GLOBAL OBSERVATIONS OF COASTAL AND INLAND AQUATIC HABITATS

Earth System Science Theme: *Marine and Terrestrial Ecosystems and Natural Resource Management (III).*

AUTHORS

Steven Ackelson	*Naval Research Laboratory*	Steve.Ackleson@nrl.navy.mil
Thomas Bell	*University of California, Santa Barbara*	Thomas.Bell@lifesci.ucsb.edu
Heidi Dierssen	*University of Connecticut,*	Heidi.Dierssen@uconn.edu
James Goodman	*HySpeed Computing LLC*	JGoodman@hyspeedcomputing.com
Robert Green	*NASA Jet Propulsion Laboratory*	Robert.O.Green@nasa.gov
Liane Guild	*NASA Ames Research Center*	Liane.S.Guild@nasa.gov
Eric Hochberg	*Bermuda Institute for Ocean Science*	Eric.Hochberg@bios.edu
Victor V. Klemas	*University of Delaware*	Klemas@UDel.edu
Samantha Lavender	*Pixalytics, Ltd.*	SLavender@pixalytics.com
Christine Lee	*NASA Jet Propulsion Laboratory*	Christine.M.Lee@jpl.nasa.gov
Peter Minnett	*University of Miami*	PMinnett@rsmas.miami.edu
Frank Muller-Karger	*University of South Florida*	carib@usf.edu
Joseph Ortiz	*Kent State University*	JOrtiz@kent.edu
Sherry Palacios	*Bay Area Environmental Research Institute*	Sherry.L.Palacios@nasa.gov
David R. Thompson	*NASA Jet Propulsion Laboratory*	David.R.Thompson@jpl.nasa.gov
Kevin Turpie*	*University of Maryland, Baltimore County*	KTurpie@umbc.edu
Richard Zimmerman	*Old Dominion University*	RZimmerm@odu.edu

* - Lead author.

SYNOPSIS

The proposed Quantified Earth Science Objective (QESO) is to inventory and assess coastal and inland aquatic habitats, which are extremely valuable and productive regions that are vulnerable to global anthropogenic pressures and climatic change. Basic information about sessile communities (wetlands, coral reefs, and sea grasses) includes mapping their extent and distribution, which can be gleaned from spectral surface reflectance imagery at high spatial resolution, but moderate temporal resolution. Capturing habitat characteristics, such as composition or condition requires high spectral resolution. Moderate to high temporal resolution is also required for detailed observations of sessile community change (e.g., phenology, disturbance) and high temporal resolution is required for environmental changes in the surrounding water, including variations in temperature, phytoplankton concentration and composition, and concentrations of sediment or chromophoric dissolved organic matter (CDOM). Current and upcoming satellite missions and technology could meet many of these challenges, but multiple orbiting and airborne platforms may be needed to get a more complete picture of how these vital resources are changing.

1. IMPORTANCE of understanding coastal and inland aquatic habitats

Coastal and inland aquatic ecosystems include phytoplankton; wetlands comprised of marshes, mangrove and other woody swamps; submerged aquatic vegetation; kelp forests; benthic communities, including coral reefs; water-column communities, including fisheries and plankton. These ecosystems store and are affected by material fluxes (e.g., freshwater, nutrients, minerals, pollutants, and carbon) and are amongst the most productive ecosystems on the planet (Day et al., 2012; Cebrian, 2002). Collectively, they store 44.6 Tg C yr^{-1}, including vegetation stocks and soils rich in organic matter held by seagrass, mangrove, and marsh ecosystems (Chmura et al., 2003). In addition, they provide valuable ecosystem services supporting wildlife and fisheries, providing food, livelihood, and recreation to roughly half of the global population (Barbier et al., 2011). Habitat structure, built by aquatic sessile communities, also buffers human and animal terrestrial habitats against storms and floods. Coastal and inland water habitats also provide critical freshwater for human consumption, irrigation, sanitation, industry, recreation, and play a vital role for human health and safety. Sessile communities also support ecosystem biodiversity by providing a stable environment, natural breeding grounds and nurseries for fisheries, and are the natural habitat for an extensive variety of aquatic and terrestrial fauna. They also play a key role in shoreline geological processes and in storing and moving carbon, nitrogen, phosphorous, minerals, and pollutants. Aquatic ecosystems are interconnected and influence each other, primarily through the water that flows through them. For instance, wetlands influence material storage and fluxes between land and sea of energy, fresh and salt water, and materials affecting water quality and clarity, which affect light availability for water column and benthic photosynthesis. Thus, the necessarily extensive and interdisciplinary study of aquatic habitats provides important insight to the understanding and management of coastal and inland aquatic ecosystems.

However, a growing global population of over seven billion people, and a warming atmosphere driven by carbon dioxide now in excess of 400 ppm, it has become clear that these habitats are at risk globally. Nearly half of the world's population now lives within 60 km of the ocean and three quarters of all large cities inhabit the coast (Cracknell 1999). This development has generated tremendous pressures on the myriad natural environments that occupy the boundary zone between the land and the ocean. Human exploitation of coastal resources has produced increasingly dramatic changes to coastal and inland aquatic habitats in the last 100 years. Half of the original coastal wetland habitat within the USA has been lost to development (EPA 843-F-01-002d, 2001). Over a quarter of the known areal extent of seagrass meadows has vanished globally only since 1879 and the rate of loss has risen from 0.7% yr^{-1} before 1940 to a staggering 9% yr^{-1} after 1990 (Waycott et al., 2009). Sub-merged aquatic vegetation is highly sensitive to environmental changes and a vital component of coastal ecosystems (Orth et al., 2006). Within the Chesapeake Bay, the nation's largest estuary, fully 90% of the area originally inhabited by submerged aquatic vegetation has been converted to barren sand and mud habitat, resulting in concomitant habitat losses for a diverse community of marine animals, many of which represent important fishery resources, including blue crabs, rockfish and oysters (Batiuk et al. 2000). Globally, wetland habitats have declined 64–71% and the rate of degradation continues to increase due to climate change, sea level rise, and human encroachment (Davidson, 2014). Coral reefs, the most biologically diverse ecosystems worldwide (Hoegh-Guldberg et al., 2007), provide important services to tropical and sub-tropical coastal nations. Many reef systems are in decline due to direct human impacts and changing ocean conditions linked to climate change, e.g., mechanical erosion by storms, elevated water temperature, and acidification (Hughes et al., 2003). During 2015, Australia's National Coral Bleaching Task Force assessed a worldwide coral bleaching event with an aerial survey of 911 coral reefs, finding that 93% had suffered from bleaching, of which 55% suffered severe bleaching (The Washington Post, 2015). Lakes and inland seas globally are experiencing rapid and variable rates of warming (O'Reilly et al., 2015), affecting water quality and availability. Invasive fauna and flora are becoming more prevalent and have been reported for at least 84% of the world's 232 marine eco-regions (Molnar et al., 2008). Climate change can influence rates and patterns of invasion (Guareschi et al., 2013) and complex interactions between climate change and invasive species at differing trophic levels can have profound influence on ecosystem function and biodiversity (Rahel and Olden, 2008). Therefore, the global assessment of how these ecosystems are changing is an urgent priority in the coming decade.

In addition, pressures in aquatic habitats influence the growth of many species of phytoplankton that are detrimental to humans and aquatic systems alike are forming Harmful Algal Blooms (HAB) events, which are being introduced through human activities or being driven by climatic change (Anderson et al., 2002). HAB events represent a threat in 29 coastal states, and 21 states with inland lakes, and are increasing in frequency and severity because of anthropogenic eutrophication. Harmful algae can cause damage to ecosystems and natural resources. Some harmful algae produce toxins that can lead to illness and death in fish, seabirds, marine mammals and other coastal life, and ultimately humans (Glibert et al. 2005, Anderson 2009). In addition, episodic growths of algae play a negative role in water quality often decreasing the amount of light, negatively affecting water-column and benthic photosynthesis. These blooms can grow faster than they can be consumed by natural grazers, then die creating their decomposition causing hypoxic and anoxic dead zones, having devastating effects on fisheries and benthic communities (Rabalais et al., 2002; Anderson et al., 2000).

Timely and accurate, spatially resolved environmental information on global scales is necessary to support effective resource policy and management for coastal and inland aquatic habitats and assure water quality for human health and welfare. Laboratory and field experiments, coupled with numerical models are beginning to tell us about how these habitats function in response to external pressures at the process level (e.g. Palacios & Zimmerman 2007, Zimmerman et al., 2015), but our ability to translate these mechanistic processes into reliable landscape-scale prediction tools is hampered by the inability to routinely observe ecosystem processes with sufficient temporal, spatial and spectral resolution. We are plagued by large uncertainties in relatively simple attributes such as standing biomass and their change rates simply because coastal and inland habitats have not been adequately inventoried or monitored globally (Najjar et al. 2012, in prep). These lead to the Quantified Earth Science Objectives (QESO) of inventorying and assessing coastal and inland aquatic habitats globally and monitoring change. To that end, we need to measure or map geophysical variables, including habitat extent, distribution, functional type, change and characteristics, including phenology, species composition, standing biomass, productivity, and land/sea material exchange.

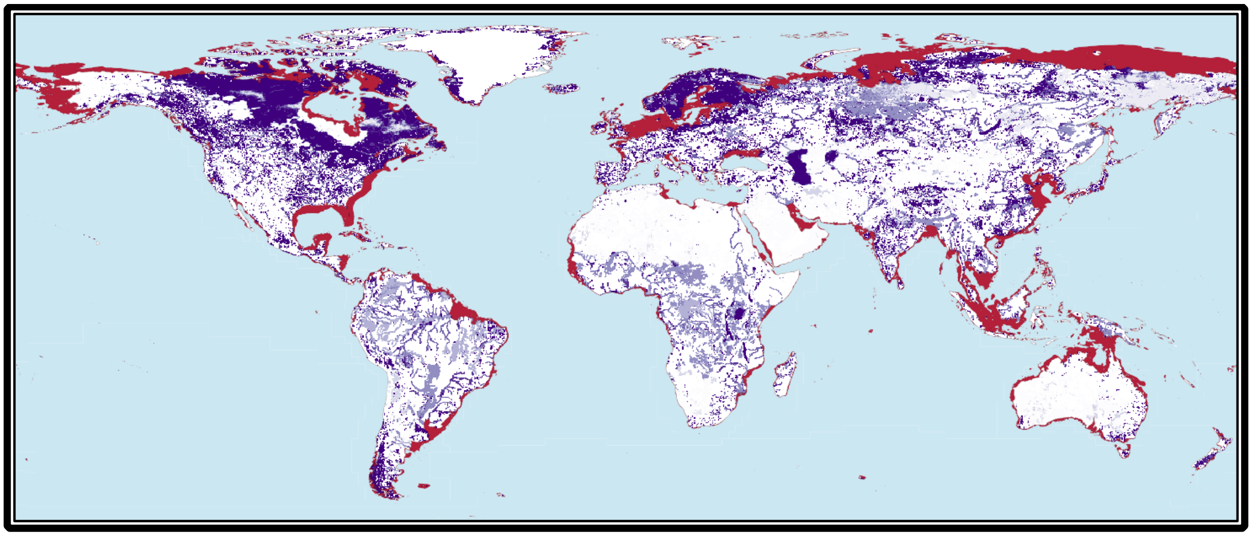

Figure 1 – Global distribution of coastal and inland aquatic ecosystems. Red indicates regions where water depth is less than 50 m and where land elevation is less than 50 m. Light to dark violent gives the concentration of inland wetlands, lakes, rivers and other aquatic systems. Increased darkness means greater percentage of areal coverage for inland aquatic ecosystems (UNEP-WCMC, 2005).

2. UTILITY of geophysical variable measurements for aquatic habitat science.

Addressing the proposed coastal and inland aquatic habitat QESOs on synoptic and global scales requires primarily satellite remote sensing imagery. Figure 1 coarsely illustrates the global distribution of aquatic habitat locations across the globe. Accurately mapping extent and distribution, functional type, characteristics and changes of these habitats can be facilitated by one or more orbiting platforms. However, these satellite observations should be accompanied with extensive support from suborbital imaging sensors to address cloud gaps and limits to temporal resolution, and a network of environmental, biological and radiometric measurements taken at the surface for vicarious calibration, algorithm parameterization, and validation, and to provide more in depth information, such as measurements of related geophysical parameters that can be difficult to measure via remote sensing (e.g., genetic information, microscopy). The remote sensing measurements that are needed to quantify the associated geophysical variables require a broad scope of radiometric, spectral, spatial, and temporal range and resolution.

Measurements of habitat extent and spatial distribution, and observing long-term changes in these, can be done through the interpretation of spectral surface reflectance, which is used to detect the presence of habitat structure formed by sessile organisms based on their spectral signature. Mapping extent and distribution of sessile communities requires moderate temporal resolution (e.g., monthly measurements or better), as these geophysical characteristics tend change more slowly. For wetlands, mapping distribution is possible because the presence of water under the vegetation canopy affects its spectral properties profoundly, especially at longer wavelengths, including the shortwave infrared (SWIR) region (1-2.5μm). In addition to spectral information, active remote sensing techniques, such as synthetic aperture radar (SAR) or LIDAR, can be used to detect wetland conditions through the resulting structural information. However, for benthic sessile communities, mapping measurements are dependent entirely on passive remote sensing in the visible region of the light spectrum, with longer wavelengths (Near Infrared to SWIR) being used mainly for atmospheric correction. This spectral regime is also commensurate for observations of phytoplankton, which further requires much higher temporal sampling (a few days to hourly) because these organisms are subject to movement and more rapid change. Determining habit characteristics (e.g., functional type or species composition) and change require surface reflectance at greater spectral resolution (<<10 nm) in general, and much greater resolution to observe biophysical spectral signatures (e.g., fluorescence lines) or to better remove atmospheric effects (e.g., absorption gases, such as NO_2). Changes in habitat characteristics for sessile communities can also occur more quickly than extent and distribution alone, and greater temporal resolution is needed to observe rapid change (e.g., weekly or better), such as the effects of disturbances and precipitation events and certain important phases of phenology (e.g., reproductive phase).

With rapid growth, HABs produce large-scale blooms that can be easily observed with satellites (see https://tidesandcurrents.noaa.gov/hab). Coastal communities will benefit from high frequency, high spatial resolution (<<100 m) satellite observations of the phytoplankton community (van den Bergh et al., 2002), perhaps building on NOAA's 1-km resolution system providing an operational HAB forecast system using the MODerate Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) instruments (see https://tidesandcurrents.noaa.gov/hab/). With upcoming hyperspectral satellites, NASA will usher in a new opportunities for identifying biodiversity objectives, such as HABs. Recent satellites, such as Hyperion, have demonstrated how cyanobacteria blooms in the western part of the Gulf of Finland can be identified using chlorophyll concentration based on bio-optical model simulations (Giardino et al., 2007). Using oceanographic parameters such as chlorophyll *a* and SST derived from satellite platforms, satellites have provided a powerful technique for tracking patches of HABs (Shen et al., 2012). Hyperspectral measurements will provide a robust opportunity to invert spectral absorption and pigments of diverse phytoplankton communities (Moisan et al., 2013). One approach to spectral inversion that holds promise in this regard is varimax-rotated principle component analysis, which has been applied to multivariate and hyperspectral data sets from the complex Case II waters of Lake Erie and other inland bodies of water in Ohio. The method enables differentiation of cyanobacteria from algae, sediment and chromophoric dissolved organic matter (CDOM) contribution, and compares favorably with traditional band ratio and semi-analytical methods employed in the same waters (Ali et al., 2012 & 2013; Ortiz et al. 2013; Ali et al. 2014). Spectral analysis of *Karenia brevis* has provided the identification of specific pigment absorption peaks and important wavelength ratios (Millie et al., 1995). Considerable research has also been done on detecting harmful cyanobacteria blooms (Kutser et al., 2006; Hunter et al., 2010; Matthews et al., 2012; Stumpf et al., 2012). Hyperspectral measurements will also provide the opportunity for hyperspectral libraries to be assembled for the identification of HABs (Kudela et al., 2015; Palacios et al., 2015).

3. QUALITY requirements for remote sensing measurements of aquatic habitats

Because of the scale and rapidity of changes being observed in coastal and inland aquatic ecosystems, the key science questions need to be addressed at national and global scales. Actionable resolutions will require immediate commitment to decades of focused research. Because aquatic ecosystems are by nature difficult to access directly on large scales, remote sensing is a vital tool for their assessment and monitoring. However, global remote sensing of aquatic ecosystems poses important technical challenges.

Spectral Resolution and Range – An important technical challenge for aquatic remote sensing is acquiring adequate spectral information. Because water strongly absorbs light at red or longer wavelengths, retrieval of in-water optical constituent concentration or benthic cover information is limited to the visible part of the spectrum, but the Near Infrared (NIR) region is useful in observing phytoplankton near-surface, blooms in lakes and along coasts. Regions where water and land meet are optically complex and host a diverse range of spectral signatures. Spectral information at 10 nm or better resolution in the visible and NIR can be used to differentiate among constituents in the water (Ortiz et al., 2013) and the shallow seafloor (Hill et al. 2014). NIR or shortwave infrared (SWIR) measurements are used to 1) separate atmospherically reflected light from light reflected from beneath the water's surface (Ahmad et al., 2010); 2) to observe the condition of emergent vegetation (Adam et al., 2010; Heumann, 2011; Bell et al., 2015); 3) to mark the presence of floating biota (Hill et al. 2014; Hu et al., 2015); 4) to separate aquatic and terrestrial habitats (Hill et al. 2014); and 5) to estimate surface blooms of phytoplankton using the red edge reflectance (Gower et al. 2008, Hunter et al. 2010, Matthews et al. 2012, Groom et al. 2014). Observations in the ultraviolet (UV) have potential to address complex atmospheric conditions near land and to better quantify in-water concentrations of organic compounds. Observations of water surface temperature, an important environmental parameter, require two or more bands in the thermal infrared (TIR). Passive microwave sensors and TIR bands can be used to measure soil moisture in watersheds (Turpie et al., 2015) and coastal salinity, while active remote sensing (SAR, LIDAR) can provide further information for emergent wetland structure.

Spatial and Temporal Resolution and Scale – Because the components and processes in these ecosystems vary on spatial scales of centimeters to tens of kilometers and time scales of hours to years, a significant technological challenge is to develop observational capabilities that span these broad spatial and temporal scales. Sessile communities require ground spatial distance (GSD) of 30 m spatial resolution or better, but only need to be sampled at monthly rates to observe seasonal phenology (Turpie et al., 2015), depending on the phenotype and growth phase. Wetlands could also be sampled at higher rates (e.g., one or more times a week), over limited time windows, in order to capture transient growth phases (e.g., reproductive phase). Similar spatial and temporal resolutions are needed to observe the majority of inland water bodies (Hestir et al., 2015). Observing variation in larger water bodies and coastal shelf waters, including changes in phytoplankton growth or composition or water surface temperature, requires 50 to 1000 m resolution (with increasing distance from shore), but needs hourly to daily sampling (Mouw et al., 2015). Spatial scales are synoptic to global and observations need to span several years to decades to capture trends stemming from climate change and global anthropogenic pressures.

Radiometric Performance – Observations of aquatic targets with low reflectance requires high radiometric performance. Sun glint avoidance is crucial to make radiometric measurements of aquatic habitats. Collecting key data across aquatic and terrestrial habitats also requires a large radiometric range and resolution, with high signal-to-noise ratio (SNR) for dark targets, typically between 100 to 1000 (Devred et al., 2014). Experience with previous sensors show that a 13 to 14-bit sensor would provide the needed radiometric resolution. Observations over clear water in the blue region of the visible spectrum and over vegetation and human-built structures in the NIR and SWIR, require a large radiometric range.

Challenges for accurate remote sensing of coastal benthic (shallow water) ecosystems are complicated by atmospheric scattering (>80% of the signal), sun glint from the sea surface, and water column scattering (e.g., turbidity). Further, sensor challenges related to SNR over optically dark targets particularly in the blue to green range of the visible spectrum as well as insufficient instrument radiometric calibration impede the value of coastal remotely-sensed data to support science related to benthic ecosystems. Robust atmospheric and water column correction of satellite and airborne remotely-sensed radiance data is crucial for deriving accurate radiance from benthic ecosystems. There have been many studies of remote sensing of benthic habitats demonstrating limitations and capabilities of remote sensing, particularly from satellites (e.g., Hedley et al., 2012; Hochberg et al., 2003). However, remote sensing of absolute standing biomass, taxonomic composition, habitat condition, and change can be quantified for many benthic communities if spectral (e.g., imaging spectrometer) and spatial requirements (e.g., cm to meter) can be met by sensor capabilities currently available on airborne sensors (Dierssen et al., 2003; Cavanaugh et al., 2010; Hill et al., 2014; Hedley et al., 2016). Beyond the identification of dominant benthic components (e.g., coral, sand, and submerged aquatic vegetation) and standing biomass estimation, remote sensing of near-shore benthic ecosystems has not advanced to the same level as for terrestrial ecosystems, largely because of the loss of information in the NIR and SWIR through water absorption. Spectral analyses of photosynthetic pigment assemblages, as related to their concentrations and reflectance, have shown promise for delineating benthic species and condition (Hill et al., 2014; Russell et al., 2016; Torres-Pérez et al., 2015). Linking the fine scale analysis to remote sensing is needed. This work supports stringent requirements for sensors to advance species detection, reef status, and change in heterogeneous coral reef environments.

Table 1 summarizes requirements by aquatic ecosystem type and Table 2 gives a synopsis of passive U.S. Earth sensors for the coming decade. These sensors collectively do not meet all the spectral, spatial, temporal, and radiometric requirements and some will miss nearly a decade of change by launch, if they launch at all. Development of remote sensing resources has tended to favor purely terrestrial or oceanic disciplines, marginalizing support of coastal and inland aquatic ecosystem research. Coastal and inland aquatic ecosystems are not simply boundary ecosystems for either land or sea; they are a vital nexus, where interaction and interdependency are greatest, leading to the most productive and diverse systems on the planet and vital resources for humans. Thus, addressing coastal and inland aquatic ecosystem science questions will require strongly interdisciplinary research supported by a diverse array of remote sensing assets developed for the study of the land/sea interface.

4. SUCCESS PROBABILITY given expected remote sensing resources in the coming decade

Based on current polar orbiting assets used to achieved global coverage, 30 m or better spatial resolution provides about a 16-day equatorial repeat period (*cf.* Landsat). Given swath widths comparable to Landsat for visible to SWIR imagery and cloud cover, this typically leads to about one or two scenes per site per season. For a more ideal minimum sampling time of monthly observations, the revisit time needs to be shorted by a factor of four or the swath width widened without compromising the ground sampling distance or 30m or less. Geostationary orbits could greatly boost temporal sampling frequency to near the limits set by clouds, but it considered too costly to measure at the spatial resolutions better than a few hundred meters. In addition, a constellation of three or more geosynchronous platforms would be needed to cover most of the globe, with little to no coverage in the polar regions at high temporal resolution. A better strategy appears to be the use of multiple polar-orbiting platforms, to greatly enhance temporal sampling, as has been demonstrated with Sentinel 1 and 2 of the Copernicus Programme funded by ESA and EUMETSAT. Multiple satellites in the same polar orbit increase the sampling rate at the same time of day corresponding to that orbit. Multiple orbits further provide sampling at different times of day. A swarm of inexpensive, small satellites populating multiple orbits could conceivable achieve and exceed what a constellation of expensive geosynchronous satellites.

The required measurements can be achieved affordably in the decadal timeframe, due to investments in response to global terrestrial/coastal coverage missions outlined in the 2007 NRC Decadal Survey (NRC 2007) and 2013 NRC sustainable land imaging report (NRC 2013) and other initiatives. The measurements would build on a legacy of airborne and space instruments including airborne: AIS (Vane et al, 1984), AVIRIS (Green et al., 1998), and AVIRIS-NG (Hamlin et al., 2011) and space: NIMS (Carlson et al., 1992), VIMS (Brown et al., 2004), Deep Impact (Hampton et al., 2005), CRISM (Murchie et al., 2007), EO-1 Hyperion (Ungar et al, 2003, Middleton et al., 2013), M3 (Green et al., 2011) and MISE, the imaging spectrometer now being developed for NASA's Europa mission.

NASA-guided engineering studies related to the Hyperspectral Infrared Imager (HyspIRI) show that a global VSWIR (380 to 2510 nm @ ≤10 nm sampling) imaging spectrometer with a 185 km swath, 30 m spatial sampling and 16-day revisit with high SNR and the required spectroscopic uniformity can be implemented affordably for a three-year mission with mass, power, and volume compatible with a Pegasus class launch. The key for this measurement is an optically fast spectrometer providing high SNR and a design that can accommodate the full spectral and spatial ranges (Mouroulis et al., 2016). A scalable prototype F/1.8 full VSWIR spectrometer (van Gorp et al., 2014) has been developed, aligned, and qualified. Data rate and volume issues have been addressed by development and testing of a lossless compression algorithm for spectral measurements (Klimesh et al., 2006, Aranki et al., 1009ab, Keymeulen et al., 2014). This algorithm is now a CCSDS standard (CCSDS 2015). An option for real-time cloud screening has also been demonstrated (Thompson et al., 2014). With compression and the current Ka band downlink offered by KSAT and others, all terrestrial/coastal measurements can be downlinked. Algorithms for automated calibration (Green et al., 1998) and atmospheric correction (Gao et al., 1993, 2009, Thompson et al., 2015, 2016) of large coastal and inland water data sets have been benchmarked as part of the HyspIRI preparatory (Lee et al., 2015), NASA AVIRIS-NG India and SIMPL Greenland campaigns and elsewhere. To enhance affordability and accelerate measurement availability, there is good potential for international partnerships.

A single orbiting platform bearing an instrument with these performance characteristics would have a high probability of achieving a significant the part of the aquatic habitat QESO. The spatial resolution would provide the minimum to globally map distribution and extent of sessile communities. The spectral and radiometric performance would potentially tease out additional characteristics, such as functional type or even species composition. However, the temporal resolution would be too low to routinely capture key phonological phases and a mission duration of one or more decades will be needed to capture long-term change. In addition, the rapid changes in water-column, such as the growth and advection of HABs or changes in suspended sediment, would not be captured. Additional platforms would be needed to increase the temporal sampling.

Orbiting TIR instruments at 60-meter spatial resolution or better have a long heritage, including Landsat TIR or Sentinel 2, which will be realized again in the current development of the NASA ECOSTRESS Mission or in the upcoming Hyperspectral Infrared Imager (HyspIRI). Companion NASA directed studies have shown the path for development of a TIR instrument with 4-day revisit that can be implemented affordably for a mission of three or more year duration, with instrument mass (91 kg), power (168 W), and volume compatible with a Pegasus class launch or rideshare. The key for this measurement is the NASA IIP PHYTIR instrument that is now the core of the NASA EVI ECOSTRESS Mission. The ECOSTRESS instrument will be completed in 2017 and mature all required technologies to TRL9 once deployed on the International Space Station in 2018. The use of such an instrument would be useful to potentially estimate wetland and watershed soil moisture and could capture changes in estuarine current dynamics or ground and surface water discharges. However, the temporal frequency for 4-days are less would be improved if the instrument were placed on two or more orbiting platforms

Table 1 – Coastal and inland aquatic ecosystem constellation measurement characteristics. Multi-spectral band sets are given in parentheses, while hyperspectral band series are not.

Aquatic Ecosystem →	**Emergent Habitats**	**Submerged Habitats**	**Water Surface**	**Lake and River Water Column**	**Estuarine Water Column**	**Pelagic/Shelf Water Column**
Example Subjects of Interest	Marshes, Mangroves, Wooded Swamps	Coral, Seagrass, Kelp, Microbial Mats	Floating Macroalgae, Microbial Scum and Slicks, Oil, Debris	Phytoplankton, Sediment, Colored Dissolved Organic Carbon, Water Quality	Phytoplankton, Sediment, Colored Dissolved Organic Carbon	Phytoplankton, Sediment, Colored Dissolved Organic Carbon
Spectral Range	0.4–2.5 µm (11,12 µm)	0.3–1.0 µm (11,12 µm)	0.4–2.5 µm	0.3–1.0 µm (1.2,1.6,2.4 µm) (11,12 µm)	0.3–1.0 µm (1.2,1.6,2.4 µm) (11,12 µm)	0.3–1.0 µm (1.2,1.6,2.4 µm) (11,12 µm)
Spectral Resolution	<10 nm VSWIR	<5 nm VisNIR	<10 nm VSWIR	<10 nm VisNIR	<5 nm VisNIR	<5 nm VisNIR
Spatial Res	<1 – 30 m	<1 – 30 m	<1 – 30 m	<1 – 100 m	50 – 250 m	250 – 1000 m
Temporal Resolution	weekly	weekly	daily	daily – monthly	1 hour – 3 days	1 hour – 3 days
Glint Avoidance	yes	yes	yes	yes	yes	yes
SNR	100 – 1000	500 – 1000	200 – 700	500 – 1000	500 – 1000	500 – 1000

Table 2 – U.S. aquatic capable remote sensing assets for the next decade. Blue text indicates a future mission. PACE is currently under development, while GeoCAPE and HyspIRI are still being planned.

Mission →	**OLI**	**HyspIRI**	**VIIRS**	**PACE**	**GeoCAPE**	**Advanced Baseline Imager**
Launch Date	2011 Landsat 8 2023 Landsat 9	after 2021	2011 S-NPP 2016 JPSS-1 2021 JPSS-2	2021	after 2021	2016 GOES-R
Orbit Type	Polar, Low Earth Orbit	Polar, Low Earth Orbit	Polar, Low Earth Orbit	Polar, Low Earth Orbit	Geosynchronous	Geosynchronous
Spectral Range	11 bands spanning 0.4–12 µm	0.38–2.5µm (4,5,7,8,9, 10,11,12 µm)	22 bands spanning 0.4–12 µm	0.35–1.0 µm (1.2,1.6,2.4 µm)	0.3–1.0 µm (1.2,1.6,2.4 µm)	16 bands (0.47-13.3 µm)
Spectral Resolution	20-30 nm VSWIR	<10 nm VSWIR	10 nm VisNIR	<10 nm VisNIR	<5 nm VisNIR	0.04 – 1.0 µm
Spatial Res	30 m	30 m VSWIR 60 m TIR	250 – 750 m	1000 m	350 m	0.5-2 km
Equatorial Revisit	16 days	16 days	2 – 3 days	2 – 3 days	2 – 3 hours	15 min
Glint Avoidance	None, seasonal data loss at mid to low lats	4° tilt along scan, some degradation at low lats	None, seasonal data loss at mid to low lats	20° tilt along track	Obs away from subsolar pt.	None
SNR	100 – 500	200 – 700	300 – 1000	500 – 1000	500 – 1000	300 (solar bands) NEΔT = 0.1K - 0.2K (IR)

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