Inland Waters

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Relevant Panels: This science and application target is most relevant to the “Global Hydrological Cycles and Water Resources” and “Marine and Terrestrial Ecosystems and Natural Resource Management” Decadal Survey panels.

Science and Application targets

Inland sources of fresh water are critical for life on our planet. Even though 50% of the world's population lives within 3 km of inland rivers and lakes, over 1.1 billion people currently do not have access to clean water (WHO, 2006). Water crises are the greatest risk facing the world today according to the World Economic Forum (WEF, 2015). Over 80% of the world’s population currently faces high level water risk (Vorosmarty et al., 2010). Half of the world’s 500 major rivers and half the world’s lakes are classified as seriously degraded or over-exploited (UNEP, 2006). The decline in the quality of water resources is causing the extinction of freshwater species and a severe loss of biodiversity. The following inland water stressors and societal challenges can be addressed with improved remotely sensed measurements over inland waters:

Eutrophication, Harmful Algal Blooms and Water Clarity

Eutrophication caused by excessive nutrient loading from anthropogenic sources can lead to excessive algal growth and toxic cyanobacterial blooms. Factors including nitrogen, phosphorus, and temperature all contribute to this excessive growth (Paerl et al., 2014; Rigosi et al. 2014) resulting in low oxygen, loss of biodiversity, loss of fisheries, decreased light penetration causing the loss of submerged vegetation, and aesthetic and odor issues that impact drinking water, commerce and tourism. Though known to be widespread across all continents, the extent and intensity of these blooms is currently unknown.

Watershed Alterations and Impacts

Inland waters are strongly influenced by land use, which can affect the timing and location of inflows and water quality. Changes in runoff, particularly due to urbanization and associated impervious surfaces, can increase flash flooding, extend periods of low flows, and alter channel morphology. Changes in land use or land use practices, often associated with agriculture, can also significantly increase nutrient delivery, thereby altering nutrient ratios and impacting biogeochemical processes in the receiving waters. The increased intensity of runoff events can also increase erosional power and entrain more soil particulates with greater particle size. The resulting water quality impacts include greater siltation in receiving waters, which negatively impacts fisheries and benthic organisms. Silt-laden water supply intakes incur greater costs to process and clean incoming waters. Nutrients, metals, and organic pollutants are also transported in association with the particulates. Watersheds can also be affected by agricultural diversions of water, for example at the Aral Sea.

Climate Change Impacts

Aquatic ecosystems are particularly vulnerable to climate change. Changes to the hydrologic cycle such as storm magnitude and frequency, extreme events, ratio of snow/rain, and water stress all affect inland waters. Variations in meteorological conditions cause changes in water temperature, evapotranspiration and runoff, lake level, evaporation rates, ice cover, hydrobiogeochemical regimes, and entire lake ecosystems. Of particular concern are the impacts of changes in inland water temperature and associated stratification, which is rising rapidly in lakes around the world (O'Reilly et al. 2015) and can result in changes in species abundance, distribution, composition, productivity and phenology (Figure 1 and 2). Changes in temperature and stratification also affect fisheries habitat, water chemistry (such as $CaCO_3$ and O_2 solubility), mercury methylation rates, carbon cycling (such as CO_2 fluxes), and bioaccumulation in sediments.

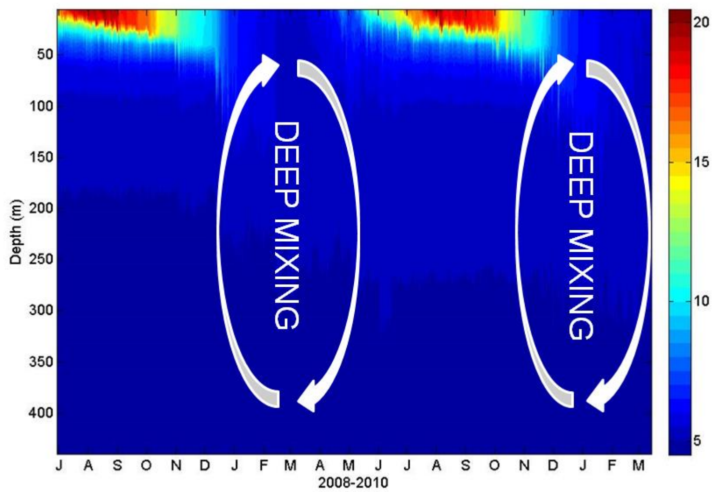

Figure 1. Stratification in Lake Tahoe CA/NV from 2008 – 2010. Deep mixing occurs in winter when water column temperature is uniform. If a permanent, warm layer is established, then mixing will become much more limited, and the lake will become increasingly anoxic from the bottom to top, and the phytoplankton communities in the surface waters will also be affected. Courtesy G. Schladow, UC Davis.

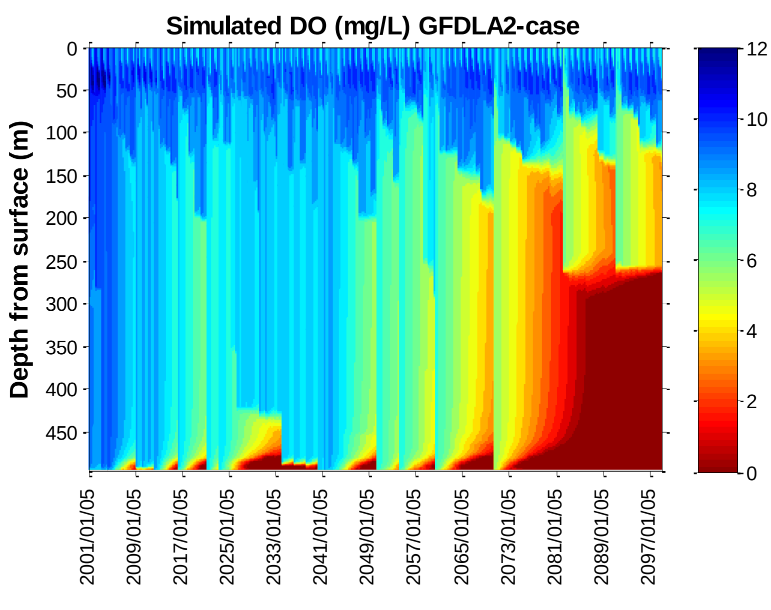

Figure 2. Forecasted dissolved oxygen for Lake Tahoe (CA/NV) with increasing warming. Warming inhibits deep lake mixing, leading to an increase in anoxic conditions. Courtesy G. Schladow, UC Davis.

Biodiversity and Invasive Species

Aquatic ecosystems are sensitive to species shifts through changes in their physical and biogeochemical characteristics. These shifts often result in the loss of native species and introduction of invasive species that can harm native ecosystems and the commercial, agricultural, and recreational activities that depend on them. The costs to control and eradicate invasive species in the U.S. alone amount to more than $120 billion annually (Pimentel, 2005). Remote sensing has been utilized to document impacts from invasive species, including Great Lakes water clarity due to invasive dreissenid mussels (Limburg et al., 2010). Satellite retrievals have also been used to distinguish between native and non-native aquatic plant species (Santos, 2012) and support bioenergetic modeling for invasive species (Anderson et al., 2015).

Globally, many lakes are in places where regular in-situ sampling is prohibitively difficult (e.g., remote, high-latitude lakes or large lakes in East Africa). In addition, management and modeling approaches require improved spatial measurements, and the scientific community needs these data to validate models and improve understanding of how aquatic systems evolve – both spatially and temporally (e.g. algal blooms) – to develop more effective management strategies.

Utility of Geophysical Variables

For large lakes numerous existing and planned satellite sensors provide water quality data (e.g., temperature, transparency, loading of suspended sediments, phytoplankton information), including platforms such as MODIS, PACE, SLSTR, and VIIRS. These sensors typically have spatial resolutions of 1 km and provide daily data. However, none of these sensors provide frequent (every few days) high spatial resolution (<100m) data. Hestir et al. (2015) showed that a spatial resolution of at least 30-60 m per pixel is required to assess many inland waters over a range of geographic scales. Resolution coarser than 60 m leads to significant spectral and spatial mixing and to un-interpretable observations of water and land types (Turpie et al. 2015). The number of EPA National Lakes Assessment water bodies that can be resolved with a 30 m pixel resolution is 100%, but only ~6% with 300 m pixel resolution.

The HyspIRI mission would provide the necessary, high spatial resolution for water quality from its Visible-Shortwave Infrared Imaging Spectrometer and Thermal Infrared Multispectral Scanner, however, the mission is currently in Pre-Phase A with no planned launch date.

Measurement and Observation Requirements

TIR Radiometer

For *lake surfacee temperature* sustained TIR radiometric retrievals from a high resolution instrument with an NEdT of 0.2K and ≥2 spectral bands between 8 and 12 μm for a split window algorithm, a spatial resolution of ~60 m together with a band at, ~1.6 μm for cloud detection and geolocation. The instrument should have a revisit of 2-3 days in order to capture upwelling and circulation in lakes (Figure 3).

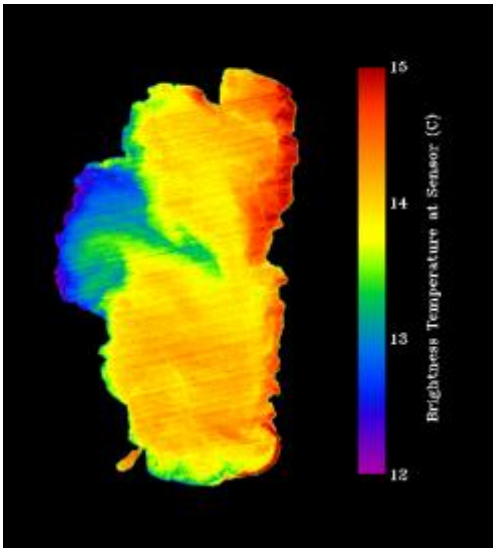

Figure 3. Advanced Spaceborne Thermal Emission and Reflection Radiometer image from Lake Tahoe CA/NV showing plume of cold water from below the surface (colored blue) which has risen in the west after strong winds and is being pushed to the eastern shore. This cold water provides nutrients and illustrates how the satellite images allow us to examine how the temperature of the lake varies across the entire lake at an instant in time. Lake Tahoe is approximately 35 km in length (Steissberg et al. 2005)

VSWIR Imaging spectrometer
Historical satellite ocean color sensors, such as CZCS, SeaWiFS, and/or MODIS, are limited in both spatial and spectral resolutions for the observation of aquatic properties in inland lakes. NASA's Hyperion is a hyperspectral sensor, but its signal-to-noise ratio is too low for reliable derivation of water properties. For the monitoring of transparency, loading of suspended sediments, information on phytoplankton types or functional groups, and concentration of dissolved organic matters in inland waters, a spectrometer with continuous spectral range from 0.4-1 µm at ≤10 nm spectral sampling, ~30 m pixel resolution, with 5-7 day observation repeat is required. In addition, the desired minimum SNR of such a spectrometer is 500 in the visible and 200 in the NIR.

Feasibility and Affordability

TIR Radiometer
NASA-led engineering studies have demonstrated the feasibility of a 3-year, Class C mission with the needed TIR radiometer at 60 m pixel resolution, and a 2-3 day temporal repeat at the equator. This radiometer would fit with a size, weight and power (SWaP) compatible with a Pegasus class launch (Figure 4). Many of the key technologies enabling the mission build on the legacy of previous investments, in particular ECOSTRESSS which demonstrates the focal plane, cryocoolers and scan mirror assembly technologies required (Figure 5). The mission has an orbital average data volume consistent with readily available onboard solid state recorded (SSR). The ECOSTRESS instrument was capped at $30M and therefore the cost for a TIR radiometer is expected to be in the same range.

VSWIR Imaging Spectrometer
NASA-led engineering studies showed that the needed imaging spectrometer can be implemented as a 3-yr class C mission (in comparison to the Class B Landsat missions) with SWaP compatible with a Pegasus class launch (Figure 6). The key for this measurement is an

optically fast spectrometer, for which a scalable prototype F/1.8 has been developed, aligned, and qualified (Figure 7). Data rate and volume have been addressed using a lossless compression algorithm and by employing a real-time cloud screening processes, thus enabling Ka band downlink of all terrestrial measurements (Figure 7). Algorithms for automated calibration and atmospheric correction are operational. The cost for this instrument is also estimated to be in the $30M range.

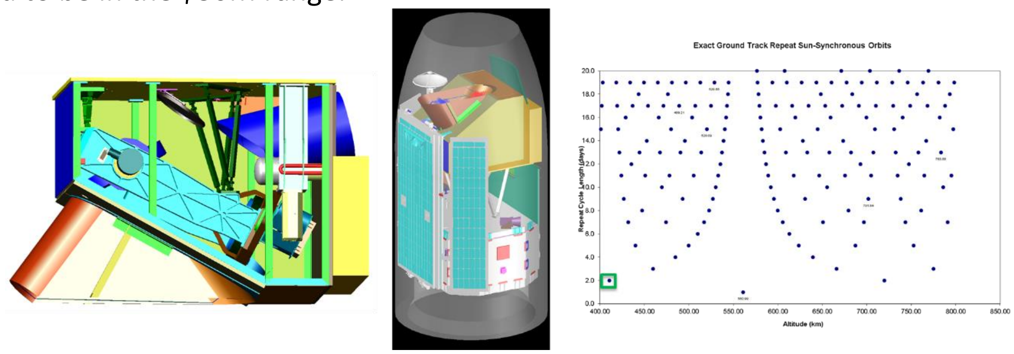

Figure 4. (left) Opto-mechanical configuration for a wide swath, high resolution TIR imaging radiometer system providing 73-degree swath and 60 m sampling. TIR Imaging radiometer with spacecraft (265 kg, 187 W) configured for launch in a Pegasus shroud for an orbit of 410 km altitude, 97.07 inclination to provide 2-day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 410 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

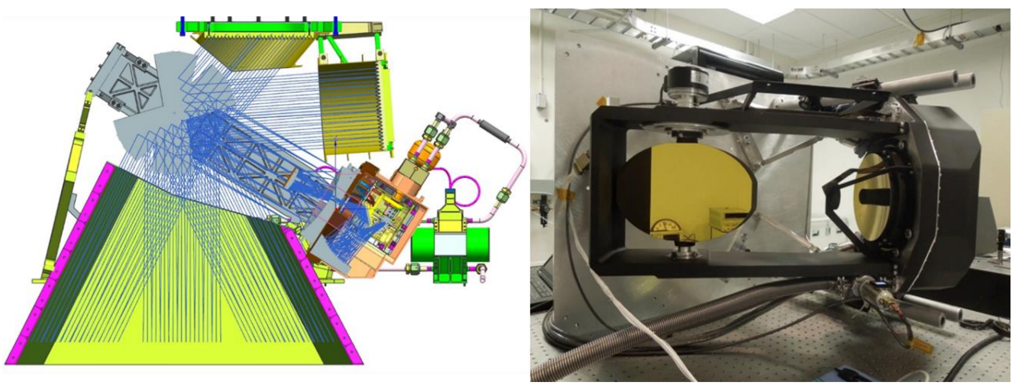

Figure 5. (left) Design of ECOSTRESS TIR Push-whisk scanning system covering a wide field of view with an 8 band SWIR to TIR sensor. (right) Developed, aligned and qualified PHyTIR push-whisk system with TIR full range multi-band detector array.

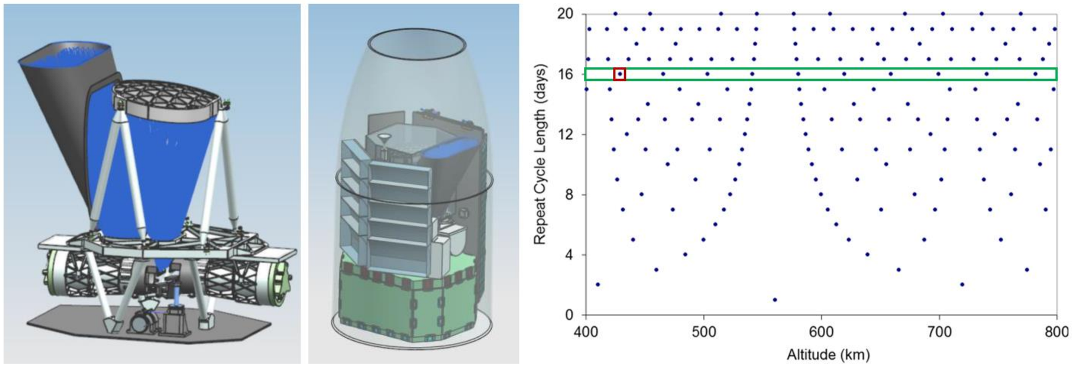

Figure 6. (left) Opto-mechanical configuration for a high SNR F/1.8 VSWIR imaging spectrometer system providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft (265 kg, 134 W) configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 429 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

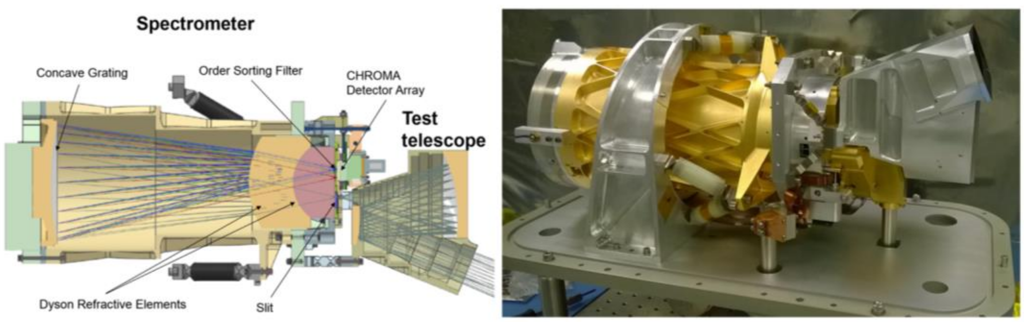

Figure 7. Design of F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Developed, aligned and qualified Dyson with CHROMA full range VSWIR detector array.

<u>Synergistic Measurements</u>

It is assumed that synergistic measurements will continue to be available from ASTER, Landsat, MODIS, VIIRS, and other instruments. However, these measurements do not have the spatial, spectral, and temporal frequency required for lake observations, especially smaller lakes.

<u>Acronym List</u>

CZCS – Coastal Zone Color Scanner
MODIS – Moderate Resolution Imaging Spectroradiometer
NIR – Near Infrared
SeaWIFS - Sea-Viewing Wide Field-of-View Sensor
PACE - Pre-Aerosol Clouds and ocean Ecosystem Mission
SLSTR - Sea and Land Surface Temperature Radiometer)
SWaP – Size, Weight and Power
VIIRS – Visible Infrared Imaging Suite
VSWIR – Visible Shortwave Infrared

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