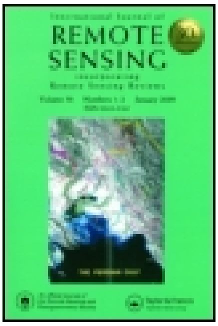

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Field calibration and validation of remote-sensing surveys

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The Optical Collection Suite (OCS) is a ground-truth sampling system designed to perform *in situ* measurements that help calibrate and validate optical remote-sensing and swath-sonar surveys for mapping and monitoring coastal ecosystems and ocean planning. The OCS system enables researchers to collect underwater imagery with real-time feedback, measure the spectral response, and quantify the water clarity with simple and relatively inexpensive instruments that can be hand-deployed from a small vessel. This article reviews the design and performance of the system, based on operational and logistical considerations, as well as the data requirements to support a number of coastal science and management projects. The OCS system has been operational since 2009 and has been used in several ground-truth missions that overlapped with airborne lidar bathymetry (ALB), hyperspectral imagery (HSI), and swath-sonar bathymetric surveys in the Gulf of Maine, southwest Alaska, and the US Virgin Islands (USVI). Research projects that have used the system include a comparison of backscatter intensity derived from acoustic (multibeam/interferometric sonars) *versus* active optical (ALB) sensors, ALB bottom detection, and seafloor characterization using HSI and ALB.

1. Introduction

Remote-sensing data and tools are increasingly being used in supporting coastal ecosystem studies, coastal zone management, seafloor characterization, and ocean planning (Green et al. 1996; Cracknell 1999; Kenny et al. 2003; Brock and Purkis 2009). However, a topic that often receives insufficient attention is the field component of calibration and validation of coastal remote-sensing data. As these data and derived coastal geospatial products are frequently used in supporting planning and policy decisions (e.g. coastal land use, coastal engineering projects, habitat protection, and restoration), it is imperative to be able to answer questions relating to the performance of various sensors under different environmental conditions and the level of detail that can be resolved by each sensor's observations.

Complicating the calibration and validation of coastal remote-sensing data is the fact that the area of interest comprises both land features and submerged features. Because water transparency varies with wavelength and depth, it is difficult to relate even submerged features at different water depths. Many studies aim to integrate observations from different sensors (data fusion) and infer the seafloor facies and/or habitat classes, which can increase

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the amount and quality of information available, but further complicates the calibration and validation of the fused data sets.

Without significant meaningful ground control, coastal remote-sensing surveys are incomplete. *In situ* measurements are required as ground truth to validate the data interpreted from airborne lidar bathymetry (ALB), hyperspectral imagery (HSI), and swath-sonar surveys (Fonseca et al. 2009; Pe'eri, Ackerman, et al. 2011; Pe'eri, Gardner, et al. 2011; McMullen et al. 2011). Ground-truth facilitates decoupling topographic and bathymetric surface characteristics (e.g. elevation or depth, rugosity, aspect, and slope) from the physical characteristics of the site (e.g. sediment type, submerged aquatic vegetation species, and abundance). Intensity and backscatter images may vary from one survey line to another because of changes in vehicle orientation, slope of the seafloor, angles of incidence, water clarity, and the tidal stage (water level).

This article describes a new *in situ* benthic sampling system that incorporates video imagery with spectral measurements, depth measurements, and GPS. The ability to simultaneously extract colour and texture information at the same location makes the Optical Collection Suite (OCS) system a useful tool for adding baseline control points to data acquired from the ALB, HSI, and swath-sonar surveys in shallow water. The uses of and technical requirements for the OCS system are presented with the specifications of the components selected to satisfy those requirements. Technical details of the components of the OCS system (including WAAS-enabled GPS, seafloor reflectance spectra, diffuse attenuation coefficient, and underwater video imagery) are described, followed by a discussion of the data sets acquired by the various instruments, and a description of the use of the data sets in a number of coastal science and mapping applications since 2009.

2. Optical remote sensing

HSI is a remote-sensing method that has been used successfully for many years as a tool for classifying sediment and vegetation over terrestrial environments (Goetz et al. 1985; Landgrebe 2003). Most airborne hyperspectral sensors are pushbroom scanning radiometers that record imagery in narrow spectral bands ($\sim$10 nm) that can range from ultraviolet (350 nm) to short-wave infrared (2500 nm). The data are commonly delivered as a hyperspectral cube, where the entire sets of scanned images are stacked on top of the other. The XY plane of the hyperspectral cube represents the spatial space of the observed area and the Z axis represents the spectral response as a function of wavelength of the surveyed area at a given location (Bethel, Lee, and Landgrebe 2000; Petrie 2005). The plot of the spectral response is commonly known as a spectral signature (Goetz, Rowan, and Kingston 1982; Goetz et al. 1985). The response of electromagnetic radiation differs between the varieties of land-covers types, such as soils, variety of vegetation types, and manmade materials, where each land-cover type has a unique spectral signature (Goetz et al. 1985). These differences in the electromagnetic response of land covers allow the analyst to segment the land covers into a thematic map using image-processing techniques, known as classification methods. Spectral signatures collected over areas that contain only one type of land cover (end-members), are used as reference signatures to aid in the classification process. Remote-sensing sensors that produce data that are similar to HSI are red-green-blue (RGB) and colour-infrared (CIR) frame cameras. Although RGB and CIR cameras operate with only three or four broad spectral bands that typically range between 80 to 150 nm, their products are commonly used to segment the land covers into a thematic map using image-processing techniques similar to hyperspectral cube processing.

ALB is a technique that is typically used to measure the depths of moderately clear, nearshore coastal waters and lakes from a low-altitude aircraft that operates a scanning, pulsed laser beam (Hickman and Hogg 1969; Guenther 1985; Penny et al. 1986). ALB systems use a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser that emits pulses at two wavelengths that fall within the spectral range of the hyperspectral sensor: (1) a 1064 nm wavelength in the infrared (IR), the fundamental wavelength of the Nd:YAG laser; and (2) a 532 nm wavelength, produced by frequency doubling of the fundamental wavelength (Penny et al. 1986; Guenther, LaRocque, and Lillycrop 1994). These wavelengths are particularly useful given the optical properties of water. Laser pulses transmitted in the 532 nm wavelength are near the spectral absorption minimum for most waters and that wavelength is considered nearly ideal for water penetration in typical coastal waters (Jerlov 1976; Mobley 2004). Laser pulses transmitted at 1064 nm do not penetrate the water more than a few centimetres, but are useful both for delineating the water surface and distinguishing water from land. Although ALB is an active sensor (i.e. it is not dependent on the sun and daylight conditions for illumination), the ALB intensity products are also from electromagnetic radiation that overlaps in range with the hyperspectral sensor (Tuell and Park 2004; Tuell et al. 2005; Park et al. 2010).

3. Spectral classification in shallow waters

In order to classify land and/or the seafloor from imagery collected by optical remote sensing, the intensity data should be normalized to the environmental condition at the time of the survey (i.e. sky condition, angle of incidence from the sensor to the ground, and water clarity). Otherwise, decision rules made to characterize a given data set of remote-sensing imagery are invalid with respect to the environmental conditions at the survey time of that given data set. The operator needs to normalize the spectral radiance reflected back from the ground, $L(\lambda)$, with the downwelling irradiance, $E_d(\lambda)$ (magnitude of the radiance product that is dependent on the solar radiation reaching the earth's surface), and the solar zenith angle, θ. Following Mobley (2004) and Gordon and Wang (1994), the remote-sensing reflectance, $\rho(\lambda)$, is expressed as

$$\rho(\lambda) = \frac{\pi}{\cos\theta} \times \frac{L(\lambda)}{E_d(\lambda)}. \tag{1}$$

In recent years, coastal and watershed hyperspectral data sets have become available through federal programmes (e.g. the National Coastal Mapping Program (NCMP) of the US Army Corps of Engineers), which has resulted in an increase in the number of academic hyperspectral studies of shallow-water environments. However, the challenge of aquatic studies compared to terrestrial studies that used hyperspectral imaging is the non-linear contribution from the water body to the signal received from the seafloor. The sunlight transmittance through the water column varies as a function of solar wavelength. Hence, the light decay through the water column is an exponential function of the diffuse attenuation function $K(\lambda)$ and depth (Jerlov 1976; Mobley 2004). The observed radiance in shallow waters can be expressed as (Lyzenga 1978; Philpot 1989)

$$L_{\text{obs}} = (L_b - L_w)\, e^{-2k(\lambda)z} + L_w, \tag{2}$$

where L_{obs} is the radiance observed at the sensor's detector, z is the water depth, L_b is the radiance contribution from the bottom, and L_w is the observed radiance over optically deep water with no bottom contribution. As a result, only a subset of the spectral range from

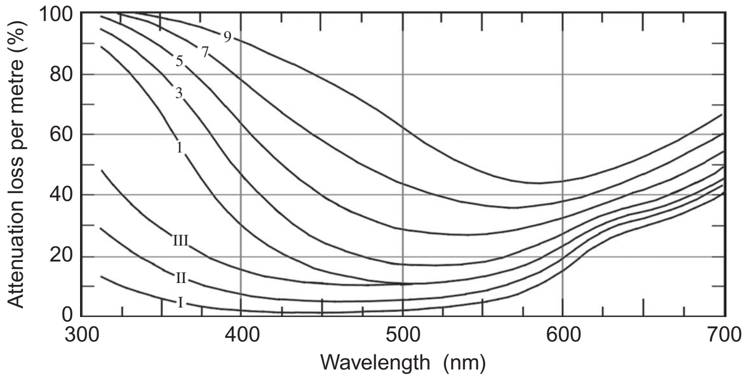

Figure 1. Percentage light loss per metre as a function of wavelength in oceanic (curves I to III) and coastal waters (curves 1 to 9) with varying degrees of turbidity (from Jerlov 1976).

the downwelling irradiance reaches the bottom and is reflected back. Because the subset is dependent on the solid angle of the detector, the measurement is in radiance with units of watts per square metre per steradian. The wavelength of the spectral range is typically between 350 nm to 700 nm, depending on the water clarity and water depth (Jerlov 1976; Mobley 2004). The water clarity is typically classified based on the spectral shape of the diffuse attenuation coefficient, known as Jerlov curves (Figure 1). The additional benefit using radiance is that in optic sensors that have a fixed gain within an observation (i.e. designed to have linear response over the sensor's spectral sensitivity range) there is a linear relationship in the raw intensity values of the sensor.

In situ ground-truth measurements are required to characterize the water column and the deep water with no bottom contribution. Without ground truth, the bottom reflectance can be difficult to decouple from water depth. In situations in which the downwelling irradiance was not collected, an alternative approach is to collect direct spectral measurements of different seafloor types. This can be done either by *in situ* spectral sampling or through the analysis of a grab sample from that area (Mazel 1997; Lesser et al. 2004). In this case, the water properties can be inferred from the HSI data set by using the seafloor spectral measurements and a bathymetric data set.

4. Operational requirements

The OCS system was built at the University of New Hampshire's (UNH's) Center for Coastal and Ocean Mapping (CCOM) and its design was based on the acquisition and logistical requirements for ground-truth procedures of remote-sensing surveys. The data requirements of the system included the collection of underwater imagery with real-time feedback, measurements of the colour of the seafloor, measurements of the spectral response, and the quantification of the water clarity. The logistical requirements of the systems included the following.

Weight. One person should be able to deploy and retrieve the system by hand from a vessel of opportunity. The weight of the system should be small enough to avoid the risk of the operator being pulled by the system.

Assembly and storage. The system, in operational mode, should be a coherent unit such that its components can remain contained within the system's frame during a survey. When not in operation, the system should be easy to take apart for storage or shipment. It should also be easy to put the system back together again.

Modular. The sensors on board the system can be replaced and upgraded without the need to reconstruct the whole system. Ideally, all sensors should be able to connect to a single coaxial cable that provides power to the sensors and streams real-time data up to the survey vessel.

Power. If needed, the system should operate with a small external battery (12 or 24 VDC) that is easy to carry onboard a small vessel and can provide at least 3 hours of operation. In keeping with the vessel of opportunity paradigm, power connections should be designed to accommodate connections to various battery posts and to DC outputs of generators.

Single control station. Data from all sensors should be collected by a single computer. This assures that all data is retained in one system and avoids the need to transfer data from different acquisition computers/devices after the survey.

Depth. The system should be able to reach the seafloor at depths of at least 20 m. This depth is defined from the typical survey depths achieved by ALB and HSI systems.

Horizontal and vertical controls. The position and depth of each station should be automatically logged during operation. To achieve the best possible horizontal position, the GPS antenna should be mounted as close as possible to the deployment point on the survey vessel. An offset measurement can be applied between the deployment location from the deck to the OCS system on the seafloor. However, this may not be logistically feasible.

5. System design

The heart of the OCS system is an analogue camera where the streaming video data is digitized topside. As such, the design of the system relies on a 50 m high-quality coaxial cable with a strength member to support the load on the cable and to minimize damage to the conductors. The frame dimensions of the system were defined by the resolution and field-of-view (FOV) of the camera in the system. Although, many different types of cameras are available, commercial-off-the-shelf drop cameras are affordable and easy to operate. A drop camera is an underwater video camera that does not require a water-proof case and is able to stream live imagery back to the operator (or with minimal delay) over a chosen cable length. The resolution of a typical analogue drop camera is between 480 to 600 TV lines with a FOV of 70° to 120°. In the past year (2011–2012), the RGB camera in the OCS system has been upgraded from a SeaView (480 TV lines) camera to a Delta Vision camera (520 TV lines) .

The drop camera is mounted on the top of the frame at a height of 0.4 m above the base in order to acquire frame captures of the seafloor with a 1.2 mm pixel resolution. The camera base (0.3 m × 0.3 m) was derived from the 0.3 m × 0.4 m FOV of the camera at the mounting height. A black and white 2 cm interval scale was added to the base of the frame to allow manual ortho-rectification without the need to apply a lens distortion correction to the images. The top plate of the frame is a 2 cm Delrin plate that serves as a mounting surface for the camera and lifting hardware. The choice of Delrin was because of its ability to be machined, its strength, and its low water absorption. The colour of the Delrin plate used in the system is black in order to minimize the reflection. The frame elements are 9.5 mm diameter stainless-steel tubing. The elements are fastened together and to the top by SwageLok^{TM} connectors that allows for easy disassembly and design modification**.**

The current OCS system configuration allows the underwater spectroscopy data to be collected through a 25 m length fibre-optic cable. Because of the costs of an integrated fibre-optic cable in a coaxial cable with a strength member, a separate fibre-optic cable is connected to the rods of the frame with a metal clip. The FOV at the tip of the fibre-optic cable is 25° oriented 45° to the bottom. This configuration allows the spectral footprint to fall at the centre of the video frame. Although the metal clip in the current model is not coated in black mat colour, it is assumed that reflectance of its shiny metallic surface is minimal. The reason is that the steel tubing and the clip are holding the fibre-optic cable from the back. Furthermore, the FOV of the spectrometer is quite narrow and centred on the open area at the bottom of the frame.

The position of the station is logged using a wide area augmentation service (WAAS) GPS with a USB interface (Evermore SA-320, Hsinchu, Taiwan). In operation, the GPS with a built-in patch antenna is mounted to the edge of the ship's deck and is connected to the computer with a 6 m cable. The position of the station is logged using a the Global Positioning System Fix Data in National Marine Electronics Association (NMEA), GGA NMEA-0183 string. After the survey, the positioning data are processed to evaluate vessel motion during the deployment and to determine the position accuracy of each station. The water depth is measured using a Setra Model 526 submersible absolute pressure gauge mounted to the Delrin top plate that transmits the pressure measurements to the acquisition computer through the coaxial cord to the computer. A general sea-water density of 1025 kg m^{-3} is used to convert the pressure measurement into depth values. It is important to note that the sea-water density is not constant and does vary in value close to tidal inlets and in river and estuaries. In such cases, the pressure measurement should be converted into depth based on supplementary *in situ* measurements (i.e. salinity and temperature). Furthermore, the modular design of the OCS system allows the addition or upgrade of different sensors without the need to reconstruct the whole system for different applications. With the current coaxial cord, there is an option to stream data from two more sensors to the computer control station. The key components of the OCS system and the system deployment are shown in Figure 2 and OCS products (imagery and spectral signature) are shown in Figure 3.

Figure 2. The OCS system hardware. (*a*) Key components in the system: fibre-optic cable (top left), pressure gauge (top right), and the underwater camera (bottom). (*b*) Deployment of the system with a WAAS-enabled GPS (blue arrow) mounted to the deck of ship close to the deployment point.

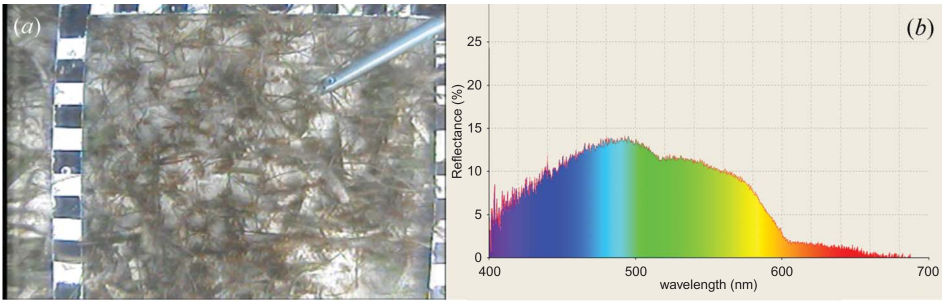

Figure 3. Products from the OCS system. (*a*) Frame image from an underwater video collected over a sandy area with sea grass (St. Croix, US Virgin Islands). The fibre-optic cable of the spectrometer is shown in the upper left corner of the image. (*b*) Radiance measurement of the seafloor.

6. Measurement of the optical water properties

In order to calculate the bottom reflectance and decouple it from the spectral measurement, two additional spectral measurements are needed. One spectral measurement is of the observed radiance over optically deep water, L_w. The second set of spectral measurements is to derive the diffuse attenuation function, $K(\lambda)$ (Equation (2)). Deep-water conditions for a spectral measurement are determined when the system is submersed close to the water surface and the bottom is not observed in the video feedback. The measurements of optically deep water are conducted under the assumption that chemistry (dissolved matter and suspended particulates) does not change. As long as the bottom is not contributing to the radiance, it is possible to conduct a measurement of the observed radiance over optically deep water. For diffuse attenuation measurements, a plastic matt white plate is mounted to the bottom of the OCS system. The white plate is calibrated as a white reference above the water surface, i.e. the reflection spectral values are 100% at all observed wavelengths. The next measurements are conducted underwater, where the change of reflection is exponentially proportional to the water depth, i.e. 0.2 m from the fibre-optic cable to the white reference. An average diffuse attenuation coefficient value at a specific location is calculated. By taking a series of relative irradiance measurements at multiple depths, Equation (3) is used to calculate the reflection and derive a sequence of diffuse attenuation coefficient values through the water column that are then averaged (Figure 4). The measurements of diffuse attenuation coefficient are typically conducted at 0.1 m to 0.2 m intervals in shallow waters (<3 m) and 0.5 m to 1.0 m intervals in deeper waters (>3 m). The multiple measurements provide a statistically optimal estimate of the diffuse attenuation coefficient value. After measuring the optical water properties, the bottom reflectance can be calculated based on Equations (1) and (2).

Because of the challenges of mounting and unmounting the white reference to the frame, an enhancement was made to the system in July 2012 for performing a radiometric calibration underwater. An underwater white reference panel, which was calibrated against a Labsphere, Inc. certified reference standard, was added to facilitate acquisition of reference spectra (Figure 5). This panel is controlled by a pneumatic actuator, with air lines run from a dive tank on the vessel, such that the panel can be swung into or out of the spectrometer's FOV by simply flipping a switch. This enhancement increases the efficiency of underwater spectra acquisition and also improves the accuracy of the spectral measurements by minimizing the time between acquisition of the white reference and seafloor spectra. Using the pneumatic-actuator-controlled underwater white reference panel, K_d estimates can be obtained simultaneously with the seafloor reflectance spectra by

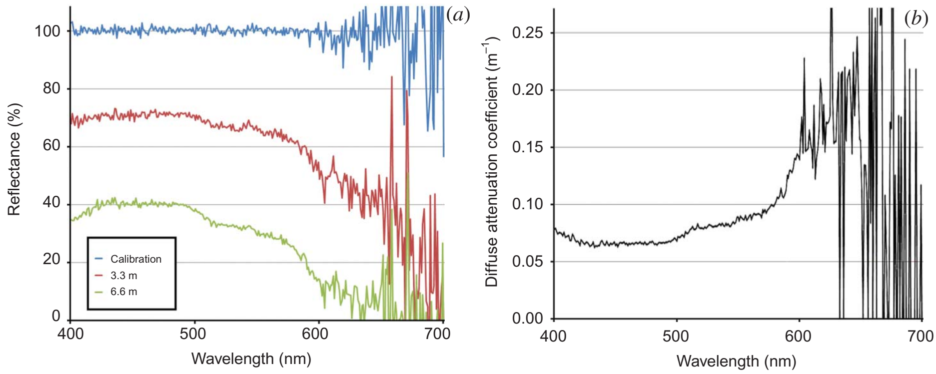

Figure 4. Extraction of the diffuse attenuation coefficient. (*a*) Reflection measurement of a white reference underwater at different water depths from the calibration depth and (*b*) the calculated diffuse attenuation coefficient indicating the water clarity conditions during the field measurements.

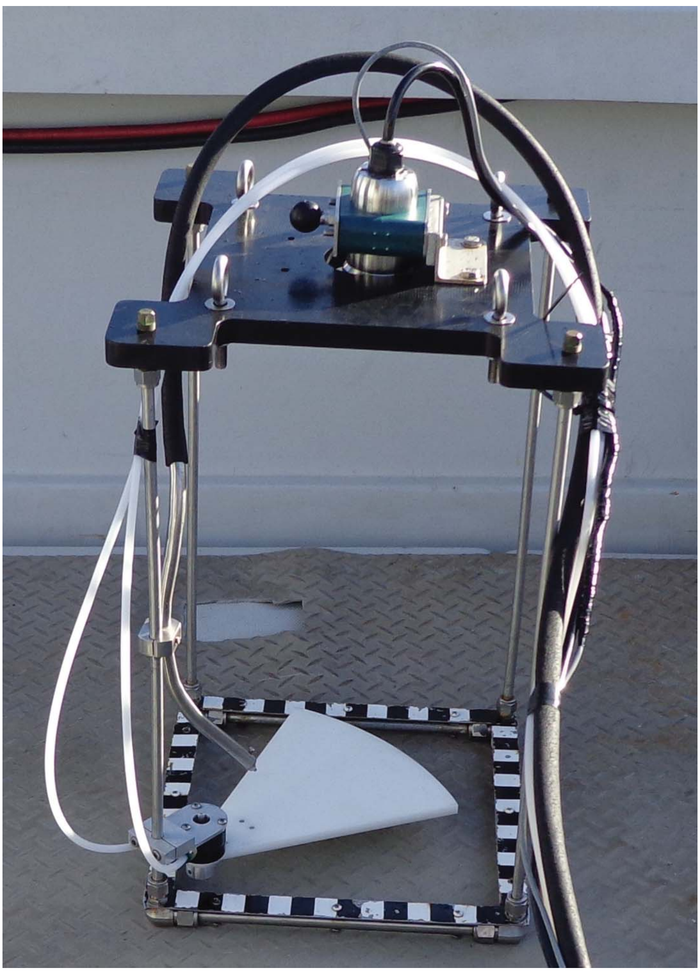

Figure 5. Modification to frame to include the white reference panel (wedge-shaped white panel at bottom of frame), which is controlled via a pneumatic actuator and operated from the surface.

also recording relative irradiance, as defined in the SpectraSuite operation manual (Ocean Optics 2007), at multiple depths as the camera frame, with the white reference in the spectrometer's FOV, is lowered through the water column. The white reference was connected to a horizontal axis to maintain a constant distance and angle of incidence in all the white reference measurements. In the case of ALB that operates at 532 nm, K_d is calculated as follows:

$$K_d\,(532) = \frac{\text{In}\left(I_{z_1,532}\right) - \text{In}\left(I_{z_2,532}\right)}{z_2 - z_1}, \tag{3}$$

where $I_{z,\lambda}$ denotes relative irradiance at depth, z, and wavelength, λ, and $z_2 > z_1$.

7. Field work

The OCS system has been operational since 2009, including several ground-truth studies that overlap with ALB, HSI, and acoustic surveys. The following are examples of different studies conducted in different environmental settings using the OCS system (Figure 6).

7.1. Ground truth of ALB and acoustic surveys

As part of an acoustic-optical inter-comparison research between multibeam/interferometric sonar backscatter to ALB intensity, underwater video measurements were made with the OCS system from Cape Ann to Salisbury, MA (Figure 6(*a*)). The study goals were to relate acoustic backscatter to ALB intensity based on the sediment type and to create a seamless thematic map of the seafloor characteristics (Ackerman et al. 2011; Pe'eri, Gardner, et al. 2011). The acoustic data set includes acoustic backscatter from a Reson 8101 (240 kHz) multibeam echosounder survey in 2004 and a SEA SwathPlus (234 kHz) interferometric sidescan (Barnhardt et al. 2009). The intensity data were collected using a SHOALS-1000 ALB system that transmitted at 532 nm and 1064 nm (NOAA 2009). Underwater imagery was collected from more than 200 stations but not during any of the acoustic or lidar surveys. Grab samples were collected to ground truth the imagery. The combined ground truth and imagery shows that the seafloor in this study area is composed of fine and coarse sands, gravel, and rocky outcrops. These results correlate well with the backscatter imagery.

A similar study that used the OCS system was conducted in southwest Alaska (Figure 6(*b*)). The goal was to use the system for ground truth to observe the seafloor characteristics and relate them to ALB bottom detection (Pe'eri, Guilford, et al. 2011). A SHOALS-1000 ALB survey was used in this study. Underwater imagery from more than 50 stations revealed a muddy seafloor composed of glacial clays with glacial debris that ranges from fine gravel to large boulders. The seafloor characteristics and water clarity conditions at different tidal stages correlated with the ALB success to detect the bottom.

Most recently, the system was used in the shallow ($<\sim$10 m) water areas surrounding the Buck Island Reef National Monument (BUIS), St. Croix, US Virgin Islands (USVI), as part of an US Geological Survey (USGS) Experimental Advanced Airborne Research Lidar (EAARL-B) topographic-bathymetric lidar calibration-validation, which is planned to be flown this year (2013) in the USVI (Wright, C.W., and J.C. Brock, personal communication). The data from this project will be used to develop algorithms and procedures for generating calibrated seafloor reflectance images from EAARL-B waveforms for BUIS and other sites in the USVI. The BUIS project also included acquisition of post-processed

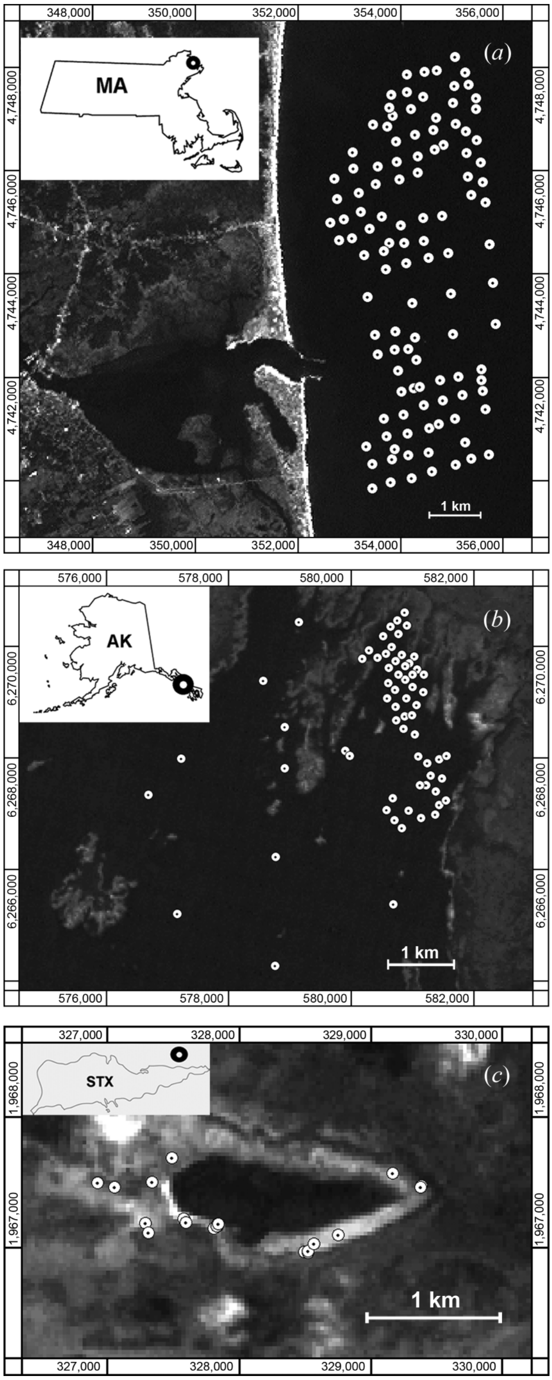

Figure 6. Study sites of ground-truth measurements using the OCS system. (*a*) Cape Ann to Salisbury, Massachusetts (MA), (*b*) Keku Strait, Alaska (AK), and (*c*) Buck Island Reef National Monument (BUIS), St. Croix (STX), US Virgin Islands (USVI). The coordinates of the MA, AK, and STX sites are Universal Transverse Mercator (UTM) world geographic system 1984 (WGS-84) zones 19 N, 8 N, and 20 N, respectively.

kinematic (PPK) and rapid static GPS shore-normal transects, which, combined with the OCS data, will enable both geometric and radiometric calibration and validation of the EAARL-B.

7.2. Ground truth of HSI surveys

A combined survey using an Norsk Elektro Optikk (NEO) HySpex hyperspectral scanner and a laser airborne depth sounder (LADS) MKII ALB was conducted on 22 February 22 2011 over and around BUIS to map the protected coral habitat (Figure 6(*c*)). Three months prior to the ALB survey, spectral measurements and underwater imagery were collected in more than 30 stations over four main types of seafloor: sand, flat hard-bottom coral pavement, coral reefs, and patches of eelgrass and macro-algae (Pe'eri, Guilford, et al. 2011). The underwater imagery and spectral measurements aided in the evaluation of the quality of the hyperspectral survey and the definition of end-members for the coral habitat classification using HSI. The spectral data was also used to characterize the waters around BUIS as tropical/subtropical oceanic water (Jerlov oceanic waters, Case II).

8. Discussion

The OCS system has proven to be a useful tool for *in situ* ground truth of optical remote-sensing surveys. The performance of the OCS system and its suitability for ground truth of remote-sensing data has been evaluated by the quality of its products and their accuracy. The pixel resolution of the frames from the video imagery is 1.2 mm. This resolution is good enough to identify general vegetation species and to discriminate a sandy bottom from a gravely or rocky bottom. However, this resolution is not sufficient to discriminate a muddy from a sandy bottom, where the grain-size threshold between the two classes is 63 μm. A mud plume can aid, although indirectly, in the detection of some mud content in the sediment. However, it is hard to infer the mud/sand ratio from the video imagery. The video imagery also supports the spectral measurements by providing images of the seafloor that are measured by the spectrometer and allows the operator to choose the appropriate locations for his study.

The video camera's footprint (0.12 m^2) and the spectral detector's footprint (0.01 m^2) are small with respect to a typical area of a single pixel from a HSI (1 to 4 m^2). A selection of a seafloor area that is uniform in its characteristics, together with multiple measurements around the same area, can provide a better statistical representation of the area. The absolute positional accuracy of the measurements depends on the horizontal control and the water depth of the measurements. Currents can potentially shift the system a horizontal distance greater than the water depth. The recommended time for deployment is at slack tide. In most open ocean conditions in waters deeper than 5 m that are not close to a river mouth or a port entrance, a horizontal accuracy of 5 to 10 m is assumed, depending on the water depth and currents. In calm, shallow (less than 5 m), the WAAS-enabled GPS accuracy is considered as the dominant error source of the horizontal accuracy.

Two additional environmental factors that need to be accounted for in the deployment of the OCS system are illumination and sea-state conditions. Downwelling irradiance at sea level in the visible wavelength band (400 nm to 700 nm) can change from 450 W m^{-2} with clear skies and the sun at 60° from the zenith to 300 W m^{-2} with hazy skies and the sun at 60° from the zenith (Mobley 2004). It is important to calibrate the system and conduct the measurements at the same illumination conditions. Otherwise, the spectral measurements are not calibrated to the same reference and it will not be possible to extract the optical water properties. The sea-state conditions can also affect the downwelling irradiance in the water column. Breaking waves and wave energy that can suspend particulates in the water column can also vary the downwelling irradiance during the ground-truth measurement.

In addition to the technical challenges that impact the accuracy of measurement at the time of the survey, there are also temporal issues. As the time period between the remote-sensing survey and the ground-truth measurements increases from days to months, the environment may change. Both the seafloor (e.g. the bottom slope and roughness, the presence of vegetation, and indirectly the presence of macrobenthic animals) and the water column (coloured dissolved organic matter and organic and inorganic suspended particulates) can change as a function of tidal and season cycles (Pe'eri, Gardner, et al. 2011). The rate of change of water column factors ranges from seconds to months. As a recommendation for planning ground truth, areas that are larger than 50 m in diameter and show uniform bottom characteristics are a preferred candidate for a ground-truth station. Intensity or backscatter images from previous surveys can be a useful tool for characterizing the seafloor and planning the locations of the ground-truth stations. All radiometric measurements should be conducted over a given ground-truth station within the same stage of the tidal cycle, ideally on the flood stage. This will reduce the variability in the water clarity during the measurements. From a statistical perspective and a practical approach, it is recommended to sample at least three stations that show similar bottom characteristics. In addition, multiple measurements over the station would strengthen the analysis of the results.

The OCS system is designed primarily as a sampling device to ground-truth data from remote-sensing surveys, but its utility can be extended for a variety of other applications where site specific, spot sampling of the seafloor is necessary. Information on aquatic vegetation (e.g. type, density, and coverage), living biota on the seafloor (e.g. corals, ground fish, and lobsters) and water conditions can aid in a variety of applications (Ackerman et al. 2006; Grizzle et al. 2008; Ford and Voss 2010). The simplicity, versatility, and portability of the OCS system make it an ideal device for detailed ground-truth applications.

9. Conclusions

The OCS system is an underwater-imagery and spectral-measurement sampling device that is used to ground-truth data from remote-sensing surveys. The system is able to collect underwater imagery with real-time feedback, measure the spectral response of the seafloor and quantify the water clarity. The system was designed to be simple, lightweight, and portable, making it easy to transport to any area and to be quickly operational to collect ground-truth data from a vessel of opportunity. The OCS system is able to log video imagery in AVI format that can later be parsed into individual 720×480 pixels frames, together with spectral information (radiance or reflectance) at a spectral resolution of 0.3 nm. The position of each station is logged using a WAAS-enabled GPS with a built-in patch antenna that can be mounted to the edge of the ship's deck and the depth is logged using a pressure gauge. In addition to seafloor characterization, the OCS system can measure the diffuse attenuation and the water radiance. These optical water properties allow the operator to quantify the water clarity and decouple the bottom reflectance observation from the scattering and absorption occurring in the water column.

The OCS system has been operational since 2009 and has proven to perform well. It has been used in several ground-truth missions that overlapped with ALB, HSI, and acoustic surveys in the Gulf of Maine, southwest Alaska and USVI. Studies that used the system included: an acoustic-optic inter-comparison between the multi-beam/interferometric backscatter to ALB intensity, ALB bottom detection, and seafloor characterization. The observed seafloor ranged from a soft muddy seafloor (Alaska) to a hard bottom coral pavement (USVI) with various levels of vegetation coverage. Although the OCS system was originally designed as a device to ground-truth data from remote-sensing surveys, the system can also be used for other applications where a site specific survey to characterize the seafloor is needed.

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