Assessing Transient Threats and Disasters in the Coastal Zone with Airborne Portable Sensors

1. Science and Application Target

How can we provide rapid input to help communities prepare, respond, mitigate and potentially recover from aquatic threats and disasters?

Every year, disasters threaten natural environments and human communities around the globe. Life, property, and commerce along the coast are vulnerable to the formidable forces of nature and threats from accidents or other human-caused problems. Hurricanes, tsunamis, harmful algal blooms, and oil spills represent just a few of the transient threats that threaten ecosystems and the services they provide. Such intermittent threats can occur on time scales of hours and can require immediate responses by communities to mitigate their impacts. *The overarching challenge is to provide useful, accurate products on the time and space scales that are appropriate for emergency responders and decision makers*.

To date, environmental hazard monitoring has primarily focused on land-based hazards, such as volcanoes, droughts, floods, landslides, and fires, and their impacts on land surfaces. Natural hazards, however, have tremendous impacts on the world's oceans, the communities residing along coastlines and the economies they support. Recent years have witnessed record-breaking events impacting coastal zones and costing millions in dollars. Large and infrequent events like hurricanes and tsunamis alter the landscape of coastline, impact water quality, devastate coastal habitats, and greatly impact organisms within the coastal zone as well as communities residing along the coasts. *Can optical remote sensing be used to help monitor large weather events and resulting impacts such as flooding of coastal communities and associated floating debris and pollution?*

Marine and estuarine phytoplankton can grow and accumulate rapidly in dense, visible patches near the surface of the water. Some of the species produce potent neurotoxins that can be transferred through the food web where they can adversely impact higher forms of life such as zooplankton, shellfish, fish, birds, marine mammals and even humans. The mechanisms producing such harmful blooms are not easy to predict and monitoring is warranted to protect communities from these toxins both in the foods they eat and the air they breathe. However, false positives are common in forecasting programs resulting in unnecessary closures of shellfish fisheries and beach access. *How can the detection of harmful algal blooms be improved and monitored and forecasted across large areas of the coast?*

Petroleum products are essential to modern society and must be transported over considerable distances over land and sea. Ten to fifteen transfers are typically involved in moving oil from the oil field to the final consumer and many of these transfers occur on ships or pipelines on the seabed. In addition to transportation accidents, oil spills can also result from the controlled release by shipping operators and from oil production platforms. Marine oil spills can be dispersed over large distances by wind, waves and currents within a few hours and severely impact organisms ranging from microscopic phytoplankton to marine birds and mammals. The livelihood of residents of coastal communities are impacted by oil spills, particularly those based on fishing and tourism. *How can the composition, extent, and depth of oil spills be detected rapidly and tracked over hourly time scales on the ocean surface?*

2. Measurement Needs

Each threat or hazard has its own set of requirements that must be addressed. However, the following general issues can be applied to a variety of aquatic hazards and include assessments of:

1) The spatial extent affected by the hazard
2) The dispersion or movement of the hazard
3) The severity or classification of the hazard
4) The impacted communities or ecosystems

Remote sensing tools need to have the appropriate spatial and temporal resolution to be of optimal use to communities and responders. Each of the above issues are addressed below.

Spatial extent. The spatial scale over which hazards occur varies according to the type of event. Hurricanes and Tsunamis are generally of large spatial scale and can cover 10 to 100's of kilometer in scale. However, the spatial extent of flooding, plumes of suspended materials and pollutants, and damage to habitats often requires fine scale spatial resolution on the scale of 1-30 m. Harmful algal blooms and oil spills can cover 100's of kilometers, but assessing plumes and dispersion requires similar spatial scales. In addition, cloud cover can be a major limiting factor in providing immediate imagery in visible wavelengths of a threat or disaster and those resulting from storms.

Movement or Dispersion. The time scale to which information about pending threats and hazards is generally on the order of hours with repeat coverage required on hourly and daily timescales depending on the location and speed of the event. Remote sensing observations can be assimilated into biophysical models of circulation to compensate for gaps in cloud cover and provide forecasts of areas most likely impacted by the threat or disaster.

Severity. The severity or intensity of a threat is generally a physical quantity such as the amount of oil or toxins within or floating on the water. In the case of oil spills both the thickness of the oil slick and the type of oil spilled is critical to cleanup efforts. Hurricane intensity is based on storm size and sustained windspeeds and impacts include the extent of flooding and amount of debris and suspended matter in the water column. Better methods are required to distinguish the optical fingerprints of various pollutants and suspended matter. And, improvements in accuracy of harmful algal bloom warning systems is warranted across the different bloom types and associated impacts.

Impacted communites/ecosystems. The ability to have prior knowledge of a coastline can be invaluable for assessing damage and mitigation strategies for threats. Such knowledge includes maps of bathymetry that are seamless from water to land and location and density of different types of coastal habitats. In the case of spills, for example, berms can be setup to protect the most vulnerable habitats and organisms. Historical data can be archived to identify the ecosystems most likely to be impacted by various natural and human-made threats and used to make adaptive sampling strategies.

3. Technology: Portable Sensors from Suborbital Platforms

Portable sensors flown on aircraft or unmanned aerial vehicles (UAV's or drones) provide a critical sampling niche distinct from satellite-borne sensors that is particularly well suited for monitoring transient threats to the coastal zone. NASA has long been a leader in developing and deploying sub-orbital remote sensing platforms. Airborne sensors can sample at fine spatial scales (< 1 m) and be deployed repeatedly throughout the day with nearly unlimited repeat coverage. UAV flight lines and scanning geometries can also be oriented to optimize retrievals (e.g., avoid sun glint) and their range can be greatly expanded by launching from ships.

With advances in sensor and platform technology, UAVs can be equipped with multiple sensors for simultaneous measurement of a diverse suite of parameters from both passive and active sensors. The following are a few of the sensors that could be incorporated effectively together on a drone.

A. Imaging spectroscopy. The Portable Remote Imaging SpectroMeter (PRISM) developed by NASA Jet Propulsion Lab was designed with a high dynamic range and signal:noise specifically for coastal applications (Mouroulis et al. 2008, 2013, **Table 1)**. The sensor is portable and has been equipped to fly on low altitude Twin Otter aircraft with 70 cm pixels and on higher flying ER-2 aircraft with 8-10 m pixels. This sensor could be adapted to be mounted on a variety of aerial autonomous aircraft as well.

Hyperspectral imagery from aircraft systems in visible and near infrared wavelengths is useful for monitoring coastal ecosystems such as seagrass and corals at high resolution (Hill et al. 2014, Hedley et al. 2016) and can be used to monitor changes in ecosystems (**Fig. 1** (Dierssen et al. 2003). It can also be used to detect sediment plumes from rivers and storm events and to delineate coastlines and water depth in flooded coastal lands (Dekker et al. 2011).

B. Fluorescence lidar. In the upper layer of the ocean, oil slicks and chlorophyll can both be detected with active fluorescence lidar. In the early 1970s, the first airborne laser fluorosensor was flown to map the extent of oil slicks (Brown & Fingas 2003) and the technology has been refined and further developed over time (Fingas & Brown 2014).

Fluorescence lidar can be used for oil identification, and to estimate the thickness of oil films at the water surface (Li et al. 2014). Both the spectral shape of fluorescence induced from surface water and the intensity ratio of two channels (I_{495}/I_{405}) can be used to characterize oil spills.

C. Bathymetry lidar. At present, the most effective means to map shallow water bathymetry is with active lidar systems ((Dierssen & Theberge 2012). Generally, two lasers are employed to estimate bathymetry: 1) an infrared laser (1064 nm), which does not penetrate water, is used to detect the sea surface and 2) a green laser (532 nm) is used to penetrate into the water column and provide a return signal from the seafloor (Quadros & Collier 2010). In coastal waters, green light is the least absorbed and generally penetrates the deepest into the water column.

In ideal conditions, depths up to 60 m have been measured with LIDAR systems (Wozencraft & Millar 2005), but most applications are limited to depths <40 m. Current LIDAR measurements with an elevation accuracy of 10–30 cm can provide point measurements from 0.1 to 8 pixels per m2. They have been successfully used to map bathymetric features, beach erosion, coral reefs, and coastal vegetation. Unlike acoustic sensors on ships, lidars can also be useful for delineating coastlines and providing a seamless transition between the land and water interface (Fig. 2).
.

4. Technology Needs

Assessing threats and hazards requires higher temporal, spatial, and spectral resolution imagery than currently available from satellite platforms. As discussed above, the technology for developing portable sensors and drones has advanced significantly over the last decade. Investment into this technology would allow for ***the development of a fleet of well-equipped drones that could be deployed to respond to immediate threats and hazards along the U.S. coastal zone.*** These drones could include state of the art sensors such as the imaging spectrometers, fluorescence and bathymetric lidars and automated processing routines to provide near real time monitoring of the coastal zone. They would also allow a platform to test new sensors and applications that could inspire the creativity of a generation of new scientists.

Such sensors may in theory be flown beneath clouds, although many challenges remain for producing quality passive imagery beneath cloud-covered skies. Active sensors that can penetrate cloud-cover may also be warranted for providing time-series of measurements and improved forecasting.

In addition to new sensors and platforms, the following issues must also be addressed:

- Rapid-assessment processing of imagery is needed that requires no ancillary data or imagery that is not immediately available. e.g., Current routine ocean color processing requires ancillary data for parameters such as ozone, humidity, wind speed.

- New and improved algorithms are needed that are not merely site-specific empirical regressions, but instead can accurately determine the quantity and composition of floating and suspended materials across diverse aquatic environments and to assess bathymetry and seafloor composition.

- Improved atmospheric correction approaches must be developed to deal with significant amounts of near-infrared reflectance and absorbing aerosols common over coastal regions and potentially correlated with particular hazards (e.g., dust, precipitation, ice clouds, etc…).

- Integrated modeling and data assimilation efforts will be required to tie together in situ measurements and diverse remote sensing data, such as sea surface temperature, vector winds, bathymetry, and delineation of coastal fronts and other surface phenomena (e.g., using Synthetic Aperture Radar) into biophysical models. Expanded model testing to different regimes would be necessary to improve skill for future predictions.

The creation of a fleet of airborne drones was included in "Earths Living Ocean: The Unseen World", the Advanced Plan for NASA's Ocean Biology and Biogeochemistry in 2006 (**Fig. 3**). Airborne drones would fill a unique niche that would allow NASA to rapidly and repeatedly observe transient threats and hazards along the coastal zone in an integrated, comprehensive, and organized manner.

Authored

Heidi Dierssen, University of Connecticut, heidi.dierssen@uconn.edu
With input provided by the NASA Decadal Survey Advance Planning Team, W. Scott Pegau Oil Spill Recovery Institute.

References

Brown CE, Fingas MF (2003) Review of the development of laser fluorosensors for oil spill application. Mar Pollut Bull 47:477–484

Dekker AG, Phinn SR, Anstee J, Bissett P, Brando VE, Casey B, Fearns P, Hedley J, Klonowski W, Lee ZP, others (2011) Intercomparison of shallow water bathymetry, hydro-optics, and benthos mapping techniques in Australian and Caribbean coastal environments. Limnol Ocean Methods 9:396–425

Dierssen HM, Theberge AE (2012) Bathymetry: Assessing Methods. In: Encyclopedia of Ocean Sciences. Taylor and Francis, New York, NY

Dierssen HM, Zimmerman RC, Leathers RA, Downes TV, Davis CO (2003) Ocean color remote sensing of seagrass and bathymetry in the Bahamas Banks by high resolution airborne imagery. Limnol Ocean 48:444–455

Fingas M, Brown C (2014) Review of oil spill remote sensing. Mar Pollut Bull 83:9–23

Hedley J, Russell B, Randolph K, Dierssen H (2016) A physics-based method for the remote sensing of seagrasses. Remote Sens Environ 174:134–147

Hill VJ, Zimmerman RC, Bissett WP, Dierssen H, Kohler DD (2014) Evaluating Light Availability, Seagrass Biomass, and Productivity Using Hyperspectral Airborne Remote Sensing in Saint Joseph's Bay, Florida. Estuaries Coasts:1–23

Li X, Zhao C, Ma Y, Liu Z (2014) Field experiments of multi-channel oceanographic fluorescence lidar for oil spill and chlorophyll-a detection. J Ocean Univ China 13:597–603

Mouroulis P, Green RO, Wilson DW (2008) Optical design of a coastal ocean imaging spectrometer. Opt Express 16:9087–9096

Mouroulis P, Van Gorp B, Green RO, Dierssen H, Wilson DW, Eastwood M, Boardman J, Gao B-C, Cohen D, Franklin B (2013) The Portable Remote Imaging Spectrometer (PRISM) coastal ocean sensor: design, characteristics and first flight results.

Quadros ND, Collier PA (2010) A New Approach to Delineating the Littoral Zone for an Australian Marine Cadastre.

Wozencraft J, Millar D (2005) Airborne lidar and integrated technologies for coastal mapping and nautical charting. Mar Technol Soc J 39:27–35

Table 1. Characteristics of an imaging spectrometer for coastal ecosystems (Mouroulis et al. 2013)

Table 1. Spectrometer Characteristics

Spectral	Range	349.9–1053.5 nm
	Sampling	2.83 nm
	Resolution (FWHM)	3.5 nm typ
	Calibration uncertainty	<0.1 nm
Spatial	Field of view (FOV)	30.7°
	IFOV sampling	0.882 mrad
	IFOV resolution (FWHM)	0.97 mrad
	Cross-track spatial pixels	608
Radiometric	Range	0%–99% R
	Sampling	14 bit
	Calibration uncertainty	<2%
	Signal-to-noise ratio[a]	500 at 450 nm
	Polarization variation	<1%
Uniformity	Spectral cross-track uniformity	>95%
	Spectral IFOV uniformity	>95%

[a]At a single integration (167 Hz rate) and three-band aggregate (8.5 nm), 5% reflectance, 45° solar zenith, MODTRAN standard atmosphere.

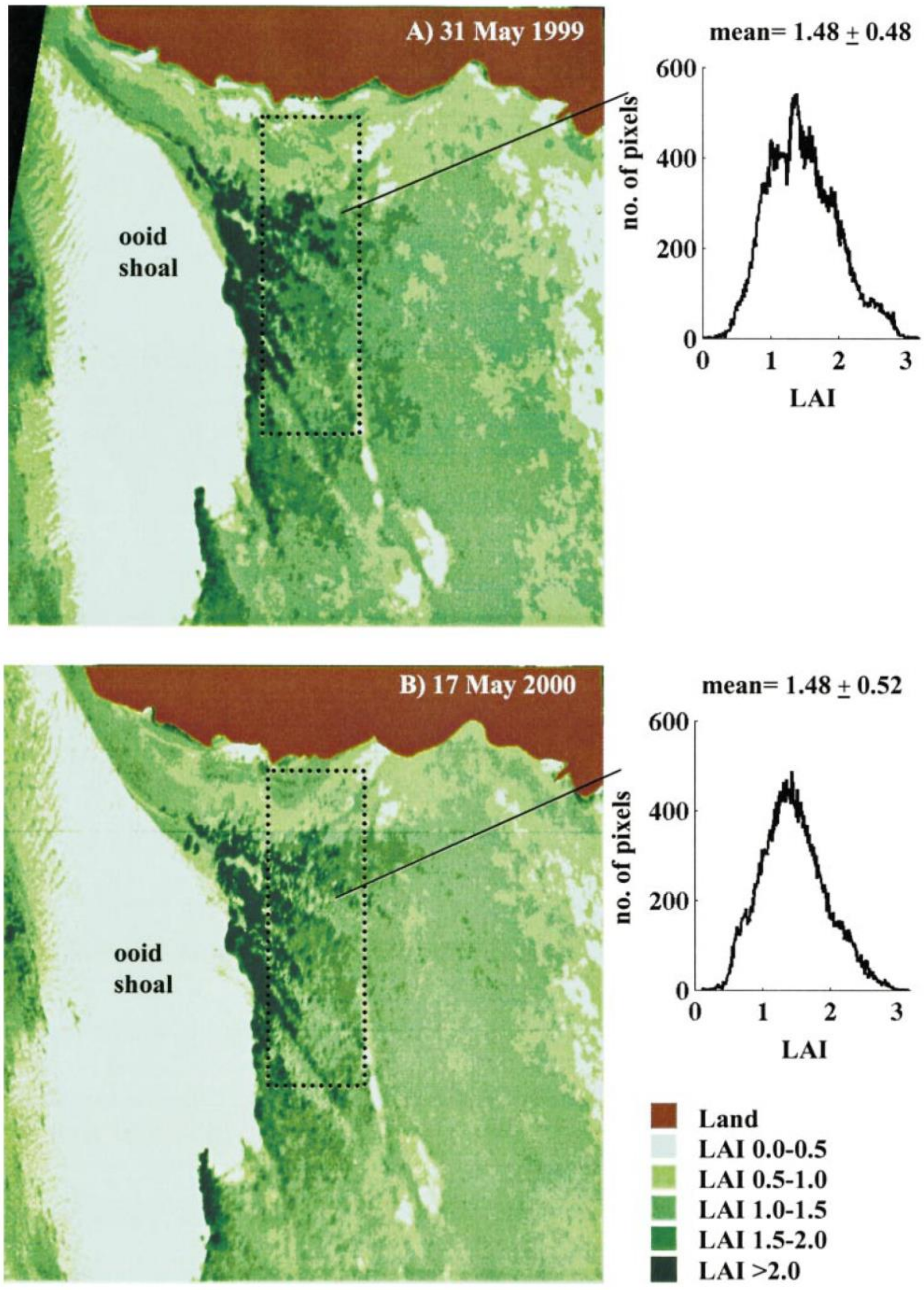

Fig. 1. Adapted from Dierssen et al. (2003). Seagrass Leaf Area Index (LAI) modeled with PHILLS imagery before and after Hurricane Floyd, a category 4 storm with winds of 135 mph and gusts up to 190 mph, passed directly across this area on 14 September 1999. Although this storm inflicted significant damage to structures on neighboring Lee Stocking Island, the turtlegrass distributions in this relatively protected site to be virtually undisturbed.

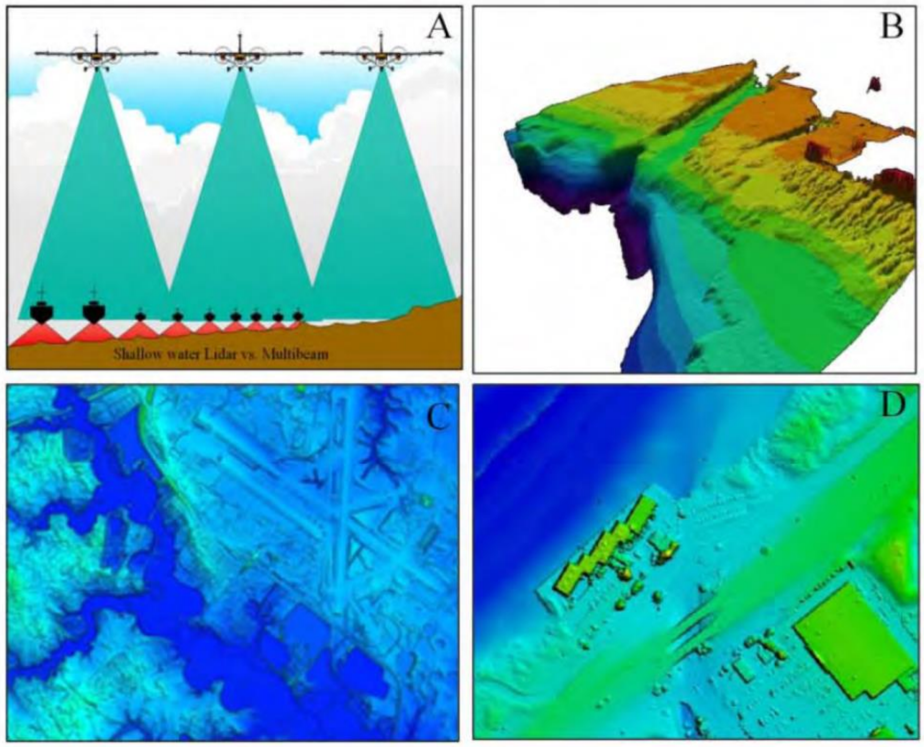

Fig. 2. Adapted from Dierssen and Theberg (2012). A) Airborne LIDAR provides a large sampling swatch for collecting bathymetry data compared to ship-based sonar systems and B) can seamlessly blend water and land elevations in one image for precise coastline delineation. LIDAR data collected in C) coastal Delaware can be used for mapping projected sea-level rise; and D) Monterey Bay for evaluating erosion patterns along a seawall jutting into the coastal zone. Images in Panel A and Panel B provided courtesy of Optech Industries. Images from Panel C and Panel D are available from the NOAA Coastal Services Center Digital Coast project.

Immediate (1-5 years)

Continued development of airborne lidar and imaging systems for algorithm and technology improvement in coastal waters. Develop partnerships with science and technology groups at NASA to develop strategies for sub-orbital platforms for use in understanding habitats and hazards in coastal ecosystems.

Near-term (5-10 years)

Develop and implement portable sensor technologies which can be deployed on Unmanned Aerial Vehicles (UAV). Deploy the prototype coastal ocean habitat / hazard UAV system.

Long-term (10-25 years)

UAV fleet development with portable sensors deployable throughout the globe at short notice to track hazardous spills, storm surges, changes in critical coastal habitats, red tides, and shipping lanes. Development activities include optimization algorithms for UAV deployment.

Fig. 3. From the NASA Ocean Biology and Biogeochemistry Advanced Plan (2006) outlining the desired priorities from immediate (0-5 years, which has been pursued) to long-term (10-25 years) outlining the fleet of UAVs with portable sensors.