Roadmap: Technologies for Cost Effective, Spatial Resource Assessments For Offshore Renewable Energy

Annual Report

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Award Number: **M10PC00096**
www.mrec.umassd.edu

LONG-TERM GOALS

It has been estimated that the renewable energy in the oceans (offshore wind, waves and tides) could provide all of the world's demand for electricity, but many challenges must be met prior to realizing even a small fraction of that potential. One of the challenges is the ability to sense the resources and their surrounding environments. Today the standard is to place a fixed structure in the ocean or to have people periodically visit a location to do assessments. This is unacceptable for two reasons:

1) Cost – The costs of a ocean meteorological (Met) tower is in the range $2-4 million. Site surveys are less expensive, but they are manpower intensive, and it is difficult to acquire simultaneous observations.

2) Spatial Information – There is a need to measure environmental parameters from the seafloor through the top of the marine atmospheric surface boundary layer, and over areas of hundreds of square miles. Current techniques, for example using anemometers, current meters and wave buoys, provide information only at discrete points, and understanding spatial correlations requires careful inter-calibration and maintenance of separate sensors. This is difficult enough on land, where there is generally easy access to the instruments, but is unrealistic at sea. By

contrast, remote sensing technologies can provide continuous observations over extended spatial regions (in either the horizontal or vertical). Such information can be applies by developers and operators of wind and MHK power conversion devices for a wide range of tasks from local control and response optimization to predicting short-term fluctuations in winds, waves and currents, to long-term resource assessment.

The New England Marine Renewable Energy Center (MREC) is funded under National Ocean Partnership Program (NOPP) solicitation, M10PS00152 to develop a roadmap for cost effective, spatial resource assessments for offshore renewable energy development.

OBJECTIVES

The objectives of this effort are to review the current state of technology available for remote sensing of ocean energy resources, conducted additional testing as necessary to answer questions concerning capabilities of technologies, and to develop a roadmap document to asses how these technologies can be employed to address the ocean renewable energy industry needs.

APPROACH AND WORK PLAN

To accomplish this broad scope of work MREC assembled a team of leading researchers from four academic institutions: the Universities of Massachusetts Dartmouth (UMD), Massachusetts Amherst (UMA), Hawaii (UH), and Washington (UW); the Woods Hole Oceanographic Institution (WHOI); and three companies: Battelle Memorial Institute (BMI), Imaging Sciences Research (ISR), and Teledyne RDI (TRDI). The team is led by John Miller, UMD, Project Lead, and Dr. Eugene Terray, WHOI, Technical Lead.

Remote sensing techniques can be characterized by the range of spatial scales they can cover.

Long Range: HF phased array radar (ISR, UH and WHOI).

Task 2. Statistical characterization of winds, waves and currents over large area.

HF radar has the potential to assess winds, waves and currents over an area of several hundred square kilometers. This information can be used for resource assessment and for forecasting on the order of hours. This information would be of great value to grid operators seeking to balance load and generation. The use of these devices to map currents is well-established, but work needs to be done to demonstrate their ability to remotely sense winds and waves.

Intermediate Range: Doppler microwave radar (UW and ISR).

Task 3. High resolution, spatial imaging of wind, waves, currents, and bathymetry

It is well-accepted that Doppler microwave radar can provide high resolution maps of winds and waves over areas of order a few square kilometers. Currents and bathymetry can be inferred indirectly by their effect on wave propagation, although the spatial resolution and accuracy of this technique remains to be demonstrated. These radars can provide “look-ahead” measurements of wave height and direction with prediction on the order of minutes possible.

This would be useful for prediction of extreme events (i.e. Large waves that might endanger maintenance personnel.) and for real-time control of wave power devices. They can also provide spatially-detailed information about the waves in topographically complex areas that can be used in decisions concerning siting.

Short Range: Wind and current profiling and bottom surveys (UMA, UMD, TRDI and WHOI).

Task 1. Vertical wind profiling from buoys and small boats.

Vertically-profiling LIDAR (and possibly SODAR) has the potential to replace fixed meteorological towers with inexpensive floating platforms to provide measurements of the mean wind and turbulence profiles over the rotor disk of large wind turbines. We currently are conducting a review and evaluation of several commercially-available systems, and their suitability for use from moving platforms. 3D scanning Lidar has the potential to map winds over areas of tens of square kilometers, and hence in many applications might be shore-based.

Task 5. Surveys of the sub-bottom, bottom sediment, and benthic biotic communities using automated underwater vehicles (AUVs).

This technique has the potential to significantly improve spatial resolution and spatial coverage as compared to diver surveys. We are testing various optical sensors from a AUV to determine exactly what information can be obtained, and what additional information will be required (grab samples, etc.) to interpret the AUV-based spatial maps.

Task 4, Mapping of currents and waves using Doppler sonar.

Doppler sonar can sense currents, waves and turbulence, and has the potential to provide look-ahead observations of waves and turbulence that can be used for active control of both wave converters and underwater turbines. Outstanding issues that we are investigating are how well individual wave trains can be measured in real-time, and how well individual coherent turbulent motions can be diagnosed.

Task 6. Geo-referencing and data management.

This task was included in anticipation of the challenges posed by spatially-diverse measurements in order to properly geo-spatially aligning these data. This task was not directly funded as part of this proposal, and specific requirements will be defined as data becomes available.

RESULTS

A program review was conducted on October 18th and 19th at the National Renewable Energy Lab (NREL), Wind Technology Test Center. NREL personnel provided a tour of the NREL test center, background briefings on the status of ocean energy development and acted as a "voice of the customer" to better define the data needs of the industry. The Principal Investigator (PI) from each organization reviewed his progress, and the program status was updated. These are included here as Attachment 1.

Roadmap: Technologies for Cost Effective, Spatial Resource Assessments For Offshore Renewable Energy

The program, as a whole, is progressing satisfactorily. Production problems with the UH HF radar, weather issues at the radar test site, some delays in establishing the various subcontracts, and scheduling obligations for some PI's have resulted in a some delays, but no impact on the final delivery is anticipated. The original schedule had the most demanding task, testing of four radars, scheduled for the Fall of 2011, and other analysis tasks anticipated to be completed by the end of 2011, with time for additional testing and analysis in 2012. The radar testing has been delayed until Spring of 2012, leaving sufficient time for analysis and report writing.

Specific comments by task follow:

Task 1. High resolution wind profiling from buoys and small boats.
Significant data has been assembled, but much of the remaining information is proprietary and requires further discussions with the relevant companies.

Task 2. . Statistical characterization of winds, waves and currents over large area. Supplier issues and loss of critical personnel at UH have resulted in a delay in final equipment assembly until the end of 2011, with delivery of the instrument to WHOI in the spring of 2012. ISR already has operating radars at the test site. Their analysis of existing data confirms the ability of their HF radar to measure wind direction and wave spectra at large distances, confirming the usefulness of this technology in mapping waves, currents and wind direction over a wide area and for forecasting hours into the future for grid operators. Questions on optimal wavelengths and other configuration issues will be addressed with the side by side testing of the UH and ISR units.

Task 3. High resolution, spatial imaging of wind, waves, currents, and bathymetry.
ISR is currently field-testing its microwave Doppler radar. Analysis of existing data confirms the ability to measure wind speed and direction, wave spectra to distances of several kilometers. The data demonstrate the usefulness of this technology to image and deterministically-predict the evolution of oncoming waves, which can provide for extreme event warnings and is useful for active control of wave power devices.

Task 4. Mapping of currents and waves using Doppler sonar.
Initial testing and data analysis have demonstrated the advantages of horizonally-oriented profilers using both vertically-fanned and pencil beams to more accurately measure waves and turbulence at high resolution.

Task 5. Surveys of sub-bottom, bottom sediment, benthic biotic communities using AUVs.
On going physical survey of biota has been repeated with optical devices on AUV's, with excellent results. Continued optical monitoring will be supplemented with acoustic devices and vision recognition software evaluated. The complexity of assessing biota on the sea bottom and sub-bottom will require some ancillary physical survey information. The testing to date demonstrates that sensors on AUV's will be usable in minimizing the number of physical sample locations required and great extending the areas surveyed to better map critical habitats.

Task 6. Geo-referencing and data management.
No requirement for this task has yet been noted.
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IMPACT AND APPLICATIONS

It is still early in the project for it to have specific impacts. However, we review below areas where our work is likely to have application.

National Security (Delete this section if there are none)

Many of the technologies being reviewed here were developed for Department of Defense applications. The use of these technologies in new ways will inevitably lead to improved methods of deployment, signal processing, etc. The commercialization of these technologies will potentially result in lower cost production and, therefore, lower acquisition costs. For example, the phased array HF radars being tested here are less than 25% of the cost of existing commercial devices.

Economic Development (Delete this section if there are none)

The ability of provide spatially-resolved measurements over a large area will significantly reduce the costs of resource assessment and device siting, in connection with the development of offshore renewable energy sources, thereby accelerating the growth of this potentially billion dollar industry. Further, the ability to provide wind and wave forecasts hours in advance will aid grid operators in more effectively managing the electrical system, and the owners of the generators in pricing their power on the spot market.

Quality of Life (Delete this section if there are none)

A major issue with renewable energy sources is that they tend to be intermittent and unpredictable. Thus, continuous, baseload, generation that usually includes carbon sources cannot be taken off line because of the unpredictability of renewables. Accurate forecasting hours into the future would allow some of these sources to be taken off line, reducing fuel costs and carbon release.

Science Education and Communication (Delete this section if there are none)

The images produced by mapping resources over large spatial areas provide highly effective teaching aids for meteorology, renewable resource appreciation, and resource management. The increased bottom coverage provided by AUV surveys will greatly increase the access that students and researchers have to benthic communities.

TRANSITIONS (For the 4 NOPP evaluation factors below, please describe how the results (hardware, software, knowledge) are being utilized by others. Transition is taken to mean, “products which are being incorporated into more developmental (or operational) programs or have already been incorporated in other’s plans.”)

National Security (Delete this section if there are none)

HF over the horizon radar is being investigated by the Department of Homeland Security for the detection of small vessels operating close to shore.

Economic Development (Delete this section if there are none)

Increased production of HF radars will reduce manufacturing costs and make these detection systems affordable for non-DOD Homeland Defense agencies.

Quality of Life (Delete this section if there are none)

The mapping and continued monitoring of renewable energy resources provides a very effective coastal zone management tool, allowing the integration of ship tracking and other ocean uses.

Science Education and Communication (Delete this section if there are none)

In a few sentences, please describe the transitions related to Science Education and Communication.

RELATED PROJECTS

The New England Marine Renewable Energy Center (MREC) has proposed a Northeast Offshore Renewable Energy Innovation Zone (NOREIZ) for the study of ocean renewable energy in the Atlantic Ocean. Two test sites have been identified (a tidal site in Muskeget Channel and an offshore wind test site south of Nantucket) and resource and environmental surveys are in progress. To the extent possible, the work provided in this study will be applied to those surveys.

REFERENCES (*DELETE THIS SECTION IF THERE ARE NONE)*

References are provided by the individual investigators.

OUTREACH MATERIALS *(DELETE THIS SECTION IF THERE ARE NONE)*

Photos are provided in individual investigators presentations.

Attachment 1

National Ocean Partnership Program

Roadmap for Cost Effective, Spatial Resource Assessments
for Offshore Renewable Energy

Program Review
19-19 October 2011
National Renewable Energy Lab National Wind Technology Center
Boulder, CO

Program Goals and Schedule Status		J. Miller
Program Technical Overview		E.Terray
<u>Principle Investigator Status</u>	<u>Task</u>	<u>Author</u>
The Use of Doppler Sonar for Wave and Turbulence Measurements in Support of Offshore Renewable Energy Development	4	Blair Brumley, Jerry Mullison
High Frequency radar activities, University of Hawaii	2	Pierre Flament
Capabilities of AUV's for Environmental Assessment	5	Brian Howes
High Resolution Wind Profiling from Buoys, Platforms, and Small Boats	1	Jon McGowan
Measurement of Winds, Currents and Waves with Coherent Microwave Radars	3	William Plant
HF & Coherent Marine Radars for Ocean Wave Spectrum and Surface Current Measurement	2 3	Dennis Trizna

Program Review

Roadmap: Technologies for Cost Effective Spatial Resource Assessments for Offshore Renewable Energy

Contract M10PC00096
Bureau of Ocean Energy Management (BOEM)
Department of Interior

John R. Miller
Project Lead
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508.999.MREC (6732)

Agenda

MREC

Contract Review

Project Goals

Schedule

Marine Renewable Energy Center

Purpose

Foster the Sustainable Growth of Marine Renewable Energy (Tidal, Wave, Off-Shore Wind, and Others) In New England Through Research, Development and Demonstration

Mission

The New England Marine Renewable Energy Center (MREC) is an organization that involves all stakeholders (Academic, industry, governmental/regulatory, and public interest groups) to promote the sustainable development of renewable energy in New England ocean waters.

- A world class university research consortium.
- Permanent ocean test sites to facilitate research and demonstration.
- An industry user group to elicit research needs and to assist in advocating.
- Involvement of public interest groups to minimize ocean ecosystem impact.
- Education and training to support the marine renewable energy industry.

New England Marine Renewable Energy Center
MREC

University Research Consortium Members

UMASS DARTMOUTH
ADVANCED TECHNOLOGY & MANUFACTURING CENTER

MIT

UNIVERSITY of NEW HAMPSHIRE

University of Massachusetts Amherst 1863

University of Massachusetts UMASS Boston.

UMass | Dartmouth

SMAST

UNIVERSITY OF Rhode Island

WOODS HOLE OCEANOGRAPHIC INSTITUTION

Roger Williams University

University of Connecticut

UVI St. Croix, USVI
OTEC

MERC³
Maritime & Energy Research Campus & Commercial Cluster

The University of Edinburgh

Urban Harbors Institute

Contract Review

Contract

- National Ocean Partnership Program
- Contract in Response to BAA M10PS00152, Topic 4

  Evaluation of Environmental Monitoring Technologies for Offshore Renewable Energy

  - Contract Award Number: M10PC00096
  - Contract Period: 24 Months
  - Key Personnel

    Contraction Officer: Contracting Officer – Lisa Algarin

    Contracting Administrator – Joanne Murphy

    Contracting Officer's Representative – Angel McCoy

    Project Lead: John Miller, j2miller@umassd.edu, 508.999.6732

    Technical Lead: Eugene Terray, eterray@whoi.edu, 774.392.0070

Partners/Principle Investigators

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University of Washington
Dr. William Plant, PI, plant1944@gmail.com,206.543.7836
Imaging Science Research
Dr. Dennis Trizna, dennis@isr-sensing.com,703.801.1417
Teledyne RD instruments
Jerry Mullison, jmullison@teledyne.com,858.842.2600

Focus Areas for Research

- High resolution wind profiling from buoys & small boats
- Spatial mapping of winds, waves and currents over a large area
- High resolution imaging of winds, waves, currents & bathymetry
- In-situ measurements of waves and currents using Doppler sonar
- Automated surveys of bottom sediment and biotic communities
- Geo-referencing and data management
- Other? (Not addressing hydrography, wind turbine control)

New England Marine Renewable Energy Center
MREC

Focus Areas for Research

High resolution wind profiling from buoys and small boats

- Applications: Site resource assessment, turbine dynamics (wind loading; wake interaction, real-time control)
- Data requirements: Well-resolved profiles of mean winds & turbulence (gustiness) over the blade span (~150m for 3.6 MW GE offshore turbine)
- Instrumentation: Radar, Sodar, Lidar, Other?, Platforms (buoys)
- Investigators: McGowan (UMA-RERL), Terray (WHOI)
- Research questions: Operating characteristics of sensors (precision, accuracy, power, size), assessment of platform motion – are special buoy designs needed?
- Challenges: Participation by Lidar, Sodar, Radar(?) vendors

Focus Areas for Research

Spatial mapping of winds, waves and currents over a large area (~ 10 x 10 km)

- Applications: Resource assessment, operations monitoring
- Data requirements: Statistical characterization (means + spectra)
- Instrumentation: HF/VHF Doppler radar (CODAR – currents & winds; Phased-array – currents, winds & waves
- Investigators: Terray (WHOI), Flament (UH), Trizna (ISR)
- Research questions: Spatial resolution; inversion for waves; LERA field validation with ISR; antenna design
- Challenges: Improving the practical utility of phased-array HF/VHF radar (price, footprint)

Focus Areas for Research

High resolution imaging of winds, waves, currents & bathymetry (~ 1 x 1 km)

- Applications: Siting, control of wave and current generators
- Data requirements: High spatial & temporal resolution, ability to resolve individual waves and turbulent large eddys
- Instrumentation approaches: Rotating microwave (X-band) radar
- Investigators: Plant (UW-APL), Trizna (ISR), Terray (WHOI)
- Research questions: Is Doppler necessary (is WaMoS sufficient)? Currents and winds from low grazing angle measurements?
- Challenges: Improve the readiness of coherent Doppler radar; Participation by OceanWaves GmbH?

New England Marine Renewable Energy Center
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Focus Areas for Research

In-situ measurements of waves and currents using Doppler sonar

- Applications: Siting, control of wave and current generators
- Data requirements: High spatial & temporal resolution; ability to resolve individual waves and turbulent large eddys; high resolution wave spectra
- Instrumentation approaches: Vertical & horizontal Doppler sonar (V-ADCP, H-ADCP)
- Investigators: Mullison, Brumley (TRDI), Terray (WHOI)
- Research questions: Fan vs pencil beams? Individual wavetrains? Bistatic? Turbulence? Delayed correlation?
- Challenges: Inclusion of other Doppler sonar vendors?

Focus Areas for Research

Automated surveys of bottom sediment and biotic communities

- Applications: Site characterization; Post-installation monitoring
- Data requirements: High spatial resolution; Good areal coverage;
- Instrumentation: High definition video & still photography, multibeam & sidescan sonar, sub-bottom profiler (chirp sonar), AUVs, ROVs and towed bodies
- Investigators: Howes (UMD-SMAST), Anderson (OST)
- Research questions: AUV navigation; image registration; mapping; AUV endurance; system cost (AUV + sensors)
- Challenges: Inclusion of other vehicle & sensor vendors?

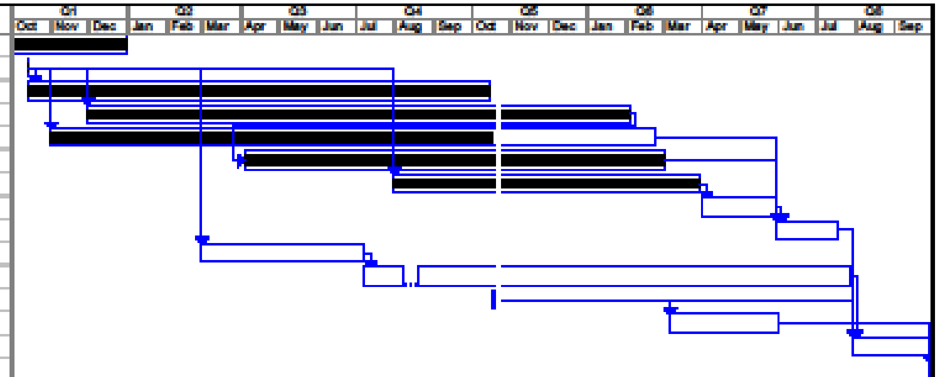
Focus Areas for Research

Geo-referencing and data management

- Applications: Making spatio-temporal data easily accessible and useful to developers, regulators, and researchers
- Data requirements: High spatial resolution but good areal coverage
- Approach: Develop tools to geo-reference, manage, manipulate and visualize data
- Investigators: Baptiste-Carpenter (Battelle) + Everyone else
- Research questions: How to deal with multi-dimensional data?
- Challenges: Interfacing science community formats (NetCDF, DODS, etc.) with existing data standards and geospatial visualization tools

Program Schedule

ID	Task Name	Start	Finish	Predecessors	Resource Names
1	Contract Definition	Fri 10/1/10	Fri 12/31/10		
2	Kick-off	Thu 10/14/10	Thu 10/14/10		
3	Equipment Definition/Purchase	Fri 10/15/10	Fri 10/14/11	2	
4	SONAR Wave Study	Wed 12/1/10	Fri 2/3/12	2	
5	SODAR/LIDSAR Study and Evalu	Mon 11/1/10	Fri 2/24/12	2	
6	SONAR Turbulence Evaluation	Mon 4/4/11	Fri 3/2/12	4	
7	RADAR Installation	Mon 8/1/11	Fri 3/30/12	2	
8	RADAR Test	Mon 4/2/12	Tue 5/29/12	7	
9	Preliminary Data Assessment	Wed 5/30/12	Tue 7/17/12	8,6,5	
10	AUV Configuration	Tue 3/1/11	Thu 7/7/11	2	
11	AUV Tests	Fri 7/8/11	Fri 7/27/12	10	
12	Program Review	Tue 10/18/11	Wed 10/19/11		
13	Data Review	Wed 3/7/12	Fri 6/1/12	12	
14	Additional Testing, Report Writing	Mon 7/30/12	Thu 9/27/12	12,9,11	
15	Final Report	Fri 9/28/12	Fri 9/28/12	13,14	



Roadmap:
Technologies for Cost Effective, Spatial Resource Assessments for Offshore Renewable Energy

A Proposal to the Bureau of Ocean Energy Management, Regulation, and Enforcement
Under the National Oceanographic Partnership Program

Study Opportunity Number M10PS00152: Developing Environmental Protocols and Monitoring to Support Ocean Renewable Energy and Stewardship

Participants

Project Coordinator: **Mr. John Miller**
New England Marine Renewable Energy Center (MREC)

Technical Coordinator: **Dr. Eugene Terray**
Woods Hole Oceanographic Institution (WHOI)

Participating Institutions:

- **U. Massachusetts, Dartmouth, School of Marine Science & Technology (UMD-SMAST)**
  - **Dr. B. Howes - Benthic habitats**
- **U. Massachusetts, Amherst, Renewable Energy Research Laboratory (UMA-RERL)**
  - **Dr. J. McGowan – Wind profiling**
- **University of Washington, Applied Physics Laboratory (UW-APL)**
  - **Dr. W. Plant – Microwave radar**
- **University of Hawaii, Radio Oceanography Laboratory (UH-ROL)**
  - **Dr. P. Flament – HF radar**

Participating Companies:

- **Imaging Science Research (ISR)**
  - **Dr. D. Trizna – Microwave & HF Radar**
- **Teledyne RD Instruments (TRDI)**
  - **Drs. J. Mullison & B. Brumley – Doppler Sonar**
- **Ocean Server Technologies (OST)**
  - **Mr. R. Anderson – AUVs**
- **Battelle Eastern Science and Technology Center**
  - **Dr. Ellie Baptiste-Carpenter – GIS mapping & data management**

Project Goal: Environmental sensing /technology roadmap to support offshore renewable power development

Objectives:

Identify measurement requirements with regard to
- regulatory needs
- science constraints

Evaluate appropriate measurement technologies in terms of
- feasibility
- performance
- cost

Research Focus:

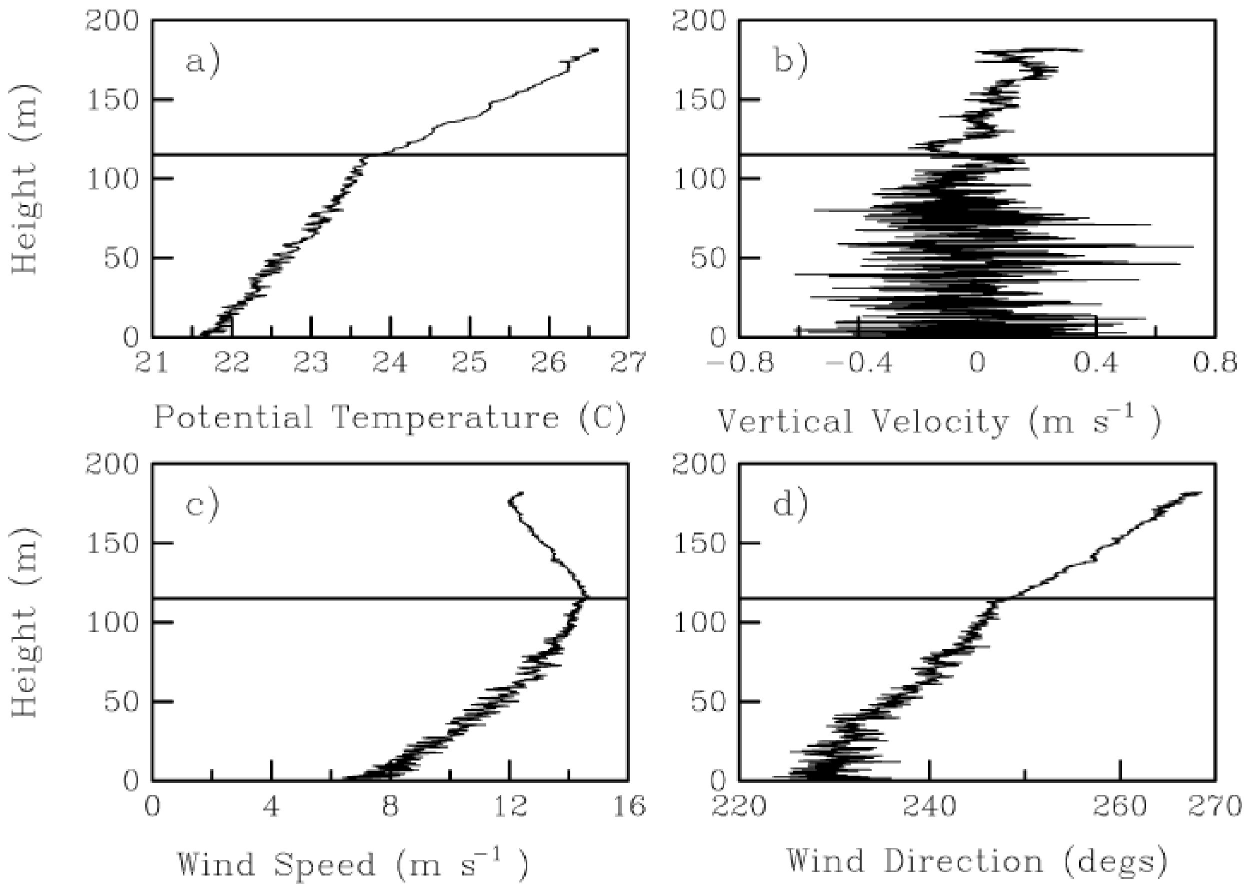
Spatial measurements of winds, waves, currents, bathymetry and benthic habitat characteristics

WHOI Focus Topics

- [1] Wind profiling from buoys & small boats (w/ UMass A)
  - Performance of Lidar and Sodar in the marine environment
- [2] Spatial mapping of winds, waves and currents over a large area (w/ U Hawaii & ISR)
  - Utility of HF radar for measuring currents, waves & winds
- [3] Effects of moving platforms (w/ TRDI & UMass A)
  - Inertial sensing of platform motion
  - Effect on vertical wind profiling & correction
  - Effect on Doppler sonar & correction
- Coordinate final report

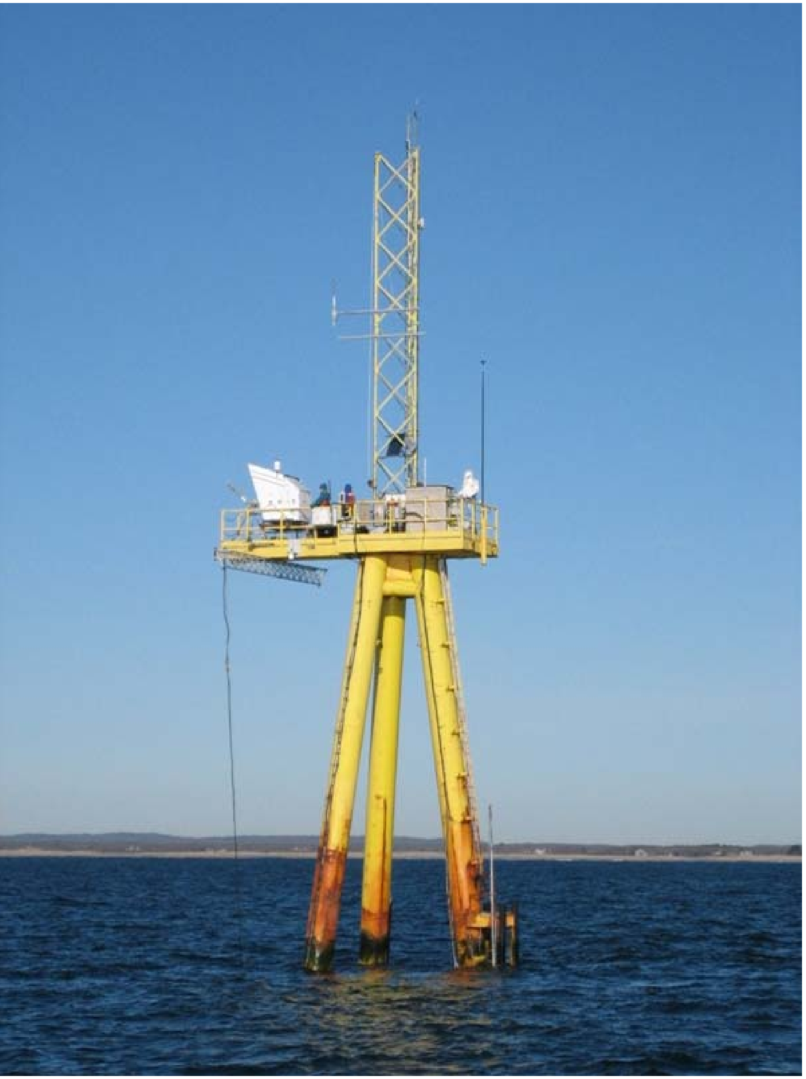
Topic 1: Vertical Wind Profiling using Sodar or Lidar

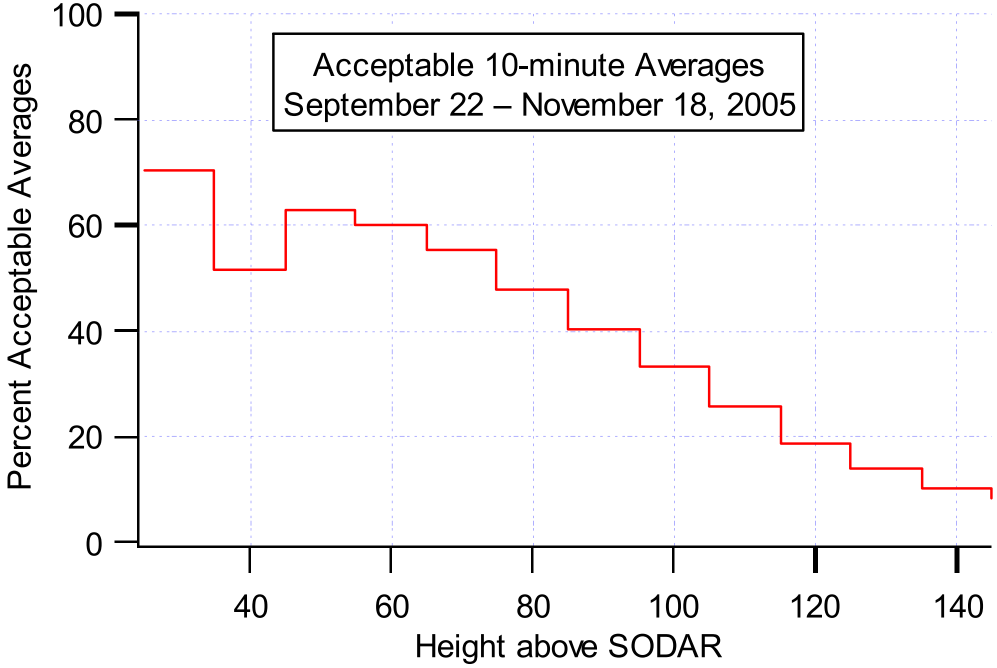
Low level jets are the challenge



Vickers & Mahrt (2004) J. Appl. Met. 43   CBlast - MVCO

UMass-RERL ART-VT1 Sodar Deployment on the WHOI Air-Sea Interaction Tower (ASIT)





Why does SODAR data availability degrade so rapidly at sea?

- Platform motion may not be the primary problem (Berg, WHOI/MIT Thesis, 2006)
- Study effect of ambient noise
  - Deploy Scintec SFAS on ASIT
  - Multiple frequencies (chirp)
  - Record single ping data

Scintec SFAS

Vertical LIDAR

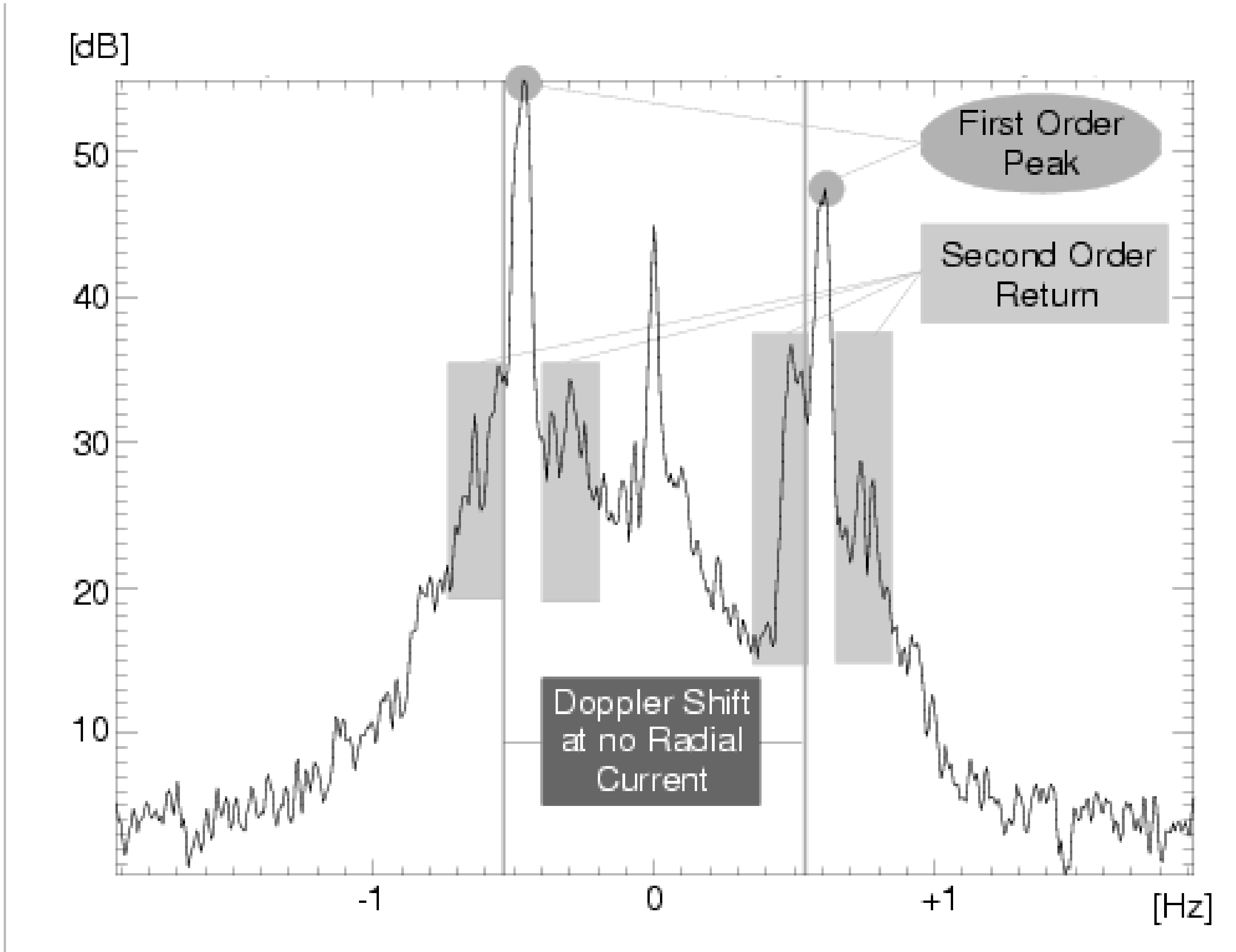
- Approach is to partner with vendors to obtain access to data and technical details
- To date we have an agreement to collaborate with AXYS Technologies (Vindicator) and have approached NRG (Windcube)
- We currently are analyzing 1 s data provided by AXYS for a fixed & moving Vindicator

AXYS Technologies WindSentinel

Topic 2: Spatial mapping of currents, waves & winds over ~ 10s x 10s km using HF Radar

- Goal is to evaluate use of low cost phased-array HF radars to measure currents, waves & winds
- Approach is to work with UH & ISR radars
- At present we are looking into wave inversion and the possibility of estimating wind speed from the measurement of waves
- Field deployment at USAC FRF in spring 2012

HF Radar Doppler Spectrum



Inverting the HF Radar Echo for Ocean Surface Properties

- Backscatter from “Bragg waves” –i.e. ocean waves with wavelength $\lambda_0/2$ (Z.B. 12.5 MHz, λ_{wave}= 12 m)

- Usual connection between the backscattered power and the ocean surface is through a perturbation expansion in k_0H_s (D. Barrick, 1972)

- Easy: Estimate currents from 1st order terms via the Doppler shift of the Bragg lines (from $\pm$c at U = 0)

- Hard: Invert 2nd order terms to estimate wave properties (height & directional spectra)

Conventional Perturbation Theory

- For near grazing, Barrick's expansions for the 1st and 2nd order backscattered power are

$$\sigma^{(1)}(\omega) = 2^6 \pi k_0^4 \sum_{m=\pm 1} S(-2mk_0, 0)\delta(\omega - m\omega_B)$$

$$\sigma^{(2)}(\omega) = 2^6 \pi k_0^4 \sum_{m_1, m_2 = \pm 1} \int_{-\infty}^{\infty} dp \int_{-\infty}^{\infty} dq \, |\Gamma|^2 S(m_1 \mathbf{k}_1) S(m_2 \mathbf{k}_2) \times \delta\left(\omega - m_1\sqrt{gk_1} - m_2\sqrt{gk_2}\right)$$

$\mathbf{k}_1 = (p-k_0, q)$ $\mathbf{k}_2 = (-p-k_0, -q)$ $\mathbf{k}_1 + \mathbf{k}_2 = -2\mathbf{k}_0$ $\omega_B^2 = 2gk_0$

- Coupling coefficient to 2nd order: $\Gamma = \Gamma_H + \Gamma_E$
  - Hydrodynamic (Γ_H) due to bound (nonlinear) waves
  - Electromagnetic (Γ_E) due to double scattering

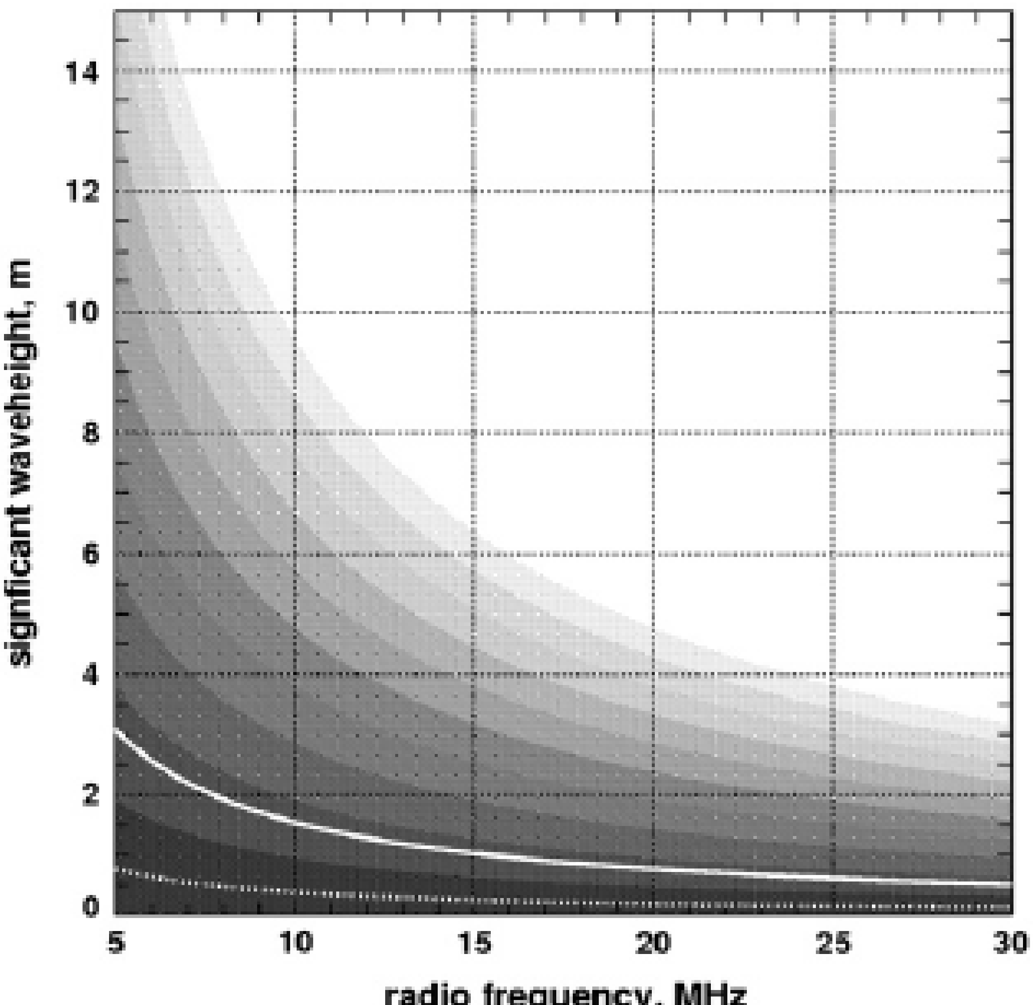
In deep water

$$\Gamma_{\mathrm{H}} = -\frac{1}{2} i \left[k_1 + k_2 - \frac{(k_1 k_2 - \mathbf{k}_1 \bullet \mathbf{k}_2)(\omega^2 + \omega_B^2)}{m_1 m_2 \sqrt{k_1 k_2} (\omega^2 - \omega_B^2)} \right]$$

$$\Gamma_{\mathrm{E}} = \frac{1}{2} \left[\frac{(\mathbf{k}_1 \bullet \mathbf{k}_0)(\mathbf{k}_2 \bullet \mathbf{k}_0) / k_0^2 - 2\mathbf{k}_1 \bullet \mathbf{k}_2}{\sqrt{\mathbf{k}_1 \bullet \mathbf{k}_2} - k_0 \Delta} \right]$$

where Δ denotes the impedance of the surface

Perturbation expansion requires $k_0 H_s < 1$
=> restricts the range of measurable sea states



Wyatt et al. (2011) Coastal Engr. 58, 327-336

- 2nd order “hydrodynamic correction” in the Barrick expansion dominates at high wavenumber, implying that the hydrodynamic perturbation expansion does not converge

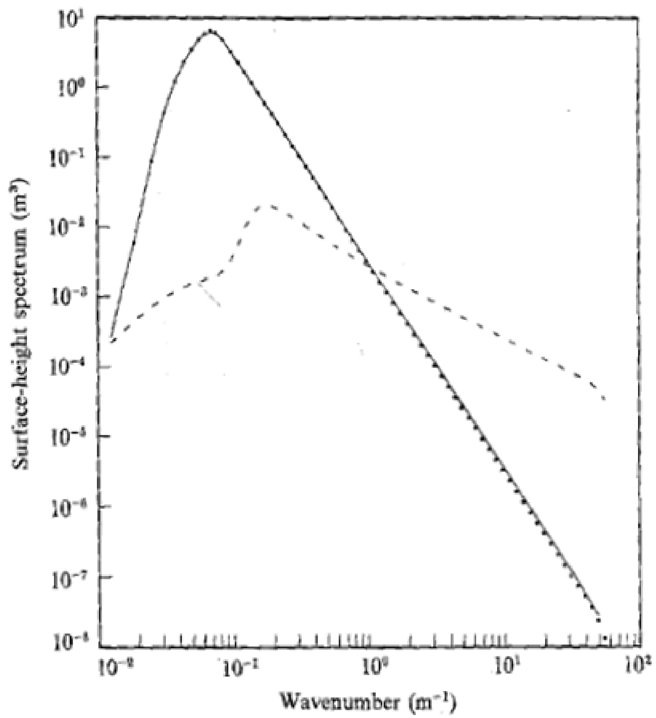
- Creamer et al. (1989, JFM 205) showed in 1-D that the Barrick expansion missed a contribution from 3rd order terms in wave amplitude. Their reorganization becomes an expansion in the mean-square slope and does not diverge at high wavenumbers.

- Janssen (2009, J Fluid Mech. 637) generalized to fully 2-dimensional waves in arbitrary depth – to date this advance has not been incorporated into the forward models used for wave inversion

Creamer et al. expression for the 2nd order spectrum

$$S(k) = S_0(k) + \frac{k^2}{2}\int dq\{S_0(q)S_0(k-q) - 2S_0(k)S_0(q)\}$$

The 2nd (quasi-linear) term in the integrand compensates the high k divergence



Unperturbed Phillips spectrum (dots), the Creamer et al. result, and the Barrick correction (dash) [from Creamer et al.]

What about the electromagnetic scattering term?

- Question: When is this effect important relative to the hydrodynamic contribution?
- The 2nd order electromagnetic scattering correction appears to dominate at high wavenumber. Hisaki (1999, J.Atmos. & Oc. Tech. 19) showed that the 3rd order expansion diverges more rapidly
- Question: Is there a better expansion (analogous to the Creamer et al. result for the nonlinear hydrodynamic correction)?

Topic 3: Effects of Moving Platforms

- Goal is to evaluate the precision and accuracy of inertial sensing required for various applications
- Approach
  - Analysis of buoy-based Lidar data (w/ AXYS & UMass Amherst)
  - Analysis of AUV-based ADCP measurement of waves (w/ TDRI & WHOI/MIT JP student – early 2012 deployment)