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DESIGN CONSIDERATIONS FOR AN AQUATIC ECOSYSTEM IMAGING SPECTROMETER: RESULTS OF A CEOS FEASIBILITY STUDY)

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Abstract

Many Earth observing sensors have been designed, built and launched with primary objectives of either terrestrial or ocean remote sensing applications. Often the data from these sensors are also used for freshwater, estuarine and coastal water quality observations and bathymetry and benthic mapping. However, such land and ocean specific sensors are not designed for these complex aquatic environments and consequently are not likely to perform as well as a dedicated sensor would. As a CEOS action, CSIRO and DLR have taken the lead on a feasibility assessment to determine the benefits and technological difficulties of designing an Earth observing satellite mission focused on the biogeochemistry of inland, estuarine, deltaic and near coastal waters as well as mapping macrophytes, macro-algae, sea grasses and coral reefs. These environments need higher spatial resolution than current and planned ocean colour sensors offer and need higher spectral resolution than current and planned land Earth observing sensors offer (with the exception of several R&D type imaging spectrometry satellite missions). The results indicate that a dedicated sensor of (non-oceanic) aquatic ecosystems could be a multispectral sensor with ~26 bands in the 380-780 nm wavelength range for retrieving the aquatic ecosystem variables as well as another 15 spectral bands between 360-380 nm and 780-1400 nm for removing atmospheric and air-water interface effects. These requirements are very close to defining an imaging spectrometer with spectral bands between 360 and 1000 nm (suitable for Si based detectors), possibly augmented by a SWIR imaging spectrometer. In that case the spectral bands would ideally have 5 nm spacing and FWHM, although it may be necessary to go to 8 nm wide spectral bands (between 380 to 780nm where the fine spectral features occur -mainly due to photosynthetic or accessory pigments) to obtain enough signal to noise. The spatial resolution of such a global mapping mission would be between ~17 and ~33 m enabling imaging of the vast majority of water bodies (lakes, reservoirs, lagoons, estuaries etc.) large than 0.2 ha and ~25% of river reaches globally (at ~17 m resolution) whilst maintaining sufficient radiometric resolution.

Keywords: (Earth observation, aquatic ecosystems, multispectral remote sensing, imaging spectrometry, optical sensor specifications, environmental applications)

Acronyms/Abbreviations

CEOS=Committee on Earth Observing Satellites.
CSIRO=Commonwealth Industrial and Scientific

Research Institute. DLR= German Aerospace Laboratories. GEOSS = Group on Earth Observations System of Systems. EO = Earth observation. VIS-NIR= visible and nearby infrared wavelength region. TSM= total suspended matter. K_d= vertical attenuation of diffuse downwelling light, CDOM= coloured dissolved organic matter. MODIS= Moderate resolution imaging spectrometer, MERIS=Medium resolution imaging spectrometer. OCM-2=Ocean colour monitor 2. SWIR= Shortwave infrared wavelength region. FWHM=full width at half max. ha= hectare.

1. Introduction

Initially this work had a more limited scope to focus on inland waters only. It started as a Committee on Earth Observation Satellites (CEOS) response to the Group on Earth Observations System of Systems (GEOSS) Water Strategy [1] developed under the auspices of the Water Strategy Implementation Study Team that was endorsed by CEOS at the CEOS 2015 Plenary. As one of the actions, CSIRO took the lead on recommendation C.10: A feasibility assessment to determine the benefits and technological difficulties of designing a hyperspectral satellite mission focused on water quality measurements. This inland water focus was considered a too limited scope as there has never been dedicated study to assess the requirements for an aquatic ecosystem imaging spectrometer or multispectral sensor (excluding ocean requirements). The GEOSS Aquawatch suggested that alternative approaches, involving augmenting designs of near future planned spaceborne sensors for terrestrial and ocean colour applications to allow improved inland, near coastal waters and benthic applications, could offer an alternative pathway. Accordingly, this study also analyses the benefits of this option as part of this feasibility study.

We performed a feasibility assessment of the benefits and technological challenges of designing a passive multispectral or hyperspectral satellite sensor system focused on biogeochemistry of inland, estuarine, deltaic and near coastal waters - as well as mapping macrophytes, macro-algae, seagrasses, coral reefs and shallow water bathymetry. Compared to any existing sensors, this sensor shall need to have a significantly higher spatial resolution than 250 m, which is the maximum spatial resolution of dedicated current aquatic sensors such as Sentinel-3 and future planned aquatic sensors such as the Coastal Ocean Color Imager at 100 m spatial resolution). Further, the GEO Community of Practice AquaWatch suggested that alternative approaches, involving augmenting designs of space-borne sensors for terrestrial and ocean colour applications to allow improved inland, near coastal waters and benthic applications, could offer an alternative pathway to addressing the same underlying science questions. Accordingly, this study also analyses the benefits and technological difficulties of this option as part of the high-level feasibility study.

The approach was to follow a science and applications traceability approach of required aquatic ecosystem variables to be measured, the level of accuracy required, the level of temporal, spatial, spectral and radiometric resolution required. Although we were aware of current bounds of what was technically feasible, we did believe that the requirements should lead this study and therefore may not (yet) be technically feasible

2. Key considerations

In addition to providing a global service, because there are global pressures (e.g., growing human exploitation of coastal and inland resources and changing climate), we need to study effects on global scales. A global observation system is thus an appropriate and invaluable tool to assess the impact on commensurate scales. In many countries, field-based monitoring efforts are currently insufficient to provide national-scale assessments of aquatic ecosystems. In improving the design of such assessments using earth observation, key considerations include:

1) Temporal sampling to i) represent the dynamics of water quality, benthic and water depth change and the range of conditions that can occur over diurnal, seasonal, and annual cycles (e.g., droughts and flooding), ii) develop time series for understanding phenology and trend analysis, including the effects of climate change, iii) retrospective processing of satellite images, archives of relevant data, which date back to the early 1980's, may also reveal temporal changes, trends, and anomalies across inland water and near-coastal water systems.
2) Spatial sampling that is representative of the processes and dynamics in aquatic ecosystems under consideration to provide understanding of system processes, such as for water bodies: heterogeneity, environmental flows, interrelationships between water bodies, and catchment runoff effects, global climate change effects; and for benthic ecosystems the effects of these flows as well as predation, smothering, trophic state and global warming effects such as water temperature changes, increasing acidification, and coral bleaching. End-user requirements should determine the optimal spatial sampling scheme, but logistical, operational, and financial constraints usually prevent the optimal sampling scheme from being realised. Extensive distances and

remoteness, for instance, may make capturing the spatial distribution of measurements using field-based methods infeasible. EO-derived aquatic ecosystem information, albeit on a more limited set of parameters, may be used to overcome the challenges in sampling schemes based solely on field-based approaches.

3) Capability building should focus on the integration of EO data and field-based observations, and the development of early-warning tools such as for algal blooms and coral bleaching.

We analysed past existing and upcoming satellite sensor systems of relevance for aquatic ecosystem assessment. While policy, legislative, environmental, and climate change drivers should steer the development of a global, operational system for aquatic ecosystem monitoring, the ideal satellite sensor system does not yet exist. Different satellite systems show different trade-offs between the temporal frequency (once a day to once a year), spatial resolution (2.0 m to 1.2 km pixels), spectral resolution and range (and the related issue of more aquatic ecosystem variables at higher confidence level), radiometric resolution (how accurate and how many levels of reflectance are measureable as well as the dynamic range measureable), and the costs of unprocessed satellite data acquisition (ranging from publicly available to commercially available very high spatial resolution data at ~30 USD per km^2 for the most expensive type of single scene acquisition). These trade-offs also influence the usefulness for aquatic ecosystem assessment.

Spatial resolution (the size of the area being measured on the ground) has consequences for imaging (i) small water bodies such as small- or medium-width river systems or small lakes. In such situations, high spatial-resolution imagery (with pixel sizes of 2 to 10 m) may be the only option, possibly leading to significant data-acquisition costs. A similar argument exists for mapping habitats in coastal and ocean waters formed by foundational species, including submerged plants such as macrophytes (in inland waters) and seagrasses; kelp; corals; sponges; and benthic micro-algae, and environments such as rock reefs and various bottom substrates. However, for a global mapping mission spatial resolution between 10 and 30 m may be suitable.

Spectral resolution and range (the number, width, and location of spectral bands) ultimately determines the amount and accuracy of aquatic ecosystem variables that are discernible from a water body. Sensors with few broad VIS-NIR bands (usually a blue, a green, a red and a nearby infrared spectral band) may only be used to detect those variables that have a broad spectral response: TSM, K_d, Secchi disk transparency, turbidity, and CDOM as water column variables and presence – absence of underwater flora and fauna (e.g. corals). Algal pigments such as chlorophyll-a and cyano-bacterial pigments such as cyanophycoerythrin and cyanophycocyanin may also be detected. However, at low concentrations, accuracy will be low, as broad spectral bands cannot discriminate narrow pigment spectral absorption features from other absorbing and backscattering materials in the water column or benthos. As the number of narrower and more suitably positioned spectral bands increases (e.g., the coarse spatial resolution ocean colour sensors MODIS, MERIS, OLCI, and OCM-2), chlorophyll-a becomes an accurately measureable variable, and other cyano-bacterial pigments may become detectable.

Radiometric resolution determines the lowest level of radiance or reflectance that the sensor can reliably detect and discriminate per spectral band. As the spectral and spatial resolution increase, the useful signal relative to noise in the data decreases. This trade-off in spectral, spatial, and radiometric resolution is countered by improvements in instrument design and technology, for example, detectors which have much better performance than older sensors. An added complexity is that the water leaving signal at the satellite sensor (typically at an altitude between 450 and 800 km) is only a very small part of the total measured signal, composed of the water leaving signal plus the reflections at the air-water interface plus the signal from reflected sun and skylight in the atmosphere, hence radiometric resolution should be sufficient to detect relevant levels of aquatic ecosystem variables through a set of atmospheric and air water interface conditions and solar angles. In addition, temporal radiometric stability is a key requirement to ensure generations of consistent products like TSM, K_d, Secchi disk transparency, turbidity, and CDOM.

3. Method

We considered three approaches to determine the specifications for an aquatic ecosystem earth observing sensor: i) a literature study with a focus on quantitative research that focuses on end user requirements as well as the sensor specifications required to properly be able to detect and assess aquatic ecosystem variables, ii) a simulation of bottom of atmosphere (or water leaving) radiance and reflectance for inland, coastal and coral reef waters with different depths, coupled with spectral libraries of substratum types such as sands, seagrasses, macro-algae and corals using the WASI-2D software package [2] augmented by non-algal particulate matter absorption and phytoplankton backscattering inputs, and iii) the identification of the requirements of various types of algorithms for retrieving these variables. Often in literature one of these aspects is considered but seldom has a study considered all three aspects simultaneously (see [5] for more detail.

An important distinction to be made is between those water bodies where the incoming sun- and skylight does not reach the bottom and the bottom reflectance does not leave the water; these are the optically deep waters. Optically shallow waters are those waters where there is a measurable amount of reflected light from the bottom passing through the water column and reaching the Earth observing sensor.

4. Results, Conclusion and Discussion

As a result of the above mentioned three approaches we identified that the following requirements should determine a comprehensive aquatic ecosystem Earth observing capability: i) ability to estimate algal pigment concentrations of chlorophyll-a, accessory pigments, cyanobacteria pigments (cyanophycoerythrin and cyanophycocyanin especially as well as other wavelengths relevant for phytoplankton functional types research, ii) Algal fluorescence (especially chlorophyll-a fluorescence at 684 nm), iii) ability to measure suspended matter, possibly split up into organic and mineral matter, iv) ability to measure coloured dissolved organic matter and discriminate terrestrial from marine CDOM, v) spectral light absorption and backscattering of the optically active components, vi) measures of transparency of water such as Secchi disk transparency, vertical attenuation of light and turbidity. For optically shallow waters also: vii) estimates of the water column depth (bathymetry) and viii) estimates of substratum type and cover (e.g. muds, sands, coral rubble, seagrasses, macro-algae, corals, etc.) as well as plants floating at or just above the water surface. For residual sun glint correction (if sun glint mitigation measures are insufficient) and for estimating the atmospheric composition it is also required to have spectral bands to measure O_3, NO_2, water vapour and aerosols as well as have some bands in the nearby infrared and/or SWIR for sun glint correction.

The results [5] indicate that a dedicated sensor of (non-oceanic) aquatic ecosystems could be a multispectral sensor with ~26 bands in the 380-780 nm wavelength range for retrieving the aquatic ecosystem variables as well as another 15 spectral bands between 360-380 nm and 780-1400 nm for removing atmospheric and air-water interface effects. These requirements are very close to defining an imaging spectrometer with spectral bands between 360 and 1000 nm (suitable for Si based detectors), possibly augmented by a SWIR imaging spectrometer. In that case the spectral bands would ideally have 5 nm spacing and FWHM, although it may be necessary to go to 8 nm wide spectral bands (between 380 to 780nm where the fine spectral features occur -mainly due to photosynthetic or accessory pigments) to obtain enough signal to noise. The spatial resolution of such a global mapping mission would be between ~17 and ~33 m enabling imaging of the vast majority of water bodies (lakes, reservoirs, lagoons, estuaries etc.) large than 0.2 ha [3]and ~25% of river reaches globally (at ~17 m resolution [4]) whilst maintaining sufficient radiometric resolution.

A cost-effective alternative solution of obtaining improved data over aquatic ecosystems could be to augment near future planned Earth observing sensors to make them significantly more useful for aquatic ecosystem Earth observation. Two spectral bands (one between 615-625 nm) and one between 670-680 nm) would greatly enhance the capability of these terrestrial focused sensors to determine two important aspects of water quality in inland and coastal waters: respectively. cyanobacterial (or blue-green algal) concentration and overall abundance of algae via the main photosynthesis pigment of chlorophyll-a.

As spectral and spatial resolution are the core sensor priorities the radiometric resolution and range and temporal resolution need to be as high as is technologically and financially possible. A high temporal resolution could be obtained by a constellation of Earth observing sensors e.g. in a various low earth orbits augmented by high spatial resolution geostationary sensors.

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