Optical Detectors for Integration into a Low Cost Radiometric Device for In-Water Applications: A Feasibility Study

ABSTRACT

Higher water temperatures and nutrient loads, along with forecasted climate changes are expected to result in an increase in the frequency and intensity of eutrophication-linked algal blooms.[1] The destructive impact such phenomena have on marine and freshwater systems threaten aquaculture, agriculture and tourism industries on a global scale.[1] An innovative research project, Safe Waters Earth Observation Systems (SWEOS) proposes the use of space-based remote sensing techniques, coupled with in-situ radiometric technology to offer a powerful and potentially cost effective method of addressing algal bloom related hazards. The work presented in this paper focuses on the decision making processes involved in the development of autonomous bio-optical sensors whose purpose includes, but is not limited to; water constituent monitoring, satellite calibration validation and ocean colour satellite product matchups. Several criteria including optical throughput, linearity and spectral sensitivity were examined in an attempt to choose the detector best suited for its intended application. The CMOS based module tested in the laboratory experiments was found to have produced the best performance at the lower price and was subsequently chosen for integration into the in-water radiometric device built and tested at the CSIR.[2] Mass production of this prototype technology will commence, pending data quality comparable to that of an already calibrated, in-water radiometer; to be tested at field trials in Elands Bay, Loskop and Saldanha Bay.

INTRODUCTION

The growth of microscopic algae (called phytoplankton) is imminent as the organic content within a water body or region thereof increases. Despite the minute size of these organisms, their numbers have the potential to grow very rapidly. This explosive increase in phytoplankton biomass is dubbed a bloom. When the species of algae in the bloom cause detrimental effects to the ecosystem they inhabit, they are labelled harmful algal blooms, commonly referred to as HABs in the limnology and marine science communities. Detail on the environmental and economic impacts of HABs is discussed in detail by multiple authors. [5-7] The large scale impact HABs have on the environment drives the need for a forecasting system that helps to facilitate corrective measures and treatment procedures of affected waters[2]. The heterogeneous nature of the oceans coupled with non-trivial bloom dynamics necessitates that such a system have the required data captured at a high temporal frequency on as large a spatial scale as possible. Satellite imagery aptly satisfies these two requirements and has for the last few decades been the best tool for such initiatives.[8-10]

To better understand satellite measurements and their inherent uncertainties, it is necessary to calibrate and validate such spaceborne data. This requires in-situ radiometric measurements to be captured almost simultaneously with those acquired on board satellites. For an accurate and reliable inter-comparison the in-situ data obtained needs to have an appropriately high spatial distribution. A study conducted by the NOWPAP research group[11] suggests a minimum of 10 in-situ sampling points per satellite measurement separated by a distance dependant on the satellite spatial resolution (250 – 500m). As a result the method often employed for capturing in-situ data for calibration and validation activities is ship-based. However; regular, continuous and time-specific measurements via this method of monitoring are costly and or not always possible. The inability to access remote areas provides an added disadvantage. Hooker and McClain[12] as well as Cullen and Ciotti[13] discuss the future possibilities of basic cost effective and light-weight instrumentation as the optimal manner for gathering accurate and reliable sea-truth data. Such devices, if able to produce high quality data, would be moored at a large number of strategic locations resulting in a spatial coverage equal to or better than that offered by any other in-situ monitoring method.

Development of low-cost radiometric instrumentation for in-water applications without jeopardising performance requires careful considerations and innovative compromises. The sections that follow herein give an overview of the decisions made in choosing the sensor to be used in the prototype radiometer. An experimental, quantitative and where necessary graphical discussion outlining the capabilities of two short-listed spectrometer cores precedes a brief summary of the research completed. The paper concludes with a justification for the choice of sensor, and a mention of future endeavours planned using the resulting radiometric device.

BACKGROUND

The SWEOS project is a multi-disciplined initiative seeking to address the severe impact HABs have on water resources in South Africa; that which is documented by Oberholster and Ashton.[14] The project combines an innovative ensemble of remote sensing techniques with robust, cost effective and autonomous in-situ technology. The primary use for this Earth

Observation (EO) system is to provide a means for monitoring water quality in high impact coastal and inland water bodies.[1]

An invaluable facet of project SWEOS is the development of economically priced radiometric sensors. Deploying large numbers of these bio-optical instruments creates a network of sensors providing the ability to thoroughly characterise ecosystems by validating the pertinent satellite derived data. The sensor network also has the potential to act as an early warning bloom detection system, the need for which has been addressed by Oberholster and Claasen[15] for inland water bodies and Hutchings and Roberts[16] for coastal ecosystems.

The SWEOS mandate places low-cost as the largest driving factor for the envisaged technology. The target is to realise a system with market potential at less than 50 % the price of present commercial systems. The spectrometer core has the largest impact on cost and performance. As a result the selection of an appropriate detector has been prioritised.

A report compiled by Lysko and Griffith[17] found that two OEM sensors closely met the pre-defined selection criteria and may be the best suited candidates for integration into the radiometric device. Both the shortlisted candidates (hereafter referred to as C1 and C2) have an architecture incorporating a tightly knitted optical input and spectral dispersion mechanism. This proved advantageous as it could be easily incorporated into the intended light-weight, compact and autonomous design.

SENSOR DESCRIPTION

Architecture

Commercial ocean colour radiometers have evolved from the somewhat limited single channel detector type spectrophotometers, seen for example in Choi[18] and Robertson[19]. The current conventional ocean colour systems realise multiple channels with a silicon photodiode array, CCD array or a CMOS array. In all cases, the broad-band light source is diffracted by a dispersing element onto an imaging sensor, made up of tiny photosites (pixels). The light sensitive pixels absorb incident photons and release electrons through the photoelectric effect.[20] The accumulation of charge over the exposure time is transferred and converted to an analogue voltage which is subsequently converted into a digital number. The entire image is now a collection of numbers that can be manipulated to give the spectral signature of the source under study.

Sensors C1 and C2 employ the CMOS linear array architecture which differs from the CCD detectors (commonly found in digital cameras) only in the manner by which the charge is transferred and where it is converted to a voltage.

Optical design

The influence optics has on the fate of the light entering the system is illustrated in figure 1 for C1 and C2.[21] The optical design of C2 takes on a more conventional approach in which the light entering through a restricting slit is collimated onto a grating and the resulting spectrum focused onto the image sensor. The compactness of C1 is as a result of a coupling of the collimating and dispersing mechanisms. This is achieved by imprinting a diffraction grating onto a focusing lens. The latter offers the flexibility of a high spectral resolution within a miniaturised spectrometer head. This is an advantage for applications demanding light weight and compact payloads.

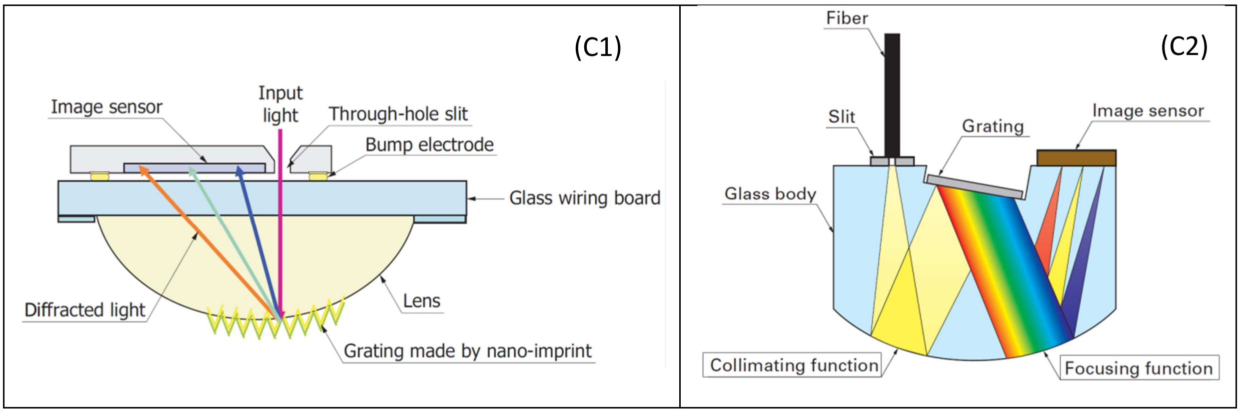

Figure 1: Input Light Relay for C1 and C2[21]

FIGURES OF MERIT

In order to quantitatively describe and compare the performance of C1 and C2, certain figures of merit have been considered. These include: spectral range, spectral sensitivity, spectral resolution, optical throughput and the Signal-to-Noise Ratio (SNR).

Spectral range and response

The portion of the electromagnetic spectrum that is pertinent to most in-water measuring applications ranges from 400 nm (visible) to 750 nm (near infrared). Choosing a detector with sufficiently high spectral sensitivity in this region is therefore a prerequisite. Both short-listed sensors, C1 and C2, are sufficiently sensitive within the required spectral window.

The plots in Figure 2, as taken from relevant specification sheets [21, 22] give the relative spectral sensitivity for C1 and C2. It is desirable to have a smooth and flat spectral response to reduce uncertainties related to spectral binning. C1 has a higher sensitivity as well as a smoother and more flat spectral response in the 400 nm to 750 nm region of interest, giving it a distinct and considerable advantage over C2.

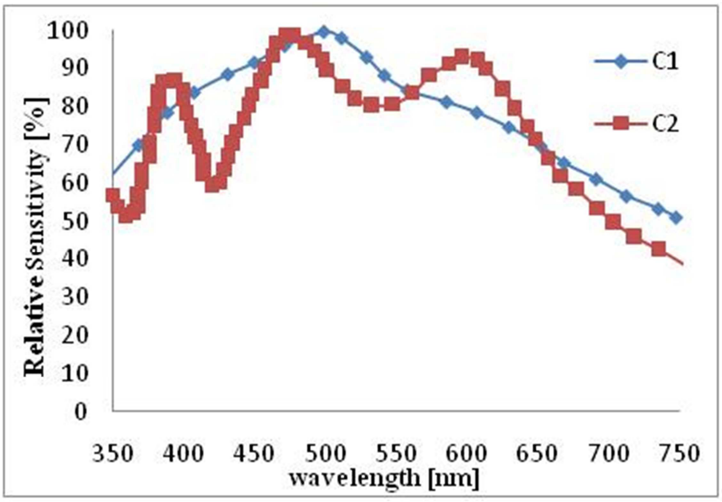

Figure 2: Typical Relative Spectral Response at 25°C Ambient Temperature

Spectral resolution

The spectral resolution offered by C1 and C2 are 10 nm[23] and 12 nm[21] respectively. These resolutions are considered to be ample for capturing the upwelling radiance in water, which usually exhibits spectral signatures devoid of sharp features, as seen in work completed by Ramkilowan and Chetty[2], Dierrsen and Kudela[7] as well as Kohler and Philpot.[22] The improved resolution of 2 nm that C2 has over C1 is insignificant to this application.

Optical Throughput

Highly turbid waters will result in low upwelling radiances which may impinge on the detectivity of the sensor. Such scenarios may be avoided by optimising geometric coupling between the light source and the detector so as to maintain optical throughput. By definition, the optical throughput G is an indication of the total flux that can pass through a system and is the product of the maximum cone of flux received at the slit entrance and the sensitive slit area.

$$G = \pi \sin^2(\theta).s, \qquad \text{equation (1)}$$

The slit area for C1 and C2 is the area of the through-hole-slit and slit in the respective diagrams of Figure 1. Clearly, *G* may be increased by increasing *s*. The slit width is nominally fixed and is pre-defined by the dispersive optics and the spectral resolution requirements. With assumption of an appropriate choice of slit width, an increase in slit height may increase stray light and also reduce resolution and bandpass. This will result in an increase in system aberrations. The entrance slit dimensions, as provided by the manufacturers, are 75 μm (height) x 750 μm (width) for C1 and 50 μm x 300 μm for C2.[21, 22] Given that C1 and C2 have the same acceptance solid angle, then from equation (1) it is inferred that C1 has the larger sensitive slit area and thus the greater optical throughput. One may expect that this is with a compromise with respect to stray-light and resolution.

Sensor Noise and Stability

From prior observations, the in-water upwelling radiance levels that are expected to be encountered will result in exposure times for a detector ranging from 0.05 seconds for oligotrophic waters, to 2 seconds in hypertrophic waters.[6]
A programmable system allows for exposure time adjustments and ensures that the signal acquired makes use of as much of the dynamic range as possible while avoiding pixel saturation. In this way acceptable levels of signal-to-noise ratio (SNR) are maintained.

A thorough characterisation of the SNR requires consideration of several contributing factors, among those being photon shot noise, dark signal noise, readout noise and digitization noise. For this research the total system noise was considered instead; an estimate of the total system noise is given by the standard deviation of an accumulation of repetitive measurements. The SNR for C1 and C2 was then calculated by normalising the central tendency to the standard deviation of a given data set. It is noted that for a uniform light source, such as the one employed during this experiment, the central tendency should be inferred using the mean of the sample set, whereas the median should be used for a light source susceptible to outliers, such as that encountered during field measurements.

The SNRs have been investigated from measurements with C1 and C2 in the laboratory by using a uniform blue-green light source. The source uniformity was realised with a 25 cm diameter integrating sphere. Spectral consistency of the radiance emanating from the source is necessary to reduce uncertainties associated with detector non-uniformity and also to ensure that each sensor is exposed to the same input radiance. The light source chosen was an approximation of the upwelling radiance measurements expected for ocean based observations.

A layout for the laboratory test is given by Figure 3. The SNR for C1 and C2 (both relative to the maximum SNR for C1 and based on a set of 10 samples per sensor at a 50 ms exposure time) is shown in the plots of Figure 4. The relative comparison of SNR for the two candidates indicates that C1 has a superior SNR across the entire visible spectrum.

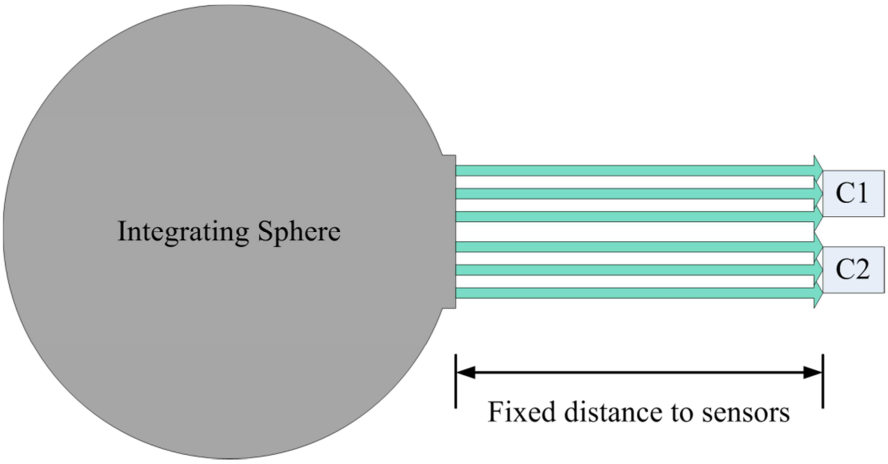

Figure 3: Laboratory Experimental Set-up for Testing C1 and C2

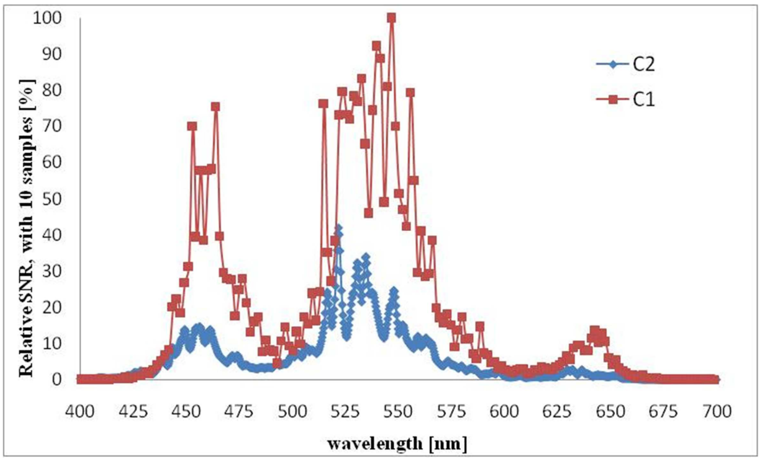

Figure 4: Normalised SNR for Sample Size = 10

MINIMISING ERRORS

For the low-cost mandate to be adhered to, the choice of candidate sensors lacked features present in some high precision commercial instruments. As a result, the performance of the prototype radiometer would be compromised. While not every feature that lends itself to the high cost of commercial ocean colour radiometers can be accurately catered for; a concerted effort was made to minimise the errors most likely to have a significant impact on quality of data. Factors that were considered but compromised on include temperature stability of the instrument, capacity to acquire dark signal measurements and correction for stray light.

Linearity

Stray light plays a major role in the non-linear behaviour of the candidate radiometric modules. While the departure from linearity (figure 5) is not ideal, sacrificing good stray light correction for low cost was a necessary compromise. The disadvantage of the minimal stray light corrections (if any) offered by the manufacturer is reasonably catered for in an experiment conducted by Ramkilowan and Chetty.[2]

Laboratory measurements using the set-up as in Figure 3 were taken at incremental exposure times to determine the linearity of the two sensors at a selected few wavelengths. The wavelengths were chosen so as to coincide with typical optical bands of sensors onboard ocean colour satellites.

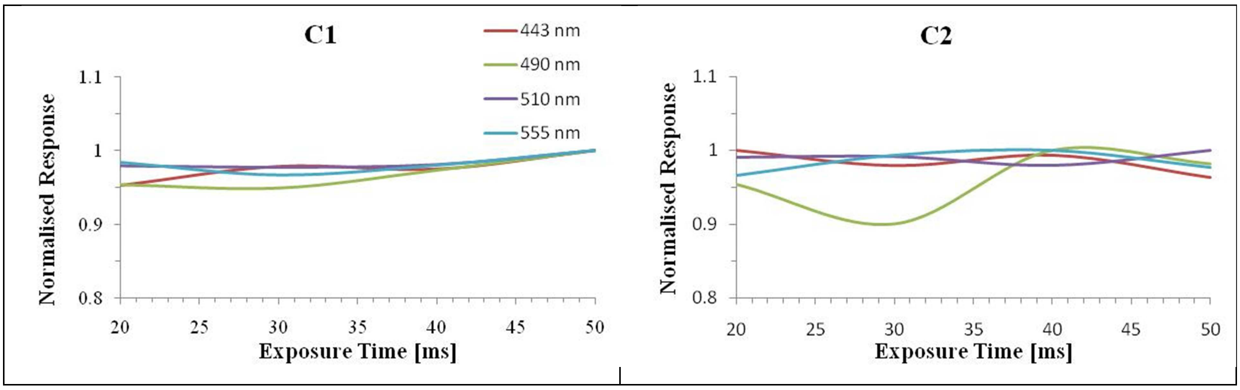

Figure 5: Linearity with respect to Exposure Time

Temperature control of detector

The benefits of a temperature controlled sensor have long since been established;[25] however the autonomous nature of the in-situ instruments provides a low power constraint. It is therefore necessary to forego cooling of the sensor and to calibrate the system at several temperatures over the full operational temperature range of 10-40 $^{\circ}$C.

Shutter

Shutters are used to prevent incoming optical radiation from entering into the instrument's photosensitive areas. The resulting measurement will therefore be an indication of the sum of the noise inherent in the radiometer and the perturbations caused by the physical environment, also known as a dark measurement. Subtracting this dark signal from a measurement taken with the shutter open will produce the true signature of the input radiance albeit uncalibrated.

The absence of a shutter in the prototype technology leads to the obvious problem of not being able to separate background signal from the true signal. A temperature dependant calibration of the instrument allows for the dark signal to be characterised as a function of temperature, allowing for dark signal to be subtracted manually post-capturing of data.

CONCLUSIONS

The performance capabilities of two candidate spectrometer cores (C1 and C2) were tested with the aim of integrating the best performing spectrometer module into a low-cost prototype radiometric device to be used for in-water applications. Strategically selected figures of merit formed the basis for comparison. C1, the less expensive of the two spectrometers has produced superior SNR, optical throughput and spectral sensitivity results making it the preferred candidate for use in the development of the prototype radiometer. The resulting instrument will be thoroughly calibrated in the laboratory before being deployed in an uncontrolled environment where its performance will tested and compared to that of a calibrated commercially purchased in-water radiometer.

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