REMOTE SENSING OF THE CHLOROPHYLL CONCENTRATION IN THE SAINT-LAWRENCE ESTUARY OF CANADA: PRE-ALGORITHMIC INVESTIGATIONS INTO THE OPTICAL COHERENCY OF SURFACE AND IN-SITU MEASUREMENTS

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ABSTRACT:

Bio-optical measurements at 50 stations in the Gulf and Estuary of Saint Lawrence were carried out over three major field campaigns in 1999, 2000, and 2001. These campaigns were performed over different periods of the year in order to obtain separate samplings of the system's seasonal cycles. The goal of these field campaigns is to arrive at a consistent remote sensing algorithm for the estimation of the chlorophyll concentration in the Case-II waters (where optical properties are influenced not just by phytoplankton and covarying constituents, but also by non-covarying constituents such as gelbstoff and suspended sediments), of the Lower Saint Lawrence estuary. The optical component of these missions included measurements of inherent and apparent in-situ optical parameters, surface reflectance spectrometry, multi-altitude reflectance spectrometry and satellite remote sensing using SeaWiFS imagery. Preliminary results show systematic differences between different regions and suggest that it is possible to classify the St. Lawrence system into sub regions characterized by different inherent and apparent optical properties. In this presentation focus will be given on the observation and analysis of variations in the surface reflectance spectrometry.

RÉSUMÉ:

Lors des missions en mer effectuées en 1999, 2000 et 2001, un ensemble de paramètres bio-optiques a été mesuré à partir de 50 stations fixes situées dans l'estuaire et dans le golfe du Saint-Laurent. L'échantillonnage a été réparti sur différentes périodes de l'année, afin d'obtenir des données sur les cycles saisonniers du système. Le but de ces campagnes consiste à développer un algorithme pour l'estimation de la concentration de la chlorophylle pour les eaux de type *Case-II* (où les propriétés optiques de l'eau sont influencées par trois quantités: la chlorophylle, le *gelbstoff* et les sédiments suspendus, dont les concentrations varient indépendamment les uns des autres). L'ensemble des données bio-optiques comprend les paramètres optiques inhérents et apparents *in-situ*, la reflectance de la surface, la reflectance à multi altitude (mesures spectrométriques aéroportées), et des données de télédétection spatiale basées sur les images SeaWiFS. Les résultats préliminaires montrent des différences spectrales systématiques selon les zones. Ceci pourrait permettre de distinguer des sous régions dans l'estuaire et dans le golfe du St. Laurent par une classification basée sur les propriétés optique inhérentes et apparentes des eaux de surface. Cette recherche se concentre principalement sur l'observation et l'analyse des variations spectrométriques de la reflectance de surface.

1. INTRODUCTION

1.1 Project

Remote sensing observations of bio-oceanographic processes in the Saint-Lawrence system project started in 1998 and concerns a number of Canadian institutions as CARTEL - Université de Sherbrooke, CRESTECH - York University, Maurice-Lamontagne Institute - Fisheries and Oceans Canada and ISMER-Université de Québec à Rimouski. The principal scientific goal of the project is to validate remotely sensed chlorophyll productivity algorithms for images acquired by the SeaWiFS sensor onboard the Orbview2 satellite, over the Estuary and Gulf of St. Lawrence system. The project is funded by NSERC (Natural Sciences and Engineering Research Council, Canada)

A set of research cruises were carried out starting from 1997, at different periods of the year in order to cover the system's seasonal cycles. These campaigns consisted of extensive monitoring along transects made by the Canadian Coast Guard Vessel *Martha L. Black*. During the period the vessel was inside the estuary, and when the weather permitted, daily transects with the Compact Airborne Spectrographic Imager (CASI) have been performed.

The ultimate goal of the project is to develop the simplest operational RS algorithm which permits the estimation of chlorophyll concentration in Case I and Case II waters of the LSLE. The RS algorithm development will be focused on SeaWiFS data while validation will be performed using multi-altitude spectro-radiometry as well as ship-based bio-physical and spectro-optical measurements.

1.2 Saint Lawrence System

Located in the eastern Canada, the St. Lawrence system is a complex environment with its both estuarine and oceanic characteristics, and with the large temporal and spatial variability of its physical and biological parameters. The overall system is a transitional one between continental and oceanic (North Atlantic) environments, influenced by large-scale

meteorological events, winds and tides. It is one of the most productive inland seas in the world, contributing significantly to the economy of eastern Canada with its finfish and invertebrate fisheries, apart from its important role as a seaway.

The estuary is fed by the St. Lawrence River input, with a yearly mean of 12000 m³s⁻¹ (but highly variable) and with a drainage area of 1 320 000 km² (Larouche, 2000). Estuarine waters are thus characterized by a salinity gradient and a flux of terrigenous particles and dissolved organic matter. The gulf is a triangular shaped semi-enclosed sea with an approximate surface area of 226 000 km². It has only two connections with the Atlantic Ocean: the Cabot Strait and the Strait of Belle-Isle (Koutitonsky and Bugden, 1991) .

Considering the size of the area and the variability of the system, remote sensing becomes a useful tool in order to observe large scale distribution of oceanographic parameters such as chlorophyll concentration in the surface waters.

1.3 Remote sensing of Case II waters of the Estuary

In estuarine waters of the St. Lawrence system, at least three relevant quantities (phytoplankton chlorophyll, SS and gelbstoff) can vary independently of each other, a case which is conventionally named as Case-II (Morel and Prieur, 1977; Gordon and Morel, 1983; cited in *Sathyendranath*, 2000). Because of this inherent variability of the bio-optical constituents, remote sensing algorithms for the retrieval of chlorophyll must be site and season specific, and relatively complex with respect to Case I algorithms where phytoplankton are alone the principal agents responsible for variations in optical properties of the water (Jacques et. al., 1998).

The complexity of Case-II waters arises from the fact that the interactions between the optically active constituents are non-linear, and have spectrally varying effects on the remotely sensed signal. The change in optical signal may be minor with respect to the change in the concentration of a variable component, and moreover, two or more substances may have a similar influence on the signal at some wavelengths. This signal competition makes it difficult to decouple chlorophyll information from the optical contributions of the other two major constituents; Gelbstoff and suspended sediments. (*Sathyendranath*, 2000).

1.4 Present study

In this work we will focus on ship-based spectral reflectance data acquired using an Analytical Spectrometer Device (ASD-FieldSpec®). This instrument has two principal advantages for this type of works: first, it has a narrow bandwidth (1,4 nm) relative to airborne and satellite sensors, and thus allows a detailed investigation of the spectral signatures. Secondly, the ship-based radiometer data do not impose atmospheric correction, even though it will provide valuable data for atmospheric correction needed for validation of the airborne and satellite data.

The ultimate usage of the ship-based spectral reflectance data consists on the validation of satellite remote sensing data.

2. MATERIAL AND METHODS

An Analytical Spectrometer Device (ASD-FieldSpec®) has been used to collect field data in this study. The instrument is a field-portable spectroradiometer, which operates in the visible-near infrared portion of the spectrum between 350-1050 nm wavelength domain. It has a 512 channel silicon photodiode array overlaid with an order separation filter. The integration time is manually adjustable through the controlling software. Dark current can be measured and sampled manually at any time, and it can be corrected either manually or automatically.

Data collecting procedure consists of taking uncalibrated radiance measurements of the seasurface radiance, the sky and the reflectance panel. In this approach, the uncalibrated sensor is used to measure signals proportional to the seasurface radiance, sky radiance and the radiance reflected from a horizontal reference panel, having a known bi-directional reflectance for the solar and viewing directions. (Mueller et. al., Chapter 10, 2000)

2.1 Seasurface radiance

In our cases, we accept the upwelling radiance above water composed of the waterleaving radiance, which has the information we seek for, and the sky radiance reflected from the seasurface. The ideal is to omit sunglints, foam, ship motion effects, ship's shadow while minimizing the surface reflected radiance. The viewing angles should be adjusted according to the previous principles, and the last convention (Mueller et. al., Chapter 10, 2000) defines the optimal angles as 40° for the zenith and 130° with the azimuth relative to the sun. In any circumstance, the sensor should view the seasurface at a zenith angle within the range 30-50° and at an azimuth angle in the range 90° to 180°. The field of view of the sensor can be adjusted to 2° or 18° (in this study it is 2°).

2.2 Reflectance panel

The information about the spectral downwelling radiance is obtained by measuring the radiance $L_g(\lambda)$ reflected from a reflectance panel (Spectralon) which is held horizontally. The reflectance of Spectralon is known and the relationship that relates the measured radiance to the incident irradiance $E_d(\lambda)$ is given by:

$$E_d(\lambda) = Q(\lambda) . 1/\rho_g . L_g(\lambda) \qquad (1)$$

Where $Q(\lambda)$ = angular and wavelength dependent factor relating the radiance to the irradiance ($Q(\lambda)$ = π for a Lambertian surface) Here, ρ_g is the irradiance reflectance of Spectralon (Mobley, 1999).

The surface of the panel must be cleaned regularly by gently rubbing the surface with a fine-sand paper under steady stream of distilled water, to get rid of the specularly reflecting film at the panel surface, as well as other particles like the seasalt.

The reflected diffuse sky radiance signal is estimated by measuring the reflected radiance signal from the shaded reflectance panel. This provide an independent estimate of the sky contribution, and it is also useful for estimating the direct solar influence on the reflected signal. The shadowing on the panel should be done with a sun shade which is as far as possible from the panel, and the geometrical configuration

(angles, the position of the panel with respect to the sun and to the sensor) should be consistent from one measurement to next.

2.3 Sky radiance

The spectral sky radiance signal is measured by pointing the ASD sensor towards the sky, in the same vertical plane in which previous measurements have been performed. The viewing zenith angle should be equal to that of a radiance beam whose specular reflection on the water would yield a radiance beam equal to the zenith angle used for the seasurface measurements. Measurements under cloudy skies are of little interest since the sky radiance distribution becomes less uniform, giving less information on the wavelength dependency. The best conditions are those for a clear, uniform sky.

2.4 Remote sensing reflectance

The reflectance Rrs (θ, ϕ, λ) is found according to following formula:

$$Rrs\ (\theta, \phi, \lambda) = Lw(\theta, \phi, \lambda)\ /\ Ed(\lambda) \qquad (2)$$

Where θ, ϕ, λ stand for zenith and azimuth angles, and the wavelength at which the reflectance is calculated. $Lw(\theta, \phi, \lambda)$ is the waterleaving radiance at a particular wavelength and at the viewing geometry. It is not possible to detect this component directly. At a given wavelength, the measured seasurface radiance is the combination of the waterleaving radiance (Lw) and the sky radiance reflected from the seasurface (Lr):

$$Lt(\theta,\phi) = Lr(\theta,\phi) + Lw(\theta,\phi) \qquad (3)$$

where Lt stands for the total radiance detected by the sensor pointed towards the seasurface at a zenith angle θ and an azimuth angle ϕ. So Lw can be found by subtracting Lr from the total radiance. To find the Lr, the sky radiance data is used, by supposing that a portion ρ of the sky radiance $Ls(\theta',\phi')$ is reflected by the seasurface:

$$Lr(\theta,\phi) = \rho\ .\ Ls(\theta',\phi') \qquad (4)$$

Here, ρ is a proportionality factor, defined as the total skylight reflected from the wave-roughened sea surface divided by sky radiance at the same given zenith and azimuth angles. Finally, starting from collected data, the reflectance at a particular geometry and wavelength is calculated as:

$$Rrs =\ (Lt\text{-}\rho.Ls)\ /\ [\ (\pi/\rho_g).L_g\ ] \qquad (5)$$

assuming to a good approximation that Spectralon is a Lambertian reflector (Mobley, 1999).

3. SAMPLING LOCATION AND PERIOD

Within the frame of the project, a set of research cruises have been performed from right after the ice cover melts to late fall. 10 subregions of the ecosystem have been predefined, based on the previous knowledge obtained from oceanographic

researches on the system. The set of parameters have been measured following SeaWiFS protocols (Mueller and Austin, 1995 cited in Larouche 2000). The stations are shown in the figures 1 and 2:
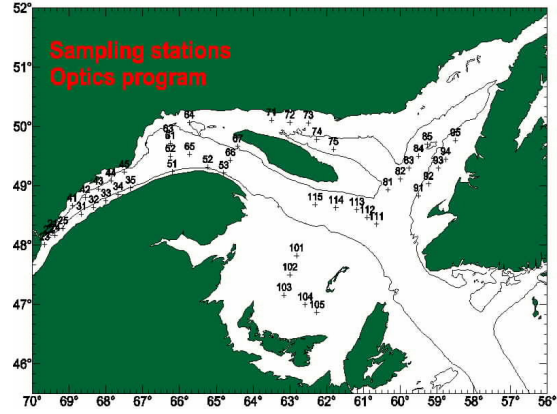

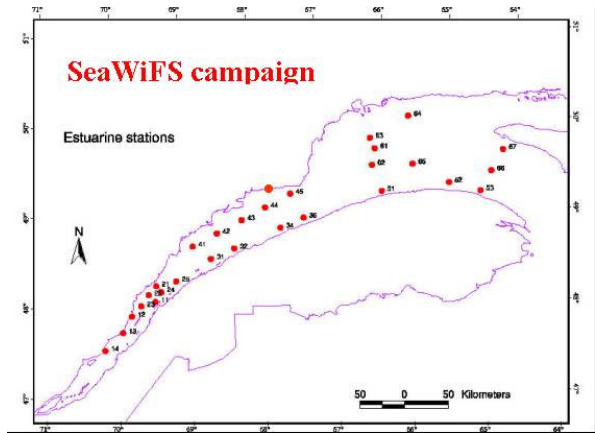Fig.1 The stations in the estuary and the Gulf of St. Lawrence.

Fig.2 Estuarine stations.

The radiance data is collected both at the stations and at the transects between stations, while the ship is in motion. A number of spectra has been obtained at each station and from each transect (except for when it rained). A spectrum is obtained by taking a series of 10 separate measurements from each of the seasurface, panel, shaded panel and sky. Before processing, the spectra must be checked to eliminate the saturated ones either manually or automatically using a software program. Furthermore, up to two spectra which deviates highly from the average are removed. Then, the remaining spectra are averaged for each series of measurements and the reflectance spectra is computed for each seasurface-panel-shaded panel-sky sequence.

4. PRELIMINARY RESULTS AND DISCUSSION

Given the high spatial variability, the first step is a spatial classification of the spectral behaviour based on preliminary investigation of data throughout the estuary-gulf system. Such an approach may eventually reveal useful correlation between

optically active components and spectral behaviour.Systematic differences between different regions suggest that it is possible to classify the St. Lawrence system into sub regions characterized by different inherent and apparent optical properties. The preliminary results suggest high Gelbstoff and low suspended sediment influence in the estuary, while gulf region is mainly dominated by oceanic Case-I waters. (Figures 3 and 4)
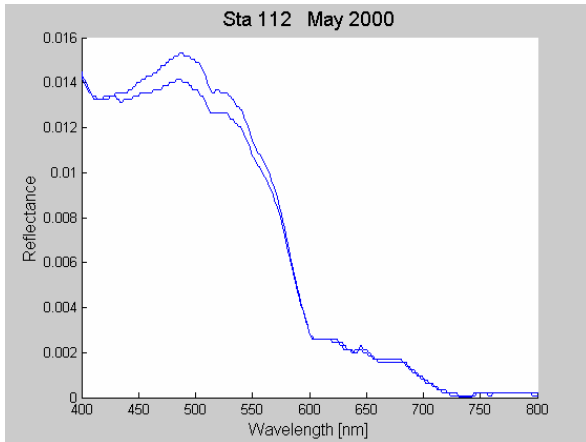

Fig.3 Station 112, Gulf. Closer to Case-I properties.
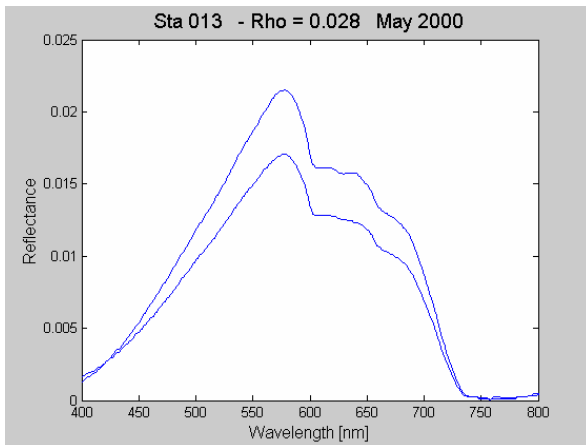(Two sets of measurement)

Fig.4 Station 13, estuary. Closer to Case-II properties.
(Two sets of measurement)

Sky reflectance by the seasurface is the main contaminant factor. Selection of ρ is the main focus and it is important as well in overcast skies, where it can be less than 0.028 (the recommended value for overcast skies in the literature, Mueller et.al, 2000) Shorter wavelengths seem to be less consistent since they are more affected from sky reflectance, whitecaps, seastate, and wind.

References

Jacques A., N.T. O'Neill and J.-C. Therriault, 1998. Chlorophyll Remote Sensing Potential in Pigment-Poor Moderately Turbid Case II Waters: Lower St. Lawrence Estuary . *CJRS*, vol. 24, no. 2, pp. 194-199.

Jacques, A. (2000). "La télédétection passive de la chlorophylle dans l'Estuaire maritime du Saint-Laurent: optimisation spectrale des algorithmes de télédétection et application au SeaWiFS" PhD thesis, Département de Géographie et Télédétection, FLSH, Université de Sherbrooke, Québec, Canada.

Koutitonsky, VG et GL Bugden, 1991. "The physical oceanography of the Gulf of St. Lawrence: A review with emphasis on the synoptic variability of the motion. In: *The Gulf of St. Lawrence: small ocean or big estuary?*, J.C. Therriault (Ed.), Can. Spec. Publ. Fish. Aquat. Sci., Vol. 113, pp. 57–90.

Mobley C.D., 1999. Estimation of the remote-sensing reflectance from above-surface measurements. Applied Optics, 38(36), pp.7442-7455.

Mueller J.L., C. Davis, R. Arnone, R. Frouin, K. Carder, Z.P. Lee, R.G. Steward, S. Hooker, C.D. Mobley and S.McLean, 2000. "Above–water radiance and remote sensing reflectance measurement and analysis protocols", Chapter 10, NASA/TM-2000-209966 OCEAN OPTICS PROTOCOLS FOR SATELLITE OCEAN COLOR SENSOR VALIDATION, revision 2 edited by Giulietta S. Fargion and James L. Mueller. NASA-GSFSC, August 2000.

Pierre Larouche, 2000. "Results from the 2nd St. Lawrence Estuary and Gulf SeaWiFS Validation Cruise", Sixth International Conference on remote Sensing for Marine and coastal Environments, Charleston, South Carolina, 1-3 May 2000.

S. Sathyendranath (2000) "Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters" Reports of the International Ocean-Colour Coordinating Group. IOCCG Report no:3, 2000.