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Remote Sensing of Coastal Resources and Environment

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Advances in sensor design and data analysis techniques are now making remote sensing systems practical and attractive for coastal ecosystem research and management. Multispectral and hyperspectral imagers are available for mapping coastal land cover and concentrations of organic/inorganic suspended particles and dissolved substances in coastal waters. Thermal infrared scanners can map sea surface temperatures accurately and chart coastal currents, while microwave radiometers can measure ocean salinity, soil moisture and other hydrologic parameters. Radar imagers, scatterometers and altimeters provide information on ocean waves, ocean winds, sea surface height and coastal currents. Using airborne lidars one can produce bathymetric maps, even in moderately turbid coastal waters. Since coastal ecosystems have high spatial complexity and temporal variability, they frequently have to be observed from both satellite and aircraft , in order to obtain the required spatial, spectral and temporal resolutions. A reliable field data collection approach using ships, buoys, and field instruments with a valid sampling scheme is required to calibrate and validate the remotely sensed information. This paper presents a brief overview of recent advances in coastal remote sensing.

Key words*: remote sensing, wetlands, estuaries, ecosystem health.*

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1. Introduction

Coastal ecosystems are transitional environments that are sensitively balanced between open water and upland landscapes. They exhibit extreme variations in areal extent, spatial complexity, and temporal variability. Protecting these ecosystems requires the ability to monitor their biophysical features and controlling processes at high spatial and temporal resolutions. Satellite and airborne remote sensors can now map and measure these features and processes cost-effectively over large areas at appropriate scales and resolutions, minimizing the need for extensive field and ship measurements.

2. Background

To study the impact of the land and sea on estuarine and coastal ecosystems, a combination of models is frequently used, which contains watershed models, hydrodynamic models, and water quality and living resource models. Most coastal watershed models require land cover or land use as an input. Knowing how the land cover is changing, these models, together with a few other inputs like slope and precipitation, can predict the amount and type of run-off into rivers, bays, and estuaries (Jensen, 2007). The Landsat Thematic Mapper (TM) has been a reliable source for land cover data. Its 30m resolution and spectral bands have proven adequate for observing land cover changes in large coastal watersheds (e.g. Chesapeake Bay or the Baltic Sea). Other similar satellites with medium resolution imagers can also be used (Klemas et al., 1993).

Hydrodynamic models require physical data on river flow, tides, winds, current patterns, waves, etc. Once the run-off has entered bay or coastal waters, many of these parameters can be obtained from radar altimeters, scatterometers and synthetic aperture radar imagers (SAR), with calibration and validation performed by a relatively small number of field or ship measurements. In similar fashion, sea surface temperature and salinity can now be extracted from thermal infrared and microwave radiometers, respectively (Robinson, 2004). Some of the ecosystem health indicators that can be observed by remote sensors include percent of impervious watershed area, natural vegetation cover, buffer degradation, wetland loss and fragmentation, wetland biomass change, hydrology, water turbidity, chlorophyll concentration, eutrophication level, salinity, temperature, etc. (Martin,2004; Lathrop et al., 2000).

3. Remote Sensing of Coastal Watersheds and Near-shore Features

A typical digital image analysis approach for classifying wetlands or land cover in a coastal watershed is shown in Figure 1. Before analysis, the multispectral imagery must be radiometrically and geometrically corrected. After image segmentation, cluster analysis is performed, alternating between unsupervised and supervised classification (Jensen, 1996). Note that throughout the process, ancillary data is used whenever available (e.g. aerial photos, maps, field samples, etc.).

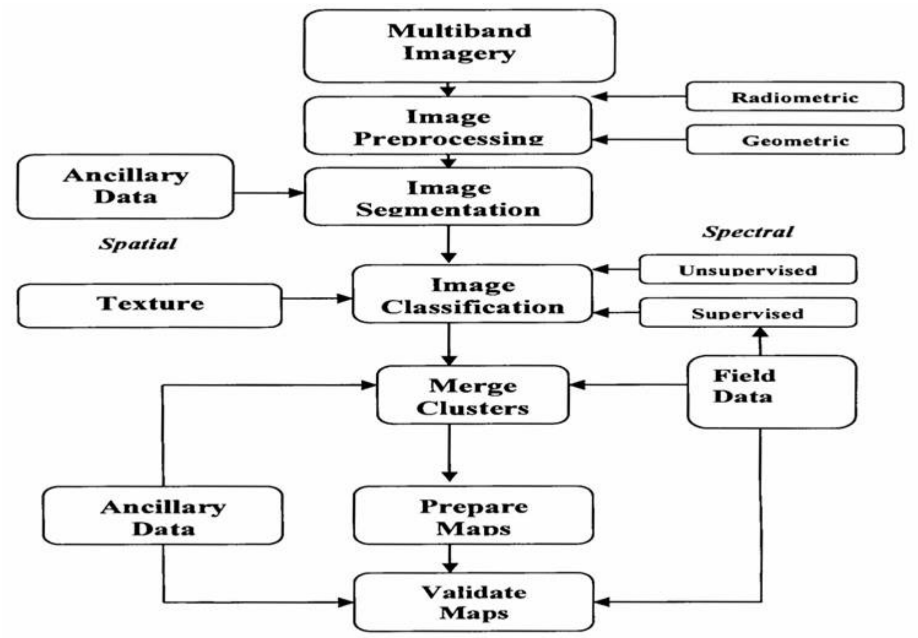

Fig. 1. Typical Image Analysis Approach

When studying critical sites or small watersheds, one can use aircraft or high resolution satellite systems. Airborne georeferenced digital cameras, providing color and color infrared digital imagery are particularly suitable for accurate mapping or interpreting satellite data. Such digital imagery can be integrated with GPS information and used as layers in a GIS for a wide range of modeling applications (Lyon and McCarthy, 1995). Small aircraft flown at low altitudes (e.g. 500 meters) can be used to supplement field data. High resolution imagery (0.6m to 4m) can also be obtained from satellites, such as IKONOS and QuickBird. However, cost becomes excessive if the site is larger than a few hundred square kilometers. Wetland species identification is difficult, although some progress is being made using hyperspectral imagers (Schmidt et al., 2004; Porter et al., 2006).

To map long-term changes of the shoreline due to beach erosion, time series of aerial photographs are used. A particularly effective approach for studying sand dynamics along coastlines includes the combined use of airborne hyperspectral data and airborne LIDAR data. The actual beach profile can be obtained with low altitude LIDAR flights. The LIDAR system must have a kd factor large enough to overcome the water depth and water turbidity at the study site (k = attenuation coefficient; d = water depth). For instance, if a given LIDAR system has a kd = 3 and the turbid water has an attenuation coefficient of k = 1, the system will be effective only to depths of 3 meters. Beyond that depth, one may have to use acoustic echo-sounding techniques (Brock and Sallenger, 2000).

More recently, Global Positioning Systems, combined with new LIDAR techniques, make it possible to obtain accurate topographic and bathymetric maps, including shoreline positions. LIDAR surveys can produce a 10 centimeter vertical accuracy at spatial densities greater than one elevation measurement per square meter. This is important for various coastal research applications of LIDAR, including mapping change along barrier island beaches and other sandy coasts. The ability of LIDAR to rapidly survey long, narrow strips of terrain is very valuable in this application, as beaches are elongate, highly dynamic sedimentary environments that undergo seasonal and long-term erosion or accretion, and are also impacted by severe storms.(Krabill et al., 2000; Stockdon et al, 2002)

Mapping submerged aquatic vegetation (SAV) and coral reefs requires high resolution (1-4 meters) imagery (Mumby and Edwards, 2002; Mishra et al., 2006). Coral reef ecosystems usually exist in clear water and can be classified to show different forms of coral reef, dead coral, coral rubble, algal cover, sand, lagoons, different densities of seagrasses, etc. SAV may grow in more turbid waters and thus is more difficult to map. High resolution (e.g. IKONOS) multispectral imagers have been used in the past to map SAV and coral reefs; however, hyperspectral imagers should improve the results significantly (Maeder et al., 2002; Porter et al., 2006).

Digital change detection using satellite imagery can be performed effectively using several techniques, including post-classification comparison or temporal image differencing (Jensen, 1996; Lunetta and Elvidge, 1998). As shown in Figure 2, change analysis results can be improved by including probability filtering, allowing only certain changes and forbidding others (e.g. urban to forest). A particularly effective method for remotely sensing wetland changes uses biomass as an indicator. To detect biomass changes, the Modified Soil Adjusted Vegetation Index (MSAVI) is used with red and near-infrared reflectances derived from Landsat/TM images (Qi et al., 1994). This biomass algorithm is applied to a time series of Landsat/TM images and used with selected thresholds to detect wetland changes. To minimize natural variations between images in the time series (e.g. atmospheric, annual, seasonal, etc.), it is assumed that the relative distribution of biomass in each sub-basin will remain essentially constant over time. Wetland pixels whose MSAVI deviation from the sub-basin mean changes from its previous deviation by more than a selected threshold value (e.g. two standard deviations), are considered as having changed. To minimize data costs, only changed sites "flagged" by Landsat/TM are studied in more detail with high-resolution systems, such as IKONOS or airborne scanners (Klemas et al., 2000; Porter et al., 2006).

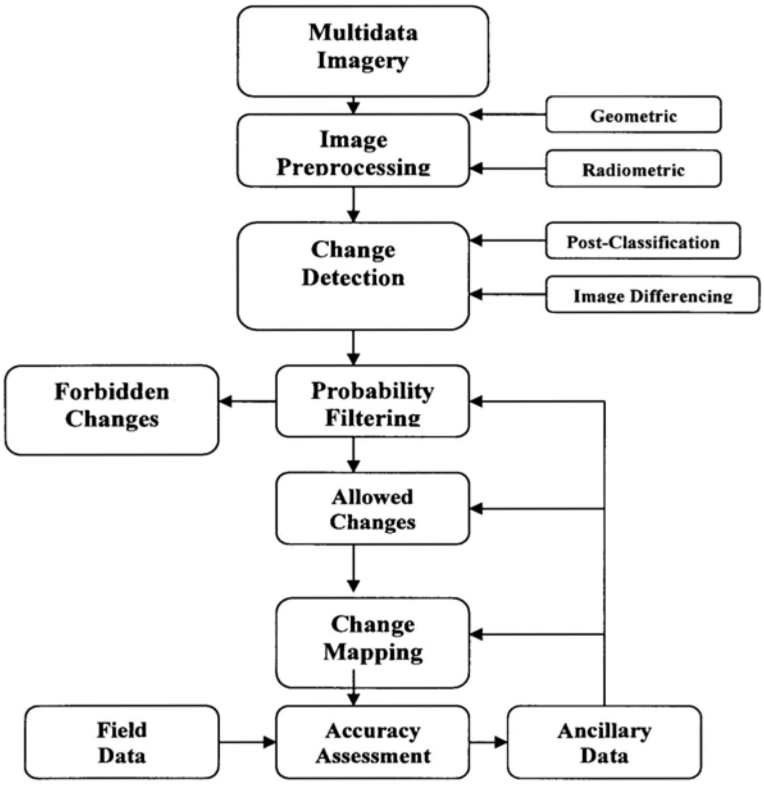

Fig. 2. Change Detection Using Probability Filtering

4. Remote Sensing of Estuarine Biology and Pollutants

The size and depth of coastal waters makes it difficult to monitor them with ships and buoys alone. Satellites with a wide range of sensors are proving to be cost-effective for observing large estuarine and coastal areas. Some of the key ocean properties which can be mapped from satellites are shown in Table 1. As shown in the Table, all electromagnetic wavelength regions are employed. For instance, ocean color, chlorophyll and productivity can be obtained with multispectral and hyperspectral imagers operating primarily in the visible part of the spectrum.

Sea surface temperatures can be mapped with the thermal infrared sensors (TIR) and ocean salinity with passive microwave radiometers

In the open ocean, biological productivity can be estimated by measuring the chlorophyll-a concentration. It is the primary substance determining the color of so-called Case 1 waters. Several satellites with multispectral imagers, such as the CZCS and SeaWiFS, were specifically designed to monitor ocean chlorophyll concentrations and sea temperatures on a global scale (Martin, 2004). With the help of calibration data from buoys and ships, these satellites have been able to map chlorophyll concentrations with acceptable accuracy.

However, as one approaches the coast and enters the bays and estuaries, the water becomes quite turbid and contains suspended sediment, dissolved organics and other substances, in addition to chlorophyll. To identify each substance in this complex mixture of Case 2 waters requires hyperspectral sensors and more sophisticated algorithms than the empirical regression models (Sydor, 2006; Cannizzaro and Carder, 2006) used in Case 1 waters in the open ocean (Martin, 2004; Ikeda and Dobson, 1995). Neural network approaches have been used to map chlorophyll and suspended sediment concentrations in Delaware Bay and other estuaries (Keiner and Brown, 1999). Neural networks, however, require extensive "training" with coincident ship and satellite observations of radiance, and shipboard measurements of chlorophyll and sediment concentrations.

High concentrations of nutrients exported from agriculture or urban sprawl in coastal watersheds, or produced by coastal upwelling, are causing algal blooms in many estuaries and coastal waters. Algal blooms are harmful in that they cause eutrophic conditions, depleting oxygen levels needed by organic life and limiting aquatic plant growth by reducing water transparency. Most algal blooms can be observed from satellites, due to their distinct color, location or repetitive seasonal appearance. Concentrations of chlorophyll-a (chl-a) and total suspended sediments (TSS) can be used as indicators of the severity of eutrophication and turbidity, respectively.

If broad criteria (orders of magnitude) are used to compare estuarine water quality and eutrophication levels, it is possible to get satisfactory results with sensors having fewer spectral bands and lower signal to noise ratios than the hyperspectral imagers needed for measuring precise concentration levels. Most riverine and estuarine plumes and some ocean-dumped waste plumes can be detected remotely due to their strong surface signatures caused by high turbidity. The drift and dispersion of coastal plumes and ocean dumped waste have been tracked with multispectral satellite imagery. (Klemas and Philpot, 1981). To study the dynamics of such plumes one can use a small number of multispectral bands; however, to detect the composition and concentration of their content is difficult, even with hyperspectral images.

Using platforms, such as ocean gliders, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) with advanced optical and acoustic sensors, marine scientists can now perform high-resolution three-dimensional measurements of biological and physical ocean features at various depths. They can view Thin Layers of high biological productivity at different depths and study the response of planktonic distributions and processes to physical forcing across a wide range of temporal and spatial scales. For instance, Thin Layers require resolutions of centimeters, whereas previous measurements were performed at meter intervals, completely missing these biologically active and important layers (Schofield,et al, 2004;Cowles and Donghay, 1998).

Thermal infrared (TIR) sensors have been deployed for over 30 years on operational meteorological satellites to provide images of cloud top and sea surface temperatures (SST). This was the first method of remote sensing to gain widespread acceptance by the oceanographic and meteorological communities. The reason for the early success of measuring SST is as follows. Since the TIR radiance depends on both the temperature and emissivity of the target, it is difficult to measure land surface temperatures, since the emissivity will vary as the land cover changes. On the other hand, over water the emissivity is known and nearly constant (98%), approaching the behavior of a perfect blackbody radiator. Thus the TIR radiance measured over the oceans will vary primarily with the sea surface temperature (SST) and allow one to determine the SST accurately (± 0.5 º C) with some atmospheric corrections (Martin, 2004; Ikeda and Dobson,1995).

Accurate large-scale, long-time observations of the sea surface temperature (SST) are important to a wide range of oceanographic studies. Sea surface temperatures are necessary, for example, for estimating the source of heat at the air/sea boundary. High resolution satellite-derived SST measurements are ideal for investigating western boundary currents, such as the Gulf Stream and Kuroshio, which exhibit displacements on large temporal and spatial scales. Satellites are also used to monitor the SST and El Nino events of major upwelling areas, such as the ones along the coasts of Peru and California. El Niño is caused by a shift in wind patterns causing warm water to move from the western Pacific, near Australia, toward the west coast of South America. As the warm water arrives off the coasts of Ecuador, Peru, and Chile, it suppresses the nutrient-rich upwelling of cold water, thus reducing the biological productivity and bringing lean times to local fishermen.

Another global-scale event which appears linked to elevated SSTs is damage to coral reefs. Long-time series of accurate, global SSTs are needed to monitor the health of the Earth's coral reefs, which support a large diversity of sea life. Sea surface temperature data has also been used by the fish and wildlife communities to study habitats over many parts of the globe.

Sea surface salinity (SSS) is critical for determining the global water balance, for understanding ocean currents and for estimating evaporation rates. Also, low salinity water can transport natural and manmade river-borne contaminants into the sea, and can directly stress marine ecosystems that are adapted to higher salinity levels. Airborne microwave radiometers have been used to determine the structure and influence of river plumes in the Great Barrier Reef, since the input of freshwater plumes from rivers is a critical consideration in the study and management of coral and seagrass ecosystems. Sea surface salinity has been the most important oceanic variable which until recently has not been measured from satellites. There are now instruments designed to provide SSS from the satellite orbit. For instance, the European Soil Moisture and Ocean Salinity (SMOS) satellite uses a fixed two-dimensional interferometric antenna. The satellite will retrieve salinity with an accuracy of 0.1-0.2 precision salinity units (psu) at a resolution of about 50 km. (Martin, 2004; Robinson, 2004).

Oil spills are best detected by imaging radars. Small aircraft are being used to verify predictive oil spill drift and dispersion models by tracking the movement and spreading of oil spills and their interactions with estuarine fronts. Coastal and estuarine fronts can concentrate nutrients, pollutants and capture oil slicks causing their paths to deviate from drift and dispersion model predictions (Klemas, 1980). A typical estuarine front may be caused by flooding higher density ocean water gliding under the lower density, lower salinity river water and thus causing a strong convergence zone, which may be marked by a foam line and color line. Estuarine fronts are narrow features, quite dynamic and have high convergence velocities. In its convergence zone, a frontal system may include a self-contained ecosystem, with high concentrations of phytoplankton, zooplankton and other marine life (Szekielda et al, 1972). To study frontal dynamics and track oil slicks in estuaries one needs spatial and temporal resolutions of 5-20 m and 0.5-3 hours, respectively.

5. Remote Sensing of Physical Off-shore Processes

Physical ocean properties can be extracted from various radar instruments, such as winds from scatterometers, sea surface elevation and currents from altimeters, and sea surface slicks and waves from synthetic aperture radar (SAR). These measurements are used by oceanographers to study the ocean and coastal circulation, its large-scale, low-frequency variability, biological mixing, turbulent eddy energy, and air-sea interaction. Some of this information, such as sea surface temperature and elevation, can be used in global change models, if the total available data covers long time periods. (Robinson, 2004; Martin, 2004)

Currents and waves strongly affect coastal ecosystems, especially in the nearshore, which is an extremely dynamic environment. Currents influence the drift and dispersion of various pollutants, and together with breaking waves mobilize and transport sediments, resulting in erosion and morphological evolution of natural beaches. On a coastal scale, the motion of a patch of water containing a toxic red tide algal bloom or industrial waste is vital for planning appropriate reactive measures. To predict the local movement of pollutants, one must track the currents in the area. Current meters are not effective for determining surface currents over large coastal regions, since current meters measure currents only at a point.

Shore-based high frequency (HF) and microwave Doppler radar systems are frequently used to map currents and determine swell-wave parameters over large coastal areas with considerable accuracy. The surface current measurements use the concept of Bragg scattering from a slightly rough sea surface, modulated by Doppler velocities of the surface currents. HF radars can determine coastal currents and wave conditions over a range of up to 200 km. (Cracknell and Hayes, 2007). While HF radar provides accurate maps of surface currents and wave information for large coastal areas, their spatial resolution, which is about 1 km, is more suitable for measuring mesoscale features than small scale currents. On the other hand, microwave X-band and S-band radars have resolutions of the order of 10 m, yet have a range of only a few kilometers.

Estimates of currents over large coastal areas, such as the continental shelf, can also be obtained by tracking the movement of drogues, dyes or natural surface features which differ detectably in color or temperature from the background waters. (L. Breaker et al., 1994). Examples of such features include sediment or chlorophyll plumes, patches of different water temperature, surface slicks, coastal fronts, etc.

Large ocean internal waves on continental shelves strongly influence acoustic wave propagation; submarine navigation; mixing nutrients to euphotic zone; sediment resuspension; cross-shore pollutant transport; and coastal engineering and oil exploration. The water column is frequently not homogeneous, but stratified. Internal waves move along pycnoclines, which are surfaces that separate water masses of different densities. The larger internal waves can attain heights of 100 meters. The period of the internal wave packets approximates the period of the tides, suggesting a cause-and-effect relationship. Internal waves can be detected visually and by radar since they cause local currents which modulate surface wavelets and slicks (Zhao et al., 2004).

Table 1. Spaceborne Ocean-Sensing Techniques

Color Scanner -	Ocean color (chlorophyll & susp. sedimt. conc., diffuse attenuation coefficient)
Infrared Radiometer -	Sea surface temperature (surface temperature, currents)
Synthetic Aperture Radar -	Short surface waves (swell, internal waves, oil slicks, etc.)
Altimeter -	Topography and roughness of sea surface (sea level, currents, wave height)
Scatterometer -	Amplitude of short surface waves (surface wind velocity, roughness)
Microwave Radiometer -	Microwave brightness temperature (salinity, surface temp., water vapor, soil moisture)

Table 2. Recent Advances in Remote Sensing

– High resolution satellite sensors (0.6 – 4 m)
– Hyperspectral imaging systems (200 + bands)
– New classification algorithms (neural networks, spectral mixture, texture, nearest neighbor, knowledge based, etc.)
– Improved GIS models and GPS techniques (1 – 10 m)
– Coastal bathymetry from Lidar-GPS combination
– Sea surface salinity from satellites with microwave radiometers
– Ocean wind, current, wave data from improved satellite radars
– New platforms and field equipment (ocean gliders, UAV’s, robots, autocopters, helikites, etc.)

6. Conclusions

Advances in remote sensing technology and decreases in cost are helping researchers and managers to take a broader view of coastal ecological patterns and processes. Environmental indicators that can be detected by remote sensors are available to provide quantitative estimates of coastal and estuarine habitat conditions and trends. Such indicators include percent of impervious watershed area, natural vegetation cover, buffer degradation, wetland loss and fragmentation, wetland biomass change, invasive species, water turbidity, chlorophyll concentration, eutrophication, etc. Advances in the application of GIS help incorporate ancillary data layers to improve the accuracy of satellite land-cover or water classification and provide a convenient means for modeling ecosystem behavior.

New satellites, carrying sensors with fine spatial (1-4 m) and spectral (200 narrow bands) resolutions are providing a capability to more accurately detect changes in coastal ecosystem health, habitat degradation, and biological productivity. Thermal infrared imagers and new satellite microwave radiometers are able to map sea surface temperatures and salinity (Table 1). Radar scatterometers, altimeters and imagers (SAR) are providing more accurate information on sea surface winds, elevation, currents, wave fields and oil slicks, which can now be used in various predictive models. As shown in Table 2, advanced software is being developed for analyzing satellite data more effectively. Ocean platforms, such as ocean gliders, ROVs, AUVs, and optical and acoustic sensors are now available for performing high-resolution three-dimensional measurements of biological and physical ocean features, including Thin Layers of high biological productivity at various ocean depths. When these new techniques for generating, organizing, storing, and analyzing spatial information are combined with watershed, estuarine and coastal ecosystem models, coastal managers and scientists have the means for assessing the impacts of alternative management practices.

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Pakrančių aplinkos ir išteklių nuotolinis stebėjimas

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Dėl technologijų pažangos jutiklių projektavimo ir duomenų analizės srityse nuotolinio stebėjimo sistemos tampa praktinėmis ir patraukliomis priemonėmis pakrančių ekosistemoms stebėti ir valdymui. Naudojant daugiaspektrinius ir plataus spektro atvaizdus, galima sudaryti žemėlapius, skirtus pakrančių dangos ir organinių bei neorganinių suspenduotų dalelių ir ištirpusių medžiagų koncentracijai vandenyje atvaizduoti. Terminis infraraudonųjų spindulių skaitytuvas gali tiksliai atvaizduoti jūros paviršiaus temperatūras ir pakrančių sroves. Mikrobangų radiometru galima nustatyti vandenyno druskingumą, grunto drėgnumą ir kitus hidrologinius parametrus. Radariniai atvaizdavimo prietaisai, reflektometrai ir aukščiamačiai teikia informaciją apie vandenyno bangas, sroves, jūros paviršiaus aukštį ir pakrančių sroves. Naudojant antžeminius įrenginius (lidarus), galima sudaryti batimetrinius žemėlapius netgi vidutiniškai drumstuose pakrančių vandenyse. Dėl pakrančių ekosistemų sudėtingumo ir nuolatinio kitimo jos turi būti dažnai stebimos satelitinėmis ir aviacinėmis priemonėmis, norint tinkamai pavaizduoti jų pasiskirstymą erdvės, laiko ir spektro atžvilgiu. Nuotoliniu būdu gauti duomenys turi būti ratifikuojami, palyginti su patikimomis priemonėmis gautais duomenimis, naudojant laivus, plūdurus ir kitus praktinius tyrimus. Straipsnyje aprašomi pakrančių nuotolinio stebėjimo pranašumai.

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