View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by NSU Works

Nova Southeastern University
NSUWorks

Oceanography Faculty Articles

Department of Marine and Environmental Sciences

10-1-2009

The Emerging Role of LiDAR Remote Sensing in Coastal Research and Resource Management Full Access

John C. Brock
US Geological Survey, Reston, VA

Samuel J. Purkis
Nova Southeastern University, purkis@nova.edu

Find out more information about Nova Southeastern University and the Oceanographic Center.

Follow this and additional works at: http://nsuworks.nova.edu/occ_facarticles

Part of the Geology Commons, Marine Biology Commons, Natural Resources Management and Policy Commons, and the Oceanography and Atmospheric Sciences and Meteorology Commons

NSUWorks Citation

John C. Brock and Samuel J. Purkis. 2009. The Emerging Role of LiDAR Remote Sensing in Coastal Research and Resource Management Full Access .Journal of Coastal Research : 1 -5. http://nsuworks.nova.edu/occ_facarticles/249.

This Article is brought to you for free and open access by the Department of Marine and Environmental Sciences at NSUWorks. It has been accepted for inclusion in Oceanography Faculty Articles by an authorized administrator of NSUWorks. For more information, please contact nsuworks@nova.edu.

BioOne RESEARCH EVOLVED

The Emerging Role of Lidar Remote Sensing in Coastal Research and Resource Management

Author(s): John C. Brock and Samuel J. Purkis
Source: Journal of Coastal Research, Number 10053:1-5. 2009.
Published By: Coastal Education and Research Foundation
DOI: http://dx.doi.org/10.2112/SI53-001.1
URL: http://www.bioone.org/doi/full/10.2112/SI53-001.1

BioOne (www.bioone.org) is a nonprofit, online aggregation of core research in the biological, ecological, and environmental sciences. BioOne provides a sustainable online platform for over 170 journals and books published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Web site, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/page/terms_of_use.

Usage of BioOne content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Journal of Coastal Research	SI	53	1–5	West Palm Beach, Florida	Fall 2009

The Emerging Role of Lidar Remote Sensing in Coastal Research and Resource Management

John C. Brock[†*] **and Samuel J. Purkis**[‡]

†*U.S. Geological Survey
Coastal and Marine Geology Program
USGS National Center, Mail Stop 915-B
12201 Sunrise Valley Drive
Reston, VA 20192
jbrock@usgs.gov

‡National Coral Reef Institute
Oceanographic Center
Nova Southeastern University
8000 N. Ocean Drive
Dania, FL 33004
purkis@nova.edu

ABSTRACT

Brock, J.C. and Purkis, S.J., 2009. The emerging role of lidar remote sensing in coastal research and resource management. *Journal of Coastal Research*, SI(53), 1–5.

Knowledge of coastal elevation is an essential requirement for resource management and scientific research. Recognizing the vast potential of lidar remote sensing in coastal studies, this Special Issue includes a collection of articles intended to represent the state-of-the-art for lidar investigations of nearshore submerged and emergent ecosystems, coastal morphodynamics, and hazards due to sea-level rise and severe storms. Some current applications for lidar remote sensing described in this Special Issue include bluegreen wavelength lidar used for submarine coastal benthic environments such as coral reef ecosystems, airborne lidar used for shoreline mapping and coastal change detection, and temporal waveform-resolving lidar used for vegetation mapping.

ADDITIONAL INDEX WORDS: *lidar, laser altimetry, remote sensing, coastal mapping, benthic habitats, storm hazards, shoreline change, dune vegetation*

INTRODUCTION

Quantitative high resolution information on coastal elevation is needed for resource management and planning, establishing political and jurisdictional boundaries, navigation, and scientific research. Accurate and up-to-date coastal topographic maps are required at the most basic level by land use planners to establish building set-backs, inventory wetland and agricultural land resources, and to identify flood and hurricane hazard zones (Liu, Sherman, and Gu, 2007).

Airborne lidar (**li**ght **d**etection **a**nd **r**anging) for bathymetric and topographic mapping has undergone extensive development and refinement since the early 1970s, enabled by advances in high speed digital and analog electronics, greatly increased computer memory and storage capacity, access and processing speed, and dramatic reductions in cost. Brisk evolution of laser ranging devices paralleled the advent of Global Positioning Systems (GPS) and kinematic carrier-phase GPS position measurement techniques in the 1980s, leading the National Aeronautics and Space Administration (NASA) to experiment with airborne laser altimetry systems for mapping terrain, high latitude ice sheets, and sea-surface height in that decade (Krabill *et al.*, 1984). NASA technology demonstrations resulted in low cost airborne lidars for mapping subaerial and shallow submerged topography, capabilities that have attained great value in a vast range of natural science investigations, and especially relevant to this Special Issue, a broad and interdisciplinary set of coastal applications (Wright and Brock, 2002).

By the late 1990s, airborne lidar mapping systems that are compact, lightweight, and have low-power requirements became available commercially, allowing operation from light single engine aircraft. Most airborne lidars used for solid earth sensing have a common basic design, employing a small-surface footprint, the capture of multiple discrete returns, and a high repetition rate to survey topography within terrain swaths. Lidar enables the rapid collection of very accurate elevation data over large areas, and during the first decade of the new century, airborne laser altimetry has been widely applied to map coastal geomorphology, leading to improved knowledge of coastal geomorphic processes (Brock *et al.*, 1999, 2004; Sallenger *et al.*, 1999, 2003; Sallenger, Wright, and Lillycrop, 2007). Moreover, applications to coastal hazard prediction and mitigation, dune, forest and wetland ecology, and benthic structure and ecosystem function have arisen (Slatton *et al.*, 2007; Xhardé, Long, and Forbes, 2006).

Recognizing the vast potential of lidar remote sensing in coastal studies, as the guest editors for this Special Issue we solicited and assembled a collection of articles that are intended to represent the state-of-the-art for lidar investigations of nearshore submerged and emergent ecosystems, coastal morphodynamics, and hazards due to sea-level rise and severe storms. We believe that this Special Issue underscores the emerging salient role of lidar remote sensing in coastal research and resource management, and hope that the example applications presented herein will inspire others to tap this remarkable new asset.

SUBMARINE COASTAL BENTHIC APPLICATIONS

Four of the papers in this Special Issue focus on benthic environments, significant because the vast regions beneath the World's oceans are in general unmapped or poorly mapped, yet human societies require this spatial knowledge for navigation, commerce, and ecosystem-based policies to guide decision-making. Various management objectives, for example, the inventory of resources, tracking change, and identifying regions

DOI: 10.2112/SI53-001.1

for protection, rely upon accurate and repeated characterizations of benthic communities and morphology. Unlike aerial photographs and satellite images that only allow the recognition of boundaries between primary cover classes in shallow clear water, blue-green wavelength lidars can provide highly resolved bathymetric surfaces. Furthermore, the high energy of the lidar laser offers a much greater depth of penetration as compared to passive technologies such as aerial photography, hyperspectral airborne surveys, or satellite, which are typically limited to 1.5 Secchi depths. For lidar, viable laser returns can routinely be retrieved from the seabed from up to 2-3 times the Secchi depth (Wang and Philpot, 2007), which can exceed sixty meters depth in the clear waters that surround coral reefs.

Airborne blue-green lidar mapping of shallow benthic environments has several advantages over boat-based acoustic surveys (Costa, Battista, and Pittman, 2009). For example, 1) navigational hazards associated with vessel operations nearshore are not an issue, 2) the lidar swath width is nearly independent of water depth, 3) hybrid blue-green lidars with high pulse rates can collect almost seamless subaerial–submarine topobathymetric surveys, and 4) airborne lidar can also collect reflected intensity images useful in benthic class discrimination (Costa, Battista, and Pittman, 2009).

Many prior lidar applications to benthic mapping have focused on coral reef tracts, as those rich environments are typically proximal to land and sit in clear shallow waters that are amenable to optical mapping techniques (Brock *et al.*, 2004, 2006a, 2006b, 2008; Purkis, 2005; Purkis and Pasterkamp, 2004; Purkis and Riegl, 2005; Purkis, Myint, and Riegl, 2006). The aggradation of coral reefs creates bottom roughness, resulting in topographic complexity ranging from centimeters to kilometers in spatial scale that both influences and reflects many ecological variables. Blue-green airborne lidar sensing of benthic topographic complexity shows great promise as a proxy for habitat complexity (Brock *et al.*, 2004), a fundamental ecological factor on coral reefs that is relevant to species diversity and richness, herbivore shelter, predation, recruitment, metabolic processes, hydrodynamics, and nutrient fluxes (McCormick, 1994; Sale, 1991; Sebens, 1991; Szmant, 1997).

Brock *et al.* (2006a) examined the ability of an experimental blue-green lidar (Wright and Brock, 2002) to discriminate cluster zones of massive stony coral colonies on patch reefs based on their topographic complexity, or rugosity. This study determined that massive coral colony formation, modified by subsequent physical and biological processes that break down patch reef framework, was the primary source of topographic complexity sensed by lidar in the northern Florida Keys reef tract. The authors concluded that lidar sensing of benthic topographic complexity shows great promise for identifying, mapping, and perhaps even the monitoring of massive coral colonies and their derivative high rugosity substratum. In a similar study, Storlazzi, Logan, and Field (2003) used bathymetric soundings from the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) instrument to define the morphology of spur-and-groove structures on the fringing reef off the south coast of Molokai, Hawaii.

The paper by Zawada and Brock in this Special Issue advances bathymetric lidar rugosity analysis by using a fractal algorithm to provide a multiscale characterization of reef tract to intra-reef roughness. The resulting spatial patterns of the computed fractal dimension are positively correlated with known reef zonation, thus demonstrating a means of capturing the essence of coral reef ecosystem morphology that surpasses previously suggested topographic metrics. The approach presented by Zawada and Brock analyzes vertical deviations within a set of increasingly larger two-dimensional geographic windows, rather than along one-dimensional profiles, a marked improvement for anisotropic surfaces. Moreover, this work reveals that reefscape structure exhibits fractal characteristics over spatial scales spanning hundreds of meters, as has previously been observed offshore Puerto Rico (Purkis and Kohler, 2008).

The paper contributed by Foster *et al.* describes the use of spatially-coincident lidar bathymetry to quantitatively guide the acoustic sensing of physical seabed characteristics within a study area that lies within the coral reef ecosystem offshore of Palm Beach County, Florida. Uncertainties in interpreting single-beam acoustic backscatter observations have limited the use of that method for producing thematic coral reef habitat maps (Costa, Battista, and Pittman, 2009). Foster *et al.* contribute to the resolution of this ambiguity by using a comprehensive high resolution lidar ground-truth data set to derive proxies for topographic complexity, reef-volume, and benthic habitat class that are then applied to evaluate the utility of acoustic energy parameters in reef benthic characterization. The authors recognize that independent lidar sounding of reef habitats is essential in unraveling the complex interactions between acoustic energy and the variable physical attributes of a coral reef ecosystem.

Recently Kuffner *et al.* (2007) investigated the possible use of airborne laser assessment of reef topographical complexity to predict reef fish community structure on shallow patch reefs in the northern Florida Keys reef tract. Once reef-by-reef variability was taken into account, the importance of lidar-sensed rugosity could be seen on individual reefs, because fish species richness and abundance were statistically higher at high rugosity stations identified by lidar. Consequently, Kuffner *et al.* (2007) and other researchers (Friedlander and Parrish, 1998) have concluded that blue-green lidar shows promise as an important mapping tool for reef resource managers as they strive to inventory and protect coral reef fish diversity and abundance.

Contributions to this Special Issue from Pittman *et al.* and Walker *et al.* further investigate the capability of airborne hydrographic lidar to quantify benthic topographic complexity in coral reef ecosystems for the prediction of marine organism distribution, abundance, and behavior. In a study sited in the reef tract off southwestern Puerto Rico, Pittman *et al.* develop seven different morphometrics based on bathymetric lidar, and quantify those measures at multiple spatial scales. Regression trees enhanced by a new statistical learning technique, stochastic gradient boosting, are then used to create lidar-based predictive models for nineteen fish metrics and two coral metrics. 72% and 68% of the variance in herbivore and parrotfish biomass, respectively, 65% of coral species richness, and 64% of fish species richness are explained by the predictive models, and moreover, Pittman *et al.* find that herbivorous fish versus piscivorous fish respond to different spatial scales of topographic complexity.

A similar study by Walker *et al.* focuses on southeastern Florida coral reef habitats and also demonstrates that lidar bathymetric mapping has great potential to aid in the spatial prediction of reef fauna, ecosystem-based management, and marine spatial planning. Walker *et al.* use analysis of variance, correlation analysis, and stepwise multiple regression to examine the possibility of using lidar measurements of reef rugosity, elevation and volume to predict reef fish abundance and species richness. These researchers find weakly significant relationships that vary across the seascape, for instance the lidar topographic complexity – species richness correlation is strongest in shallow habitats, and conversely, the relationship between lidar-assessed roughness and fish abundance is strongest in deeper offshore habitats. These studies of reef fish ecology both point out the need for improved understanding of behavior dynamics with respect to topographic complexity and other ecological factors, and demonstrate the importance of scale in identifying spatial correlation between lidar-derived metrics and reef fauna.

EMERGENT COASTAL LAND APPLICATIONS

Geomorphologists have traditionally based studies of coastal erosion and accretion, sediment transport and budgets, and flood hazards on repeated topographic profiling and shoreline mapping. Historically, shorelines and beach topography on nautical charts and topographic maps were compiled based on ground surveys and the visual interpretation of aerial photographs, until the 1920s, when aerial photogrammetry replaced plane table surveys as the primary shoreline mapping technique. In recent decades, new approaches have arisen for coast and shoreline mapping, including the use of high resolution satellite imagery, all-terrain kinematic GPS vehicles, and airborne lidar surveys (Liu, Sherman, and Gu, 2007).

Airborne lidar surveys are an efficient and powerful approach to shoreline mapping and change detection because lidar-based shorelines are referenced to the statistically established tidal datum surface, and thereby avoid problems with the interpretation of the wet – dry beach line. Airborne lidars tailored to coastal applications can provide detailed cross-environment seamless information on both nearshore bathymetry and beach topography along broad swaths that span the land – water interface. Further, lidar mapping allows analysis of beach and dune microtopography, and repeat surveys allow volumetric change analysis and the quantification of local sediment budgets (Liu, Sherman, and Gu, 2007).

During the coming decades, coastlines will respond to widely predicted sea-level rise, and detailed coastal topographic information is a key variable in understanding the likely impacts of this global natural hazard (U.S. Climate Change Science Program, 2009). Vulnerability maps that depict regions prone to flooding as sea level rises are essential to planners and managers responsible for mitigating the associated risks and costs to both human communities and ecosystems. The use of lidar in evaluating the vulnerability of low-lying coastal regions to inundation caused by relative sea-level rise is the topic of the paper submitted by Gesch. This contribution notes that sea-level rise inundation modeling relies upon a digital elevation model whose vertical accuracy and uncertainty greatly influences reliability.

Gesch points out that most maps of potential inundation along coastlines have been based on out-dated coarse elevation data, and accordingly amount to only crude representations that may serve to mislead decisionmakers. To demonstrate that the high vertical accuracy and spatial resolution of elevation data derived from lidar leads to improved identification and delineation of vulnerable lands, Gesch creates coastal inundation maps using four elevation datasets of varying resolution and accuracy. This analysis makes apparent that lidar mapping of low-lying coastal lands results in much improved assessments of vulnerability to sea-level rise.

Hurricanes are another serious coastal hazard along the Atlantic and Gulf coasts of the U.S., and airborne lidar mapping of beaches and dunes has been used extensively over the last decade in studies of barrier island vulnerability to severe storms (Sallenger, 2000). If, during hurricane landfall, the storm-induced mean water level overtops the crest of the primary dune, the entire beach system will be submerged, resulting in exposure to processes that can cause extreme coastal change, including wholesale dune removal, island breaching, and inlet formation. Recognizing the importance of dunes in predicting barrier island response to hurricane impact, Stockdon *et al.* present a novel approach to the use of lidar surveys in identifying the crest of the most seaward sand dune, the feature that defines the landward boundary of the beach system. Stockton *et al.* first apply a new algorithm to a lidar data set collected across Fire Island National Seashore, and assesses alongshore vulnerability by combining lidar-derived dune elevations to modeled wave set-up and storm surge height. By using accurate high resolution lidar topography, Stockdon *et al.* determine that the vulnerability of Fire Island to landfall of a Category 3 hurricane is not constant spatially due to longshore variability in dune height.

Hurricane storm surge also threatens coastal communities and watersheds, for example, the landfall of Hurricane Katrina near the Mississippi–Louisiana border at the Gulf Coast caused the largest natural disaster in U.S. history, with the loss of more than 1,800 lives and $81 billion in property damage (Turnipseed *et al.*, 2007). The coastal reach affected by flooding following levee failure and storm surge spanned a broad region along the north central Gulf Coast, and a regional integration of available high resolution lidar data sets was required to accurately evaluate storm surge and other effects. A myriad of disparate lidar surveys were acquired by separate projects in the aftermath of Hurricane Katrina, and Stoker *et al.* present the methodology that was developed to combine various dissimilar lidar data sets and thereby create a uniform 3-m elevation grid throughout the affected coastal region. In future, the use of the data assimilation techniques that Stoker *et al.* outline will no doubt allow rapid map creation resulting in more rapid recovery efforts and emergency response.

Interest in the role of moderate to high biomass forests in global biogeochemistry has driven the recent development of a subset of lidars designed to provide volumetric information on vegetation canopy structure (Harding *et al.*, 2001; Means *et al.*, 1999). Rather than providing several range measurements for each laser pulse, these instruments typically record the full time-resolved laser pulse backscatter from throughout the canopy to the underlying dry land surface (Blair and Hofton, 1999; Fowler, 2001). Results from experiments using these large-footprint temporal waveform-resolving lidars have confirmed capabilities to estimate the biomass and structural attributes of tall temperate and dense tropical forests (Drake *et al.*, 2002).

The contribution from Kempeneers *et al.* extends lidar vegetation mapping to the low canopy ecosystems of the Belgium coastal dune belt. The mapping of dune vegetation provides needed information on erosional resistance, and Kempeneers *et al.* evaluate the capability of a small-footprint lidar to map dune vegetation height and class. The authors find that fusion of spatially coincident multispectral imagery with lidar data provides sufficient information to create accurate and detailed maps of dune vegetative cover. Palaseanu *et al.* provide a second contribution focused on vegetation mapping, an evaluation of the capability of a small-footprint waveform-resolving lidar, the Experimental Advanced Airborne Research Lidar (EAARL), to delineate wetland vegetation assemblages in Jean Lafitte National Park in southern Louisiana. Using metrics derived from the EAARL laser soundings and ground transects of species composition, vegetative canopy, and ground cover, Palaseanu *et al.* compare two classes of statistical models for the classification of vegetative cover, generalized linear models and additive models. Although no statistically significant differences between the two model types are seen in classification accuracy, generalized additive models are superior in predicting vegetation presence/absence.

CONCLUSION

The contents of this Special Issue clearly demonstrate that airborne lidar surveys are of great value to both coastal scientists and resource managers. As evidenced by the articles presented herein, the broad applicability of airborne topographic lidar surveying to coastal studies stems from capabilities to map "bald earth" land topography and vegetation canopies, and also assess regional geomorphic change along barrier island beaches and other sandy coasts due to storms or long-term sedimentary processes. Similarly, lidar remote sensing from aircraft is of great value in defining low-lying regions susceptible to sea-level rise inundation, storm surge, or tsunamis, now enables analyses of geomorphic structure and change in shallow benthic environments, and supports spatially explicit studies of coral reef ecology. Further, blue-green lidar technology supports spatially explicit studies of coral reef ecology. Although not addressed by this Special Issue, coastal scientists are also adopting lidar remote sensing to assess landslides along seacliffs, subsidence causing coastal land loss, and the topographic monitoring of active volcanoes in continental margins.

Numerous recent studies have verified that current lidar systems, often coupled with passive optical imaging, are contributing to a wide range of coastal scientific investigations. Lidar observations acquired for most coastal research in the early 2000s were from "first generation" commercial systems that operated in the near infrared, did not penetrate water, recorded only the first and last returns, and had pulse rates of only a few thousand per second. Following rapid technological progress, current operational lidars for land surveys employ laser pulse rates in excess of 100,000 pulses per second, and make possible the mapping of hundreds of square kilometers of topography per day. The resolution of modern lidar systems is sufficient to address long standing questions regarding coastal geologic, hydrologic, and biologic processes, and provide morphological observations that are leading to a better understanding of coastal landscape change over time (Slatton *et al.*, 2007).

ACKNOWLEDGEMENTS

J. Brock and S. Purkis gratefully acknowledge T. Burress for invaluable assistance in reference searching, management of manuscript reviews, typesetting, and very thorough text editing. The editors also thank L. Travers and E. Klipp for the preparation of figures and the preparation of manuscripts for publication. The USGS Coastal and Marine Geology Program funded the publication of this Special Issue as a component of the Decision Support for Coastal Science and Resource Management.

LITERATURE CITED

Blair, J.B. and Hofton, M.A., 1999. Modeling laser altimeter return waveforms over complex vegetation using high-resolution elevation data. *Geophysical Research Letters*, 26(16), 2509-2512.

Brock, J.; Palaseanu-Lovejoy, M.; Wright, C.W., and Nayegandhi, A., 2008. Patch-reef morphology as a proxy for Holocene sea-level variability, northern Florida Keys, USA. *Coral Reefs*, 27(3), 555-568.

Brock, J.; Sallenger, A.H.; Krabill, W.; Swift, R.; Manizade, S.; Meredith, A.; Jensen, M., and Eslinger, D., 1999. Aircraft laser altimetry for coastal process studies. *Coastal Sediments '99: Proceedings of the 4th International Symposium on Coastal Engineering and Science of Coastal Sediment Processes* (Hauppauge, NY, American Society of Civil Engineers), pp. 2414-2429.

Brock, J.C.; Wright, C.W.; Clayton, T.D., and Nayegandhi, A., 2004. LIDAR optical rugosity of coral reefs in Biscayne National Park, Florida. *Coral Reefs*, 23(1), 48-59.

Brock, J.C.; Wright, C.W.; Kuffner, I.B.; Hernandez, R., and Thompson, P., 2006a. Airborne lidar sensing of massive stony coral colonies on patch reefs in the northern Florida reef tract. *Remote Sensing of Environment,* 104(1), 31-42.

Brock, J.C.; Yates, K.K.; Halley, R.B.; Kuffner, I.B.; Wright, C.W., and Hatcher, B.G., 2006b. Northern Florida reef tract benthic metabolism scaled by remote sensing. *Marine Ecology Progress Series*, 312, 123-139.

Costa, B.M.; Battista, T.A., and Pittman, S.J., 2009. Comparative evaluation of airborne lidar and ship-based multibeam sonar bathymetry and intensity for mapping coral reef ecosystems. *Remote Sensing of Environment*, 113, 1082-1100.

Drake, J.B.; Dubayah, R.O.; Clark, D.B.; Knox, R.G.; Blair, J.B.; Hofton, M.A.; Chazdon, R.L.; Weishampel, J.F., and Prince, S.D., 2002. Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment*, 79(2-3), 305-319.

Fowler, R.A., 2001. Topographic lidar. *In:* Maune, D.F. (ed.), *Digital elevation model technologies and applications: The DEM users manual.* Bethesda, MD: American Society for Photogrammetry and Remote Sensing, pp. 207-236.

Friedlander, A.M. and Parrish, J.D., 1998. Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. *Journal of Experimental Marine Biology and Ecology*, 224(1), 1-30.

Harding, D.J.; Lefsky, M.A.; Parker, G.G., and Blair, J.B., 2001. Laser altimeter canopy height profiles - Methods and validation for closed-canopy, broadleaf forests. *Remote Sensing of Environment*, 76(3), 283-297.

Krabill, W.B.; Collins, J.G.; Link, L.E.; Swift, R.N., and Butler, M.L., 1984. Airborne laser topographic mapping results. *Photogrammetric Engineering and Remote Sensing*, 50(6), 685-694.

Kuffner, I.B.; Brock, J.C.; Grober-Dunsmore, R.; Bonito, V.E.; Hickey, T.D., and Wright, C.W., 2007. Relationships between reef fish communities and remotely sensed rugosity measurements in Biscayne National Park, Florida, USA. *Environmental Biology of Fishes*, 78(1), 71-82.

Liu, H.; Sherman, D., and Gu, S., 2007. Automated extraction of shorelines from airborne light detection and ranging data and accuracy assessment based on Monte Carlo simulation. *Journal of Coastal Research*, 23(6), 1359-1369.

McCormick, M.I., 1994. Comparison of field methods for measuring surface topography and their associations with a tropical reef fish assemblage. *Marine Ecology Progress Series*, 112(1-2), 87-96.

Means, J.E.; Acker, S.A.; Harding, D.J.; Blair, J.B.; Lefsky, M.A.; Cohen, W.B.; Harmon, M.E., and McKee, W.A., 1999. Use of large-footprint scanning airborne lidar to estimate forest stand characteristics in the Western Cascades of Oregon. *Remote Sensing of Environment*, 67(3), 298-308.

Purkis, S.J., 2005. A 'reef-up' approach to classifying coral habitats from IKONOS imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 43, 1375-1390.

Purkis, S.J. and Kohler, K.E., 2008. The role of topography in promoting fractal patchiness in a carbonate shelf landscape. *Coral Reefs*, 27, 977-989.

Purkis, S.J.; Myint, S., and Riegl, B., 2006. Enhanced detection of the coral *Acropora cervicornis* from satellite imagery using a textural operator. *Remote Sensing of Environment*, 101, 82-94.

Purkis, S.J. and Pasterkamp, J., 2004. Integrating *in situ* reef-top reflectance spectra with Landsat TM imagery to aid shallow-tropical benthic habitat mapping. *Coral Reefs*, 23, 5-20.

Purkis, S.J. and Riegl, B., 2005. Spatial and temporal dynamics of Arabian Gulf coral assemblages quantified from remote-sensing and *in situ* monitoring data. *Marine Ecology Progress Series*, 287, 99-113.

Sale, P.F., 1991. Habitat structure and recruitment in coral reef fishes. *In*: Bell, S.S., McCoy, E.D. and Mushinsky, H.R. (eds.), *Habitat structure:*

Sallenger, A.H., Jr., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research*, 16(3), 890-895.

Sallenger, A.H., Jr.; Krabill, W.; Brock, J.; Swift, R.; Jensen, M.; Serdar, M.; Richmond, B.M.; Hampton, M., and Eslinger, D., 1999. Recent el Niño eroded U.S. west coast: A study conducted with the help of an airborne laser found that much of the U.S. west coast was altered due to effects of the 1997-1998 el Niño. *Earth in Space*, 5-9.

Sallenger, A.H., Jr.; Krabill, W.B.; Swift, R.N.; Brock, J.; List, J.; Hansen, M.; Holman, R.A.; Manizade, S.; Sontag, J.; Meredith, A.; Morgan, K.; Yunkel, J.K.; Frederick, E.B., and Stockdon, H., 2003. Evaluation of airborne topographic lidar for quantifying beach changes. *Journal of Coastal Research*, 19(1), 125-133.

Sallenger, A.H., Jr.; Wright, C.W., and Lillycrop, W.J., 2007. Coastal-change impacts during Hurricane Katrina: an overview. *Coastal Sediments '07: Sixth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes: proceedings* (New Orleans, LA, American Society of Civil Engineers), pp. 888-896.

Sebens, K.P., 1991. Habitat structure and community dynamics in marine benthic systems. *In*: Bell, S.S.; McCoy, E.D., and Mushinsky, H.R. (eds.), *Habitat structure: The physical arrangement of objects in space*. New York: Chapman and Hall, pp. 211-234.

Slatton, K.C.; Carter, W.E.; Shrestha, R.L., and Dietrich, W., 2007. Airborne laser swath mapping: Achieving the resolution and accuracy required for geosurficial research. *Geophysical Research Letters*, 34(23), L23S10.

Storlazzi, C.D.; Logan, J.B., and Field, M.E., 2003. Quantitative morphology of a fringing reef tract from high-resolution laser bathymetry: Southern Molokai, Hawaii. *GSA Bulletin*, 115(11), 1344-1355.

Szmant, A.M., 1997. Nutrient effects on coral reefs: a hypothesis on the importance of topographic and trophic complexity to reef nutrient dynamics. *Proceedings of the 8th International Coral Reef Symposium* (Balboa, Panama, Smithsonian Tropical Research Institute), pp. 1527-1532.

Turnipseed, D.P.; Wilson, K.V., Jr.; Stoker, J., and Tyler, D., 2007. Mapping hurricane Katrina peak storm surge in Alabama, Mississippi, and Louisiana. *Proceedings of the 37th Mississippi Water Resources Conference* (Jackson, MS, Mississippi State University), pp. 202-207.

U.S. Climate Change Science Program [Lead authors: Titus, J.G.; Anderson, K.E.; Cahoon, D.R.; Gesch, D.B.; Gill, S.K.; Gutierrez, B.T.; Thieler, E.R., and Williams, S.J.], 2009. Coastal sensitivity to sea-level rise; a focus on the mid-Atlantic region. *U.S. Environmental Protection Agency, National Oceanic and Atmospheric Administration, U.S. Geological Survey U.S. Climate Change Science Program synthesis and assessment product 4.1*, 320p.

Wang, C-K. and Philpot, W.D., 2007. Using airborne bathymetric lidar to detect bottom type variation in shallow waters. *Remote Sensing of Environment*, 106, 123–135.

Wright, W.C. and Brock, J.C., 2002. EAARL: A LIDAR for mapping shallow coral reefs and other coastal environments. *Proceedings: Seventh International Conference on Remote Sensing for Marine and Coastal Environments* (Miami, FL, Veridian International Conferences).

Xhardé, R.; Long, B.F., and Forbes, D.L., 2006. Accuracy and limitations of airborne LiDAR surveys in coastal environments. *2006 International Geoscience and Remote Sensing Symposium* (Denver, CO, IEEE), pp. 2412-2415.