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Bedform Parameterization and Object Detection From Sonar Data- Application of Finger Print Algorithms

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LONG-TERM GOALS

The long-range goals of this research are to improve our ability to characterize the seabed geometry and texture in energetic inner-shelf/bay mouth settings composed of heterogeneous sedimentary material with dynamic seabed ripples. Our purpose is to improve our understanding of bedform dynamics and spatio-temporal length scales and defect densities through the application of a recently developed finger print algorithm technique (Skarke and Trembanis, 2011) in the vicinity of manmade seabed objects and dynamic natural ripples on the inner shelf utilizing high-resolution swath sonar collected by an AUV and from surface vessel sonars in energetic coastal settings with application to critical military operations such as mine countermeasures.

OBJECTIVES

The objectives of this project are a sonar based (platform independent) bedform parameterization and acoustic object detection system applicable to the spectrum of coastal and estuarine settings.

The following are the specific objectives of this research:

1. Conduct a local field experiment at the Redbird Reef, DE dump site (objects include tires, military vehicles, shipwrecks, and over 900 former NYC subway cars) to measure, over the extent of the field site, object scour evolution, morphodynamic behavior, sediment texture, and bedform characterization through remote sensing techniques.

2. Extend and apply recently developed finger print algorithm techniques (Skarke and Trembanis, 2011) for ripple parameterization and object detection using AUV, ship, and rotary sonar derived backscatter and bathymetry data.
3. Extend the ARA system developed by UNH into energetic and heterogeneous shelf settings; particular the abundance of variously sized manmade objects will provide a unique testing set for ARA remote classification techniques

APPROACH

Our approach has been to obtain a suite of field observations by performing carefully repeated high-resolution seafloor mapping over a natural seabed system approximately 1-2 km's on a side including areas with dynamic ripple bedforms and manmade structures. We have gathered: (1) acoustic bathymetry and backscatter of surface sediment layers from an autonomous underwater platform and from surface vessel multibeam echosounder sonar; (2) small scale (sub-meter) optical imagery from a small maneuverable AUV platform, and; (3) further developed a remote acoustic segmentation and classification system (ARA) for bathymetry and backscatter data collected at the field site. We have also deployed and maintained a bottom-moored instrument package with an ADCP (waves and current) and rotary sonar (2D ripples) for time-series measurements of hydrodynamics and small-scale bedform dynamics (*sensu* Skarke and Trembanis, 2011). The fusion of these remotely sensed data (hydrodynamics and morphology) with ground truth samples and the ARA remote acoustic model were used to test existing ripple models and improve our understanding of the response of the seabed to mean and oscillatory flows (tidal and wave driven respectively) and the interpretation of acoustic imagery for surface textural properties of surficial sediments on the seabed in other settings.

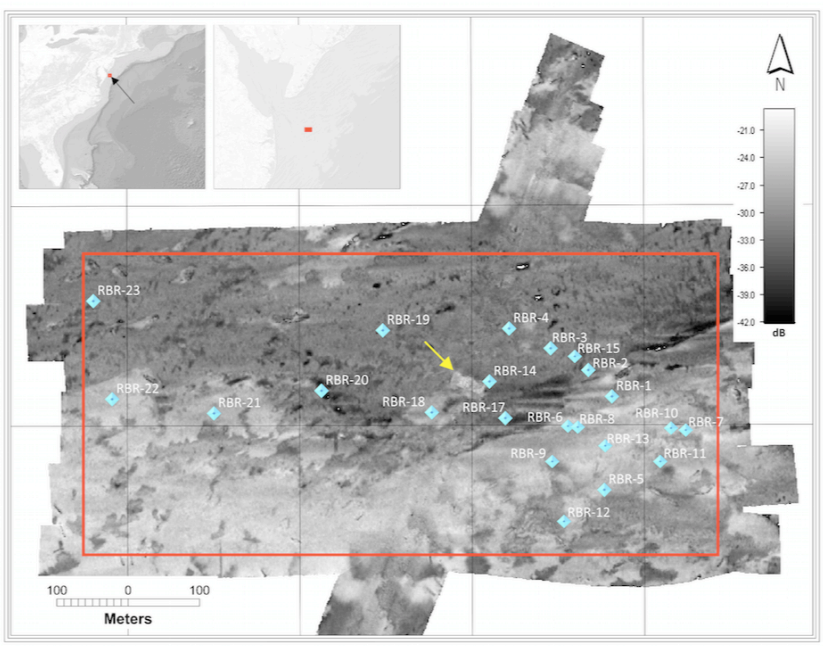

Figure 1. - Post-Sandy acoustic reflectivity surface with the project area adopted for the analysis (outlined in red). The surface has been created through the Ares library at a resolution of 0.5 m. The samples collected for ground truthing are displayed as cyan diamonds.

WORK COMPLETED

The following section highlights the major research accomplishments from this project over the final year of the project covering the period from October 2013 – May 2014.

- Conducted final cruise mapping the field site- November 2013 (1 year following recovery from hurricane Sandy)
- Hydrodynamic sensors recovered from final deployment (ADCP & rotary sonar) - July-Oct 2013
- 1 MS thesis and 1 undergraduate honors thesis completed and defended (S. Wang & C. DuVal); 2 additional MS theses (T. Metz and C. Englert) and 1 PhD (P. Kannappan) all supported by project data.
- 4 public presentations of project results including 3 invited seminars
- Angular Responses Analysis (ARA) completed with detailed comparison of before and after Hurricane Sandy. Manuscript draft prepared for publication.
- Fingerprint algorithm analysis of before and after Hurricane Sandy performed and 2 thesis chapters to be submitted as manuscripts for publication.

RESULTS

Ship Multibeam Component

A 1.0 x 0.5 km area was surveyed in detail on 5 separate repeated occasions (October 2012, November 2012, December 2012, March 2013, and July 2013, and November 2013) using a Reson 7125 SV2 system deployed on R/V *Hugh Sharp*. The 7125 system provided both detailed bathymetry and seabed imagery/backscatter. The surveys were repeated at least twice during each cruise using both the 400 kHz and the 200 kHz sonar setting in order to assess the impact of sonar system configuration on the ability of the fingerprint algorithm to detect seabed bedform features and also to utilize these data for acoustic classification via Angular Range Analysis (ARA). The first survey cruise allowed us to test and optimize the system configuration for bathymetric resolution whereas the subsequent surveys focused on precisely repeated the sonar data surveys. The multibeam system was operated at 400 kHz for the greater resolution available in this configuration: the 1.0° x 0.5° beam width for transmit/receive allowed for spatial resolution on the order of 0.5 m x 0.25 m in water depths of 27 m for the near nadir beams. Raw GPS measurements were recorded from an Applanix POSMV 330 (V5) and were post-processed using Applanix POSPac MMS to reduce horizontal and vertical positioning uncertainties. By recording the GPS measurements, the data was post-processed to allow for improved accuracies based on knowledge of the satellite constellation orbits, clock corrections, atmospheric delays, etc. Vertical positioning provided by the POSMV allowed for an ellipsoidal reference; removing uncertainties associated with poor tidal knowledge offshore, heave sensor limitations and variations in draft/squat of the vessel between surveys. Vertical repeatability between surveys is on the order of 10-15 cm.

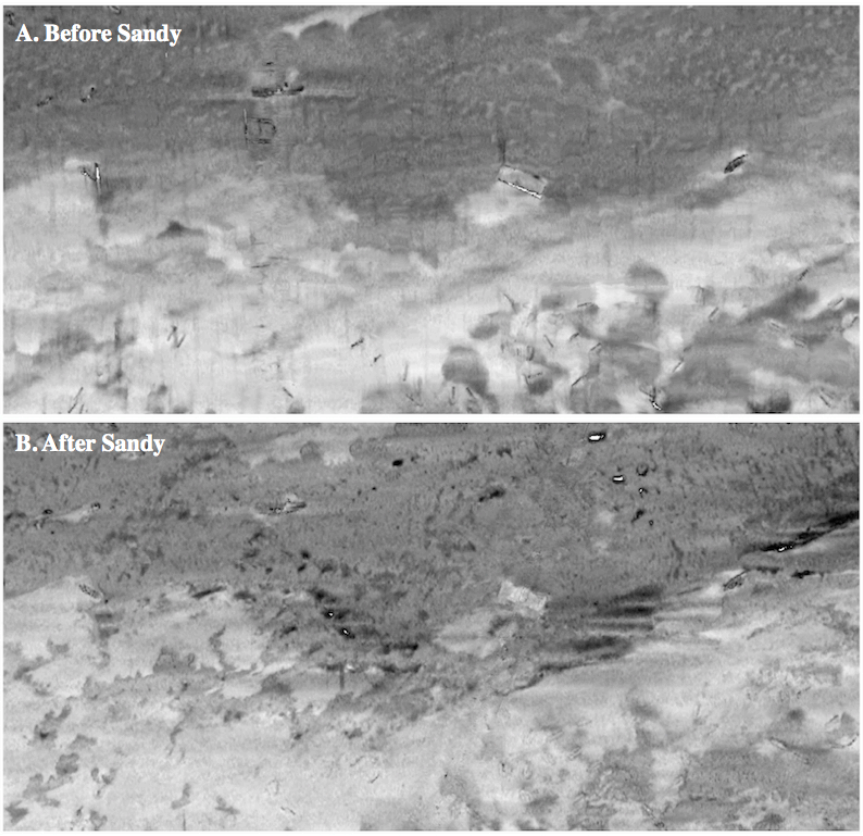

Figure 2. - Comparison bounded within the selected project area between the acoustic reflectivity surfaces obtained from the datasets collected pre- (at the top) and post-Sandy (at the bottom).

Bottom Mount Instrument Deployments

In addition to the surficial mapping activities our cruise work has included the deployment of hydrodynamic sensors on a seabed instrument frame. The instrumented bottom mount allowed us to measure the nearbed turbulence, wave, and current hydrodynamics and the temporal evolution of ripples in the coarse wave orbital ripple domain on the seabed. The frame and instruments were deployed most recently between July and November 2013 in order to record the waves, currents, and 2D planview ripple morphology. The bottom mount consisted of the following instruments:

- 600 kHz upward looking ADCP with wave and current profiling capability
- 2.25 mHz Imagenex 881 rotary fanbeam sonar for timer-series measurements of bedform planview geometry

The following sampling configuration was utilized during the deployment

RDI Workhorse Sentinel ADCP- was configured to measure profile of currents every 30 min and a 5-minute wave burst every hour

Imagenex Rotary Sonar- 2 scans every hour set to a range of 4 m and 9 m respectively

Ripple Model Predictions & Finger Print Algorithm Development

An extensive finger print ripple code tutorial and code enhancement has been completed allowing new users to quickly come up to speed on the work flow and algorithm outputs from the finger print code for use in a variety of sonar image formats (i.e. side-scan mosaic, rotary sonar images, multibeam backscatter or DEM surface). Specifically MS student DuVal adapted the code to provide improved

computation performance and to provide spatial results extracting the bedform parameters (e.g. wavelength, orientation, and defect density) over a user selected cell size applied over an entire AUV side-scan or MBES backscatter mosaic image and this analysis formed a substantial portion of his MS thesis. This process also preserves the inherent ripple/non-ripple filter step in the fingerprint algorithm and allows the user to quickly mask sonar images either for natural ripple features or man-made object features with clear applications to mine like object detection.

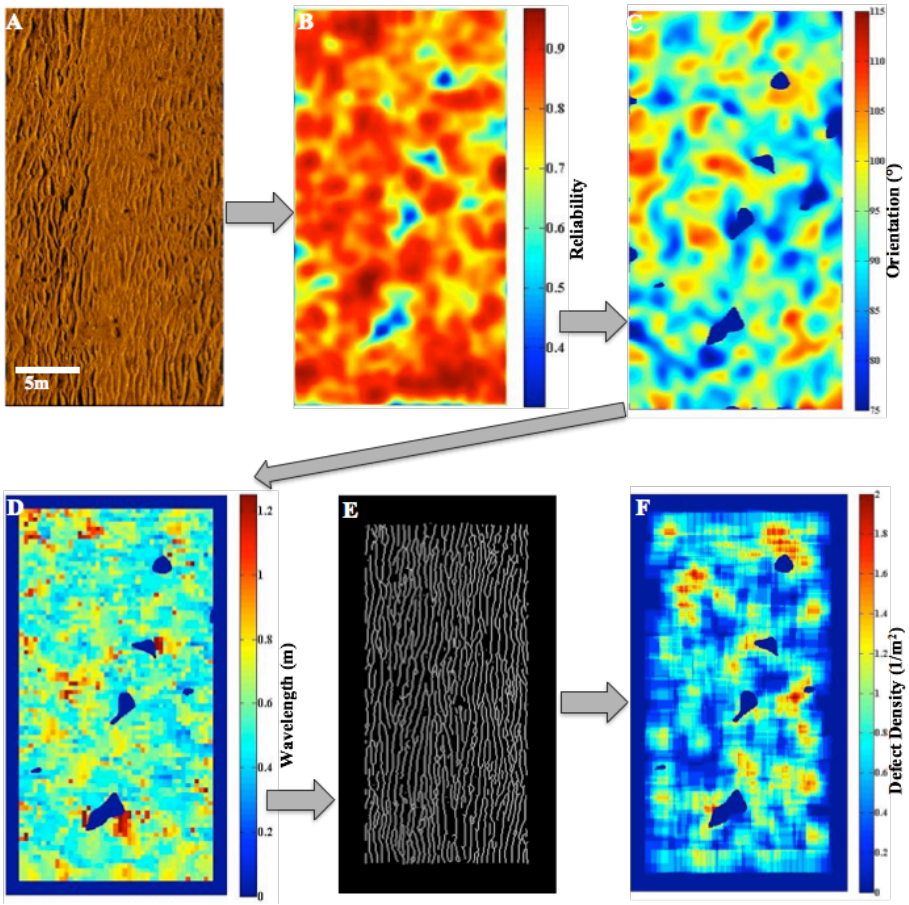

Figure 3. Fingerprint ripple algorithm analysis utilizing high-resolution side-scan sonar data.

The fingerprint algorithm has been applied to each sonar dataset gathered. Specific control sites were chosen to monitor seabed ripple creation and evolution during the course of this study. Observations were made of the ripple fields 3 days prior to and 11 days following Hurricane Sandy. Furthermore, the subsequent decay of ripple bedforms were documented a month after Sandy and also following a large Spring Nor'easter with similar wave conditions to Sandy. Sorted bedform ripple fields underwent cyclical evolution from buried and inactive states to freshly generated ripples. Post-storm conditions led to decay of ripples and return to relict states, with ripples bedforms eventually undergoing burial. The fingerprint algorithm has provided pertinent ripple characteristic data to quantify these cyclical changes.

Cross-referencing the sediment sample data to *in situ* hydrodynamic wave and current data quantified the conditions required to initiate ripple formation at the artificial reef site. Conversely, relict ripple states measured by the fingerprint algorithm quantified the moments when ocean conditions dropped below threshold for ripple movement. Deviations were observed between predicted and measured ripple wavelengths after Hurricane Sandy, with mean wavelengths above

predicted threshold values based on several commonly used wave ripple models. This indicates that ripple bedforms may not immediately scale to instantaneous ocean conditions, but have a delayed response to sharp changes waves and currents (see Traykovski, 2007). Furthermore, the fingerprint algorithm measured local variations in ripple wavelength and orientation across the study site. Increases in ripple defect density (e.g. bifurcations, terminations) were noted in ripples near reef objects, suggesting that objects may also affect ripple wavelength and orientation. Quantifying the effect of reef objects formed the focus of M.S student DuVal's research.

Angular Response Analysis-

Absolute and comparative seafloor acoustic characterization between a pre- and a post-

The 7125 system's seabed imagery data can be processed to provide a seafloor backscattering strength mosaic, normalized to an incidence angle of ~45°. If system calibrations and characteristics are well understood and compensated for the angular response of the seafloor over a range of incidence angles can be used to perform angular response analysis (ARA) in an attempt to more precisely characterize the nature of the seafloor and perhaps to even extract grain-size information (Fonseca and Mayer, 2007). The preliminary ARA grain size estimation exhibited a close adherence to the backscatter gradations across the field site. These analyses were conducted in "patch mode" – i.e. analyzing the angular dependence over a swath of seafloor that is one-half of the full swath width wide. This approach provides data across the full range of angular dependencies but limits the resolution of the analysis to a half swath width. Subsequent analysis during this reporting period focused on increasing the resolution of the analysis by first segmenting the data into much finer "themes" (Rzhanov et al, 2012) and comparison of the ARA analyses to the sediment grab samples that were acquired to provide ground truthing.

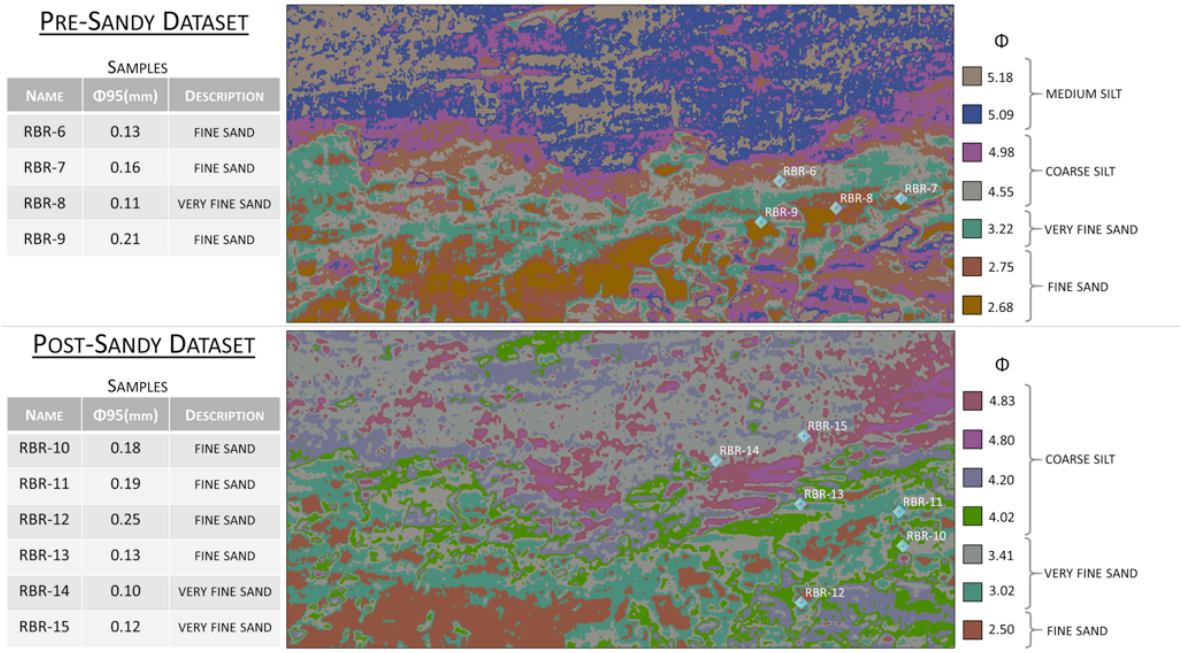

Figure 4. The theme-based analysis from both datasets and the bottom sampling results are presented. The angular response characterization has been based in both case on a mask created on the reflectivity map based on a 7-cluster k-means segmentation (1000 iterations).

Analysis difference on bathymetry in Trembanis et al., (2013) highlighted the presence of pronounced features from the impact of Super Storm Sandy: large scour patches were noted in the

southwest lee of seabed structures, while previously smooth and/or hummocky seafloor patches became scoured and/or formed into large wave orbital ripples. In addition, several subway cars were rotated, further buried or partially destroyed by the storm conditions with marine debris subsequently scattered throughout the area. The freshly formed and exposed ripple fields observed in the mapping survey provide a unique high-resolution spatial snapshot of bedform morphology imposed by the storm condition (Trembanis et al., 2013)

The main aim of this work was to evaluate the ability of sonar backscatter measurements to identify and quantify changes on the seafloor related to the impact of Super Storm Sandy. Specifically, the data processed were collected by the R/V Hugh R. Sharp with a hull-mounted Reson 7125 SV2 multibeam echosounder (200/400 kHz).

Geometric and Radiometric Corrections

The acoustic energy backscattered to a multibeam sonar head has experienced complex and variable interactions with the ocean environment. This complexity is due to the two-way (forward and back) travel through the water column, and to the impact of the acoustic wavefront over a seafloor area that may be extremely variable with respect to roughness and sediment homogeneity (Jackson and Richardson, 2007). This interaction strongly influences the amount of energy returned to the sonar (Lurton, 2010; Urick, 1983).

In order to obtain both an accurate reflectivity map (i.e., sonar mosaic) and an undistorted angular backscatter response, a full understanding of the sonar manufacturer's signal treatment and the meaning of the digital numbers stored is required (Beaudoin et al., 2002; Beaudoin et al., 2013; Fonseca and Calder, 2005l; (Beaudoin et al., 2002; Beaudoin et al., 2013; Fonseca and Calder, 2005; Hughes Clarke, 2012; Masetti and Calder, 2014). This is because many of the assumptions introduced during the real-time acquisition (e.g., a flat-seafloor, a simplified time variable gain model) should be removed and, depending of the required output, re-applied using information only available in post-processing (e.g., local slope based on a digital terrain model at the proper scale) (Beaudoin et al., 2002; Hellequin et al., 1997).

For the analyses described herein, the following processing steps were applied: 1) removal of manufacturer-specific time varying gains; 2) compensation for spherical spreading and for increasing reception beamwidth with steering angle, and; 3) compensation for attenuation in the water column and area insonified (based on actual slope and distinction between pulse- and width- limited regimes). The resulting calculation of the angular-dependent backscatter strength per unit of area and per unit of solid angle BS_θ is summarized in [1], where EL is the echo level, SL is the source level, TVG_{Reson} is the manufacturer-specific time variable gain model, TL is the transmission loss, and A_C is the correction for the insonified area.

$$BS_\theta = EL - SL - TVG_{Reson} + 2TL - A_C \qquad [1]$$

Particular care is required for the A_c to take advantage of the high-resolution bathymetry, present in the same surveylines, to calculate the effective incident angle through the scalar product of the beam vector (from the footprint on the seafloor to the transducer) and the normal to the digital elevation model (at the incidence of the projection of the principal axis on the beam on the seafloor). The effective area of insonification is then calculated based on the nominal beamwidths, pulse length, and slant range (Lurton et al., 1994). In the absence of an absolute-calibrated sonar, a conversion constant based on the sonar manufacturer documentation is used to reduce the stored digital number to sound pressure level (Fonseca and Calder, 2007; Fonseca and Mayer, 2007; Soares Rosa, 2007). Both datasets have been collected close in time and from the same system and maintaining the same sonar settings by design throughout the survey.

The resulting BS_θ represents the best estimate for the actual backscatter strength and its angular dependence on the sediment type of the seafloor. If the correction have been done properly, at a given

frequency, the resulting angular response curve represents an inherent property of the seafloor (Hughes Clarke, 1994; Jackson and Richardson, 2007).

Mosaicking and extraction of statistical features

A crucial step in seafloor characterization is the assemblage of a consistent and accurate acoustic reflectivity map, commonly called a "mosaic", that geographically locates the acoustic samples in a projection coordinate system, properly interpolating among point-wise intensity values (Beaudoin et al., 2014; Fonseca and Calder, 2005; Hughes Clarke, 1994).

A model-inversion algorithm, embedded in a software library called Arch (Angular Response Characterization), analyzes the acoustic data, after having been radiometrically and geometrically corrected, to infer from the angular variable response of the seafloor properties constrained by known physical property inter-relationships (Hamilton, 1976). The solution is obtained through an iterative approach applied to a set of parametric equations with the intent to optimize the fit between a limited number of observed and model-based features extracted from the acoustic angular response (Fonseca and Mayer, 2007).

Angular Response Characterization

The adopted characterization technique attempts to use the full backscatter time series. This is obtained in two different ways: Angular Range Analysis divides the measured backscatter angular response into discrete angular regimes (i.e., near-, far- and outer- range) to provide features useful in the characterization analysis. This technique is common to other fields of research (e.g., the amplitude versus offset analysis in multichannel seismic reflection data) (Fonseca and Mayer, 2007).
Response curve features that attempt to identify the angular acoustic signature. At a first approximation, the angular slope may be related to the seafloor roughness, while the intercept is influenced by the impedance of the insonified sediment. These relations have been demonstrated to be more composite and require complex mathematical models (Jackson and Ivakin, 1998), but the above simplifications have been proved to work enough well in many cases (Fonseca and Mayer, 2007).

Two different approaches, corresponding to two different modules in the Arch library, have been applied to obtain angular response curves with reduced stochastic fluctuations:
Patch-based, where a certain number (i.e., 60) successive half-swathes (for each side) are stacked together.

Theme-based, a statistical-driven number (i.e., 7) of seafloor areas are obtained through reflectivity-based clustering of the derived reflectivity surface.
The patch-based approach uses a stack of consecutive half-swathes that approximate the swath footprint width in the along-track direction, independently treating the port- and the starboard- side of the surveylines (Fonseca and Calder, 2007). This choice permits the reduction of backscatter fluctuations at the price of a reduced spatial resolution and the risk to merging together different seafloor acoustic *facies*.

An acoustic theme is intended as a seafloor area with similar acoustic angular response and properties (Collier and Humber, 2007; Dartnell and Gardner, 2004; Fonseca et al., 2009). Often, the definition of such regions has been based on the manual interpretation of backscatter data. This method, although effective in regions of sharp demarcations among sediment types, has the disadvantage of being intrinsically subjective, lacking effectiveness in areas where there is, for instance, a gradual change in the seabed characteristics (Blondel and Murton, 1997; Brown and Collier, 2008). The theme-based technique does not present such a limitation since it conducts objective automated classification of the acoustic data based on the backscatter signal (Fonseca et al., 2009).

The comparison between the characterization results and the ground truthing samples has provided much better performance when implemented using a theme-based approach, that attempts to distinguish between different facies, rather than a patch-based approach, where angular responses are straightly created by stacking successive half swaths.

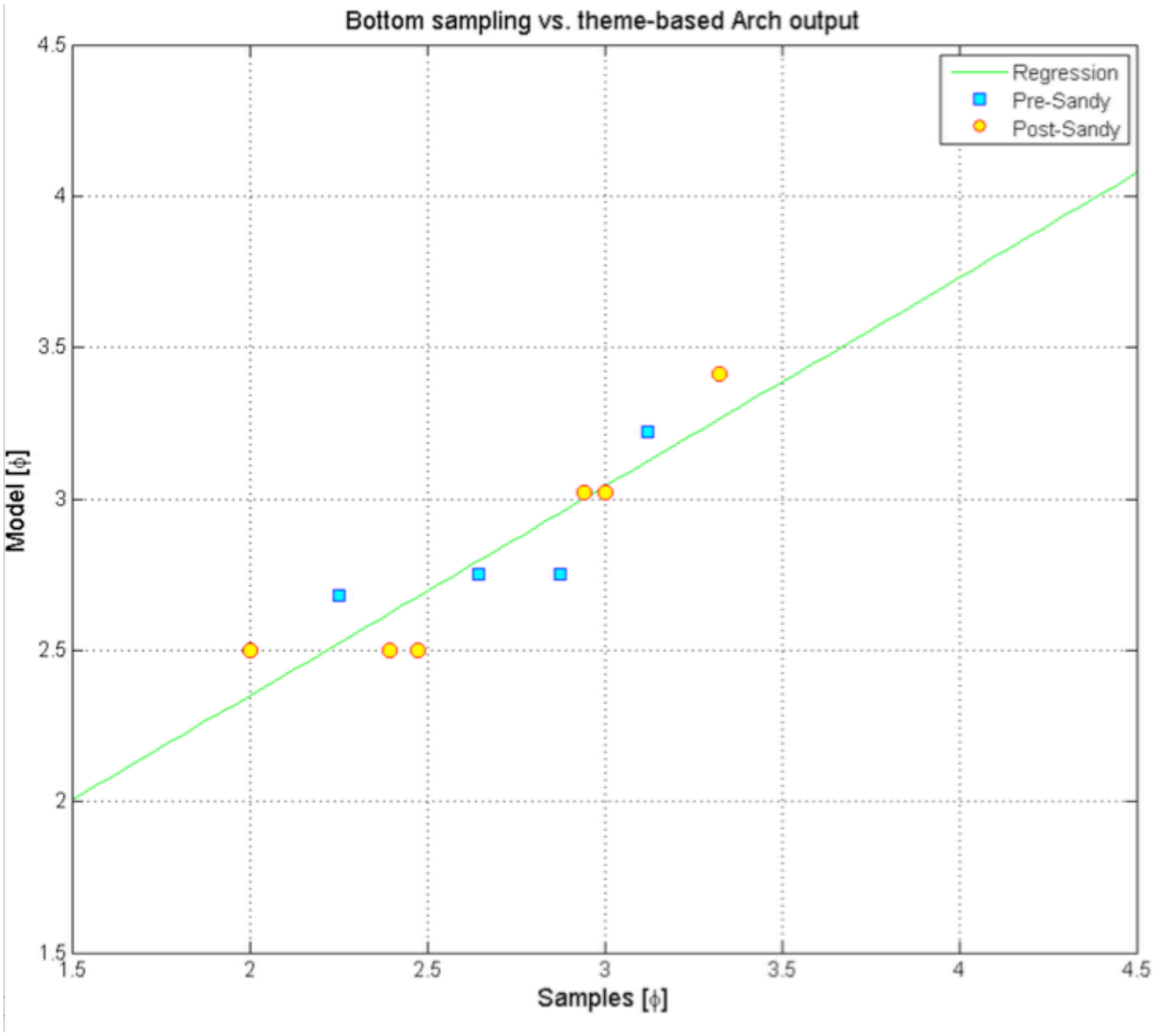

Figure 5, Scatter plot for visual comparison between the bottom sampling and the Arch theme-based analysis (Pearson correlation coefficient: 0.904; Spearman's rank correlation coefficient: 0.932; linear regression R-squared: 0.817).

TRANSITIONS

Data products from this project are now being used by several other researchers in extension of this project including an MS student (C. Lawson) of Dr. Diane Foster and also by Dr. Brian Calder at

UNH. Already this project has formed the basis of 3 existing MS student thesis projects (C. DuVal MS Oceanography UD 2014; T. Metz MS Geology expected Fall 2014; C. Englert MS UNH expected summer 2014) and one PhD (P. Kannapan, Mechanical Engineering UD expected 2016). The continued development and refinement of the ripple fingerprint algorithm code has been conducted in partnership with A. Skarke (Mississippi State University) with the objective to host and make available to the research community fully documented version controlled code with detailed examples of implementation of the fingerprint algorithm code.

This project enhanceed existing ONR sponsored Mine Burial and Mine Countermeasure research by incorporating additional detailed field observations utilizing sonar systems from both a surface ship and a small portable AUV. The application of the recently developed fingerprint algorithm technique for bedform parameterization (Skarke and Trembanis, 2011) to bedform characterization provides a novel tool for object detection with impact to mine countermeasures. This project also buildt upon and extended previously sponsored ONR efforts (Mayer and Trembanis, 2008) to develop remote acoustic techniques (ARA- angular response analysis) for seafloor segmentation and classification. This project also provided meaningful additional acoustic data, which will then be used by Trembanis and Mayer and other colleagues to specifically address the continued developed of ARA techniques.

RELATED PROJECTS

This project builds off of our previous project ONR Award Number N00014-07-1-0666 Mayer and Trembanis, 2010. Following successful AUV field ripple surveys in 2009 in the vicinity of the Martha's Vineyard Coastal Observatory we developed experience and protocols for both field operations and data analysis workflows to handle the integration and processing of the dense sonar data from the 500 kHz phase measuring bathymetric sonar. Both that project and our ongoing work in the existing grant have allowed us to further refine our ability to work with phase measuring bathymetric sonar and both have and will provide additional data for us to continue testing and expanding the frequency domain of the ARA (angular range analysis) work that will inform this and other site studies.

Benthic Hardbottom Mapping in DE Bay- NOAA Sea Grant (Trembanis- Co-PI). This project first introduced us to the Redbird reef site offshore of Delaware Bay and allowed us to conduct reconnaissance surveys of the seabed in this area between 2008-2011. This project resulted in several publications and a PhD student project (N. Raineault completed Spring 2012).

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PUBLICATIONS AND PRESENTATIONS OF RESULTS

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Trevor Metz, A. C. Trembanis, John Madsen, and C. DuVal. Consideration of Shallow Stratigraphy for an Offshore Wind Farm, Symposium 2014, Lewes, DE.

Trembanis, A.C. Inner Shelf Scour and Bedform Dynamics from hurricane Sandy. University of Rhode Island Graduate School of Oceanography. Seminar October 24th, 2013.
Trembanis, A.C. Inner shelf bedform dynamics and scour associated with hurricane Sandy- impacts at artificial reef sites. University of Maryland Center for Environmental Studies, Horn Point Lab. Invited seminar Oct 23rd, 2013.

Trembanis, A.C. Drinking from the Firehose: strategies and techniques for dealing with large and noisy datasets. Examples from crowd sourcing image analysis and Phase Measuring Bathymetric Sonars (PMBS). AUV Users Conference. Lerici Italy October 15, 2013.

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A.C. Trembanis, 2013. Impacts of Hurricane Sandy on the Delaware Inner Shelf- Observations of Bedform Dynamics and Scour from the Redbird Reef Site. Physical Ocean Science and Engineering Seminar, April 26, 2013

DuVal, C. and A.C. Trembanis, 2013. Object Scour and Bedform Dynamics at an Artificial Reef. Department of Geological Sciences Poster Seminar February 21, 2013.

Student Involvement:

While there was no direct student funding support in the project budget, this project has helped to facilitate several graduate students theses and involved participation by more than a dozen undergraduates through our research cruises. Specifically the following 4 graduate students theses involve some component of the project data: 1) Carter DuVal MS Oceanography UDel; 2) Trevor Metz MS Geology UDel; 3) Christopher Englert MS UNH; 4) Prasanna Kappannan PhD Mech Eng UDel. Additionally NSF REU summer intern Seaver Wang (UPenn) developed and completed both his summer internship and senior honors thesis utilizing project related data.

Collaborative Partners:

This project has both built upon existing collaborations and lead to the development of new collaborations with the following colleagues- Giuseppe Masetti, University of New Hampshire, Doug Miller, University of Delaware; Bert Tanner, University of Delaware; Mark Moline, University of Delaware; Tobias Kukulka, University of Delaware; Doug Levin, Washington College; and Steve Donohue, EPA