Deriving water depth, bottom features and water column optical properties using satellite remote sensing

Christopher Ilori[1] and Anders Knudby[2]

1 Geography, Simon Fraser University, BC, cilori@sfu.ca
2 Geography, Simon Fraser University, BC, aknudby@sfu.ca

Abstract

Despite 40 years of satellite observations of Earth, scholars have paid little attention to developing sustainable methods that allow retrospective and long term monitoring of coastal resources. To address this crucial shortcoming, we aim to develop remote sensing techniques to obtain baseline information about coastal ecosystems in Canada and Croatia. This will allow evidence-based coastal management, and ultimately help to build coastal resilience.

Background and relevance

Shallow coastal environments present unique challenges for navigation and security and provide valuable ecosystem services (Costanza et al., 1997). They play a crucial role in sustaining global biodiversity and mitigate the impact of storms, floods and wave damage for people living in coastal regions (Orth et al., 2006; Burke, Reytar, Spalding, & Perry, 2011). They also serve as critical habitats for submerged aquatic vegetation (SAV) - an important barometer for water quality and a highly effective sink for atmospheric carbon dioxide (Tokoro et al., 2014). Despite the ecological function and societal value of these ecosystems, our understanding of these environments is limited by their dynamic nature and our lack of effective monitoring systems. Seafloor topography is typically mapped from infrequent surveys of limited extent, and spatial and temporal dynamics of key ecosystem components such as benthic habitats are assessed on the basis of sparsely and unevenly distributed point observations collected by divers or others with limited coverage (Green & Short, 2003;Wilkinson, 2008).

Remote sensing, specifically the use of satellite data can provide global and frequently updated data coverage that allows derivation of up-to-date information on shallow water environments (Knudby, Newman, Shaghude, & Muhando, 2010; Lyons, Phinn & Roelfsema, 2012). Information obtained from the satellite data record (1972-present) allows retrospective studies that can improve our understanding of their long-term and large-scale dynamics. However, extracting information from the satellite data record is complicated because radiative (light) transfer in optically shallow water (where both the water column and the seafloor contribute to the sensed signal) is an underdetermined problem with three primary and typically unknown components: water depth, water column optical properties, and seafloor spectral reflectance (Mobley, 1994; Hedley & Mumby, 2003). Empirical methods have been developed for mapping water depth and habitat types at a local scale (Lyzenga, 1978; 1981). These methods rely on calibration from coincident field observations to estimate the unknown components. This improves habitat discrimination (Mumby, Green, Edwards, & Clark, 1997, but reliance on coincident field data, which are expensive to collect and not always available means that application in systematic regional or global monitoring systems is difficult. More recently, methods that do not require field data for calibration have been developed for hyperspectral remote sensing data. Pioneered by Lee et al. (Lee, Carder, Mobley, Steward, & Patch, 1998; 1999), these semi-analytical methods use radiative transfer models to simulate the spectral

reflectances above the water surface with a given set of inputs that include (or can be used to derive) the three unknown parameters: water depth, water column optical properties, and seafloor reflectance.
Although radiative transfer models were initially developed for airborne hyperspectral, recent studies suggest that they can even be applied to multi-spectral satellite data with acceptable results (Hedley, Roelfsema, Koetz, & Phinn, 2012). This would dramatically expand their practical application to include remote and inaccessible areas, retrospective change detection studies, and operational monitoring systems at regional and global scales.

Methods and data

The research objectives are to 1) develop methodologies that enable long-term and global-scale monitoring of shallow coastal environments, and 2) provide a comprehensive assessment of radiative transfer modeling applied to satellite multi-spectral data (from two different study areas), as the accuracy of parameter estimates derived from applying radiative transfer model to real multispectral satellite data has never been assessed. This leaves a large research gap to be filled. Research for all objectives will be based on Lee et al.'s semi-analytical model and Mobley et al.'s (Mobley et al., 2005) spectrum matching and look-up table approach.

For objective 1, we will run an open source underwater radiative transfer model (PlanarRad) (Hedley, 2008) through a database of measured seafloor reflectance and a range of realistic water depths and optical properties to produce look-up tables containing simulated above-water reflectance spectra. Reflectance spectra will be obtained in both Boundary Bay, BC, Canada and Kornati National Park, Croatia, with an OceanOptics Jaz spectrometer in an underwater housing. The database will also contain other information, e.g. on water depth and water column optical properties (absorption and scattering characteristics of water), and environmental condition such as sun angle, wind speed and tidal state. Only the range that is typical of the study sites will be needed. Each spectrum in the database has associated water column properties. For parameter retrieval, reflectance spectra from a remote sensing image (satellite imagery) of the area(s) will be taken and a search in the database will be performed to find closest match among all spectra. This match is then used as a direct indication of the water depth, water optical quality, and seafloor spectral reflectance, from which habitat type can be inferred. Maps of seafloor feature, water depth or water column properties of an area can be obtained by repeating this process for all pixels in the satellite image.

The derived water optical properties (absorption and scattering coefficients) can in turn be used to estimate concentrations of the absorbing and scattering agents in the water, which primarily include chlorophyll-a, colored dissolved organic matter, and inorganic particulate matter. The advantage of this approach over the empirical method is that 1) it does not rely on coincident field data for calibration (although, a set of possible seafloor reflectance spectra are needed, they can be assumed to be time invariant and thus need only to be measured once), and 2) it simultaneously derives all three unknown parameters. The above process can be fine-tuned to fit any coastal environment, though it is important to note that new field data typical of the environment may be needed where existing data are not representative.

To achieve objective 2, simulated spectra will be resampled to match sensor spectral response functions. Realistic levels of sensor-environment noise (error) (Brando & Dekker, 2003) will then be added to produce noise-affected look-up tables, and the resulting errors in water depth, water optical properties and seafloor spectral reflectance retrieval will be determined in a sensitivity analysis in PlanarRad. Field observations of depth and seafloor spectral reflectance from the two sites will be used with the available remote sensing data to assess errors in water depth and seafloor spectral reflectance retrievals in real/operational contexts (Dekker et al., 2011).

Atmospheric correction based on Montes and Gao's model (Montes & Gao, 2004) will be performed before modeling in PlanarRad. This will account for the effects of cloud and sun glint on an image. Other necessary image pre-processing will be implemented in R (R Development Core Team, 2008) and Python programming languages (van Rosum, 1995) for automation purposes. Existing field data for the proposed research include: For Croatia: >5000 geographically referenced depth and habitat observations, and 3 seafloor reflectance spectra. For Canada: >7000 geographically referenced depth observations, and 3 reflectance spectra. We have collected a total of 5,958 data points in Kornati National Park, Croatia between October 2-6, 2014 using an underwater video camera. In addition, the 3 collected seafloor spectra are based on a total of 163 individual spectral measurements, which were then aggregated to provide descriptions of the 3 common seafloor types in Kornati National Park: a) dense seagrass meadow, b) unvegetated sand, and c) algae-covered rock. Existing remote sensing data for this research include: For Croatia: > One high-resolution (40cm) air photo mosaic. For Canada: One RapidEye and one Worldview-2 satellite image. Additional publicly available data will be used, including Landsat and Sentinel-2 data (Sentinel-2A launch expected in April, 2015). New data to be collected for the Canadian field site include: 500 geographically referenced habitat and depth observations acquired using an instrument combination of underwater video, GPS, and depth transducer.

Conclusions

Water depth: Nautical (bathymetry) charts are crucial for nearshore navigation, including fisheries, transportation of goods, tourism, and defense, but they are time-consuming and costly to produce with traditional boat-based acoustic technology. Satellite-derived bathymetry will not replace high-resolution and up-to-date bathymetric charts for shallow areas, but the proposed research will develop and test the methodology necessary to produce regularly updated bathymetric charts from nearshore areas, a previously inconceivable task. Satellite-derived bathymetry is of great interest to national hydrographic services (recently adopted by the French hydrographic office), including in Canada where large parts of the Arctic are only covered by nautical charts, and where some charts have not been updated since the 1940'es. **Water column optical properties:** Satellite-derived estimates of chlorophyll-a, colored dissolved organic matter and inorganic particulate matter are of direct use in water quality monitoring. Satellite-derived water quality measurements, though limited to observable surface waters, enable regular and cost-effective monitoring of water quality with complete coverage of water bodies. In Canada, monitoring of water quality is particularly difficult given the numerous and large lakes that exist. Although data for the proposed research are all from marine environments, the radiative transfer model inversion methodology as well as the expected errors and error sources applies equally well to fresh water. The results will thus be of direct use both research into spatial and temporal water quality patterns in Canada. **Seafloor spectral reflectance:** Seafloor habitat can be directly inferred from seafloor spectral reflectance. The proposed research will use such inference to improve upon the accuracy of current habitat maps. Such maps are crucial for monitoring specific habitat types. For example, seagrasses meadows along the BC coast function as nursery grounds for a range of commercial fish species, but are thought to be in decline. The proposed research will allow cost-effective monitoring of seagrass and other submerged aquatic vegetation, including the possibility of retrospective change detection studies.

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