benthic substrate and roughness data for a large contiguous area (~8 km²) on the south shore of Oahu. In addition to providing further data for the analysis described here, the project will support development of new AUV-based benthic mapping applications.

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PUBLICATIONS

The following publications have been produced under support of this project.

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Jaramillo S. and G. Pawlak, AUV-based observations of rough bed hydrodynamics, *Proceedings IEEE AUV2010 Conference*, Monterey, September 2010