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HYPERSPECTRAL AIRBORNE REMOTE SENSING OF THE BELGIAN COASTAL WATERS

Sindy Sterckx, Walter Debruyn, Pieter Kempeneers

VITO, Centre for Remote Sensing and Earth Observation Processes, B-2400 Mol, Belgium; Sindy.sterckx@vito.be , Walter.debruyn@vito.be

ABSTRACT

On the 16th of June 2003 a CASI (Compact Airborne Spectrographic Imager) hyperspectral airborne remote sensing campaign took place above the Southern North Sea, just offshore of Oostende. In coincidence with the airborne overpasses seaborne measurements of water leaving reflectance and water quality parameters were performed. In addition near-simultaneous satellite imagery are available. This paper deals with the analysis of the airborne data. The CASI data have been atmospherically corrected using the in-house software WATCOR which is based on the radiative transfer code MODTRAN-4 and takes into account atmospheric and air/water interface effects. The data are subsequently geometrically corrected with PARGE. A semi-analytical approach is used to retrieve the concentration of the water constituents: for chlorophyll determination a bio-optically modelled red/NIR band ratio algorithm is applied to the data; to quantify the Suspended Particulate Matter a single band NIR algorithm, calibrated for the Belgian coastal waters is used. The results of these semi-analytical methods were compared to an analytical approach where the water quality parameters are retrieved from the subsurface irradiance reflectance spectra using a least square inversion of the Gordon reflectance model. This approach allows for simultaneous determination of chlorophyll-a (CHL), suspended particulate matter (SPM) and colored dissolved organic matter (CDOM) and requires as input the inherent optical properties (IOPs) of (specific) absorption and backscattering of the water constituents.

INTRODUCTION

There exists a high interest in CHL and SPM maps of the Belgian coastal waters. In the framework of the Oslo and Paris Commissions for the prevention of marine pollution (OSPARCOM) Belgium has to classify their coastal waters areas according to their eutrophication status. The eutrophication problems of the Belgian coastal waters results from an augmentation of anthropogenic nutrient inputs via the main rivers, the Atlantic waters and regional atmospheric deposition. Furthermore sustainable dredging is required to keep the ports of Zeebrugge and Antwerp accessible for large ships. The large quantities of dredged material is often dumped back into the sea. Besides the economic costs, dredging and dumping of dredged material can cause serious environmental problems. To optimize the dredging operations knowledge of the suspended sediment concentration is required.

The BELCOLOUR project (i) brings together three Belgian teams (ULB,MUMM and VITO) to improve the theoretical basis and the software tools for applications of suspended particulate matter and chlorophyll products from remote sensing data of coastal waters. In the framework of this project an airborne remote sensing campaign took place above the Southern North Sea, just offshore of Ostend on the 16th of June 2003. A Compact Airborne Spectrographic Imager (CASI) was installed in a Dornier 228 aircraft. The aircraft and CASI sensor was operated by NERC (Natural Environment Research Council), UK. The CASI was flown at an altitude of 2000 m, providing a spatial resolution of 4 m. The spectral configuration of the CASI was 96 channels from 405 to 947 nm with a FWHM of 6 nm. Eleven flight lines were flown in North-South or South-North direction. One flight line was acquired in East-West direction for the study of bidirectional effects. The data were acquired between 11:57 and 13:39 GMT. The flight area covered two stations where seaborne measurements were performed during the airborne data acquisition. Furthermore chlorophyll fluorescence measurements performed every 3 minutes with a Turner Design fluorometer along several transects.

METHODS

Image pre-processing

The CASI data were delivered in spectral radiance units. Almost no information was provided on the quality of the radiometric and spectral calibration. To minimize the across-track illumination differences a normalization has to be performed. For this purpose an IDL code is written. First the average radiance value is calculated for each column of pixels (along track direction) of the CASI image (excluding the land pixels). A polynomial function is then fitted to these column averages. By normalizing this polynomial function to the minimum value a correction factor for each column is calculated. Cross track illumination effects may be caused by vignetting effects, instrument scanning, direct sun reflection, or other non-uniform illumination effects (ii).

Atmospheric and Air-interface Correction

The radiance received by the sensor L_{rs} consists of atmospheric path radiance $L_{atm-path}$, background path radiance $L_{rs,b}$ and ground reflected radiation L_{target} or

$$L_{rs} = L_{atm-path} + L_{rs,b} + L_{target} \tag{1}$$

with

$$L_{target} = \frac{d^*_{direct}(\tau, \theta_v) R_{app} E_d(a)}{\pi} \quad \text{and} \quad L_{rs,b} = \frac{d^*_{diffuse}(\tau, \theta_v) A_{app} E_d(a)}{\pi}$$

where $E_d(a)$ is the downwelling irradiance above the water surface, $d^*_{diffuse}$ and d^*_{direct} are the diffuse and direct ground-to-sensor transmittance, R_{app} is the target apparent reflectance and A_{app} is the average or background apparent reflectance.

The air-water interface transfer can be written as:

$$R_{app} = \rho_{(a\to w)} + t_{(w\to a)} \frac{E_u(w)}{E_d(a)} = \rho_{(a\to w)} + t_{(w\to a)} R(0^-) t_{(a\to w)} \frac{1}{1 - s^*_{int} R(0^-)} \tag{2}$$

with $\rho_{(a\to w)} = \dfrac{\pi r(\theta_v) L_d(a)}{E_d(a)}$ the reflection function of the air-water interface, $L_d(a)$ the downwelling sky radiance above the water surface, $r(\theta_v)$ the Fresnel reflectance, $E_u(w)$ the upward irradiance just below the surface, $R(0^-)$ the subsurface irradiance reflectance, s^*_{int} the spherical albedo for illumination from below and $t_{(w\to a)}, t_{(a\to w)}$ the transmittance function of respectively water to air and air to water.

The atmospheric and air-interface correction is performed with the in-house software WATCOR. WATCOR uses the radiative transfer code MODTRAN-4 and follows the formulas given in (iii). In a first step the at-sensor radiance is converted to apparent reflectance R_{app}. The apparent reflectance R_{app} can be estimated from the at-sensor radiance L_{rs} and the background radiance $L_{rs,b}$ (i.e. average radiance of surrounding pixels, calculated with a moving window technique) according to:

$$R_{app} = \frac{c_1 + c_2 L_{rs} + c_3 L_{rs,b}}{c_4 + c_5 L_{rs,b}} \tag{3}$$

where $c_1,\ldots,c_5$ are atmospheric correction parameters.

The formula to convert the apparent reflectance R_{app} to subsurface irradiance reflectance $R(0^-)$ is :

$$R(0^-) = \frac{-d_1 + R_{app}}{d_2 + s^*_{\text{int}} R_{app}} \tag{4}$$

where d_1 ($= \rho_{(a \to w)}$) and d_2 are the air-interface correction parameters.

To estimate the visibility during the time the CASI data were acquired two different approaches were evaluated. In the first methodology the visibility was estimated using MODTRAN-4 radiative transfer simulation combined with the sun photometer aerosol optical depth measurements. This procedure is similar to the approach given in (iv) and is based on the fact that at 550 nm the aerosol optical depth is independent of the aerosol and atmospheric model and only varies with the visibility. The second method is an adapted dark target approach and assumes that there is a pixel in the deeper water regions for which the water-leaving radiance is negligible in the near-infrared. Given equation 2 this implies that the apparent reflectance equals the surface reflection. The first approach resulted in an average visibility of +/- 20 km. The average visibility derived with the adapted dark target approach was a bit lower +/- 18.8 km. Based on these results it was decided to set the visibility to 20 km for the correction of all the flight lines. The results are in close agreement with the visibility (20 km) reported by the airport of Ostend.

Geometric Correction

For the geometric correction of the CASI lines the commercially available program PARGE (PARametric GEcoding) (v) is used. PARGE requires navigation, attitude and image/sensor information for the geocoding. The attitude (roll, pitch, heading) and position of the aircraft was measured during the flight with, respectively, an Inertial Measurement Unit (IMU) and a Global Positioning System (GPS). The aircraft GPS data are differentially corrected with a ground-based GPS of the FLEPOS (FLemish POsitioning Service) network.

Water Quality Retrieval

In the first stage, a robust one-band algorithm (vi) calibrated for the North Sea was used to derive the suspended matter content and for chlorophyll determination a well established Red/NIR ratio algorithm (vii) was applied. The results of these semi-analytical methods were compared to an analytical approach where the water quality parameters are retrieved by a matrix inversion of bio-optical reflectance model.

1. The bio-optical modelling

Following (viii) the relationship between the inherent optical properties (IOP) and the subsurface irradiance reflectance can be expressed as :

$$R(0-,\lambda) = f \cdot \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \tag{5}$$

with $a(\lambda)$ the spectral total absorption coefficient (m^{-1}), $b_b(\lambda)$ the spectral total backscattering coefficient (m^{-1}) and *f* an empirical factor which depends on solar and viewing geometry and volume scattering in the water. f was set according to (vi).

The IOP $a(\lambda)$ and $b_b(\lambda)$ are linear functions of the constituents' concentrations. Equation (5) can therefore be written as (omitting the wavelengths) :

$$R(0-) = f \cdot \frac{b_{bw} + SPM \cdot b^*_{b,p}}{a_w + g440 \cdot \tilde{a}_{CDOM} + CHL \cdot a^*_{ph} + NAP \cdot a^*_{NAP} + b_{bw} + SPM \cdot b^*_{b,p}} \tag{6}$$

with

a_W the absorption of pure water (m^{-1}); b_{bW} the backscattering of seawater (m^{-1}); $g440$ CDOM absorption at 440 nm (m^{-1}); $\tilde{a}_{CDOM}$ CDOM absorption normalized by the absorption at 440 nm (m^{-1}); CHL the concentration of chlorophyll-a (mg m^{-3}) ; NAP the concentration of non-algal particles (g m^{-3}); SPM the concentration of suspended matter (g m^{-3}) with $SPM = NAP + 0.07 \cdot CHL$ (vi) ; $b^*_{b,p}$ the specific backscattering coefficient of marine particles (m² g^{-1}); a^*_{ph} the specific absorption coefficient of chlorophyll-a (m² mg^{-1}); a^*_{NAP} the specific absorption coefficient of non-algal particles (m² g^{-1}).

2. Semi-analytical method : Chlorophyll retrieval with Gons algorithm

To derive CHL from the subsurface irradiance reflectance the Gons algorithm uses a ratio of two red bands: λ_1 located within a region of high chlorophyll-a absorption and λ_2 located within 700-740 nm. A near-infrared band λ_3 is used to estimate the backscattering. The following assumptions are used in the development of the Gons algorithm :

- at λ_1 absorption other than Chl-a and water is negligible or $a(\lambda_1) = a_W + CHL \cdot a^*_{ph}(\lambda_1)$

- at λ_2 a_{ph}, a_{CDOM}, a_{NAP} are insignificant in comparison with a_W or $a(\lambda_2) = a_W$

- b_b is wavelength independent in the red/NIR region

In the study we used the CASI bands located at 671 nm (λ_1) , at 705 nm (λ_2) and at 774 nm (λ_3) . Giving these 3 assumptions the Gons algorithm can be derived from equation (6) :

$$CHL = \frac{\left(\frac{R(0-,705) * (a_W(705) + b_b)}{R(0-,671)} - a_W(671) - b_b \right)}{a^*_{ph}(671)} \quad \text{with} \quad b_b = \frac{a_W(774) \cdot R(0-,774)}{f - R(0-,774)} \qquad (7)$$

3. Semi-analytical method : SPM retrieval

For the SPM retrieval an one band algorithm calibrated for the Belgian coastal waters was used (vi):

$$MUMM - SPM = 111.21 \cdot \frac{\rho_W(708)}{0.187 - \rho_W(708)} + 4.46 \qquad (8)$$

Since the coefficients in this algorithm have been calibrated for the MERIS sensor the CASI ρ_W ($\rho_W = R_{app} - \rho_{(a \to w)}$)images were resampled to the MERIS bands in order to apply the algorithm.

4. Analytical method : Least square approach

To simultaneously estimate the concentrations of the water constituents a least-square approach was used for solving the inversion of equation (6). For m number of wavelengths this equation can be written as a linear system of equations :

$$y = A \cdot x \qquad (9)$$

with

$$A_\lambda = \frac{R(0-,\lambda)}{f}\tilde{a}_{CDOM,\lambda}, \frac{R(0-,\lambda)}{f} a^*_{ph,\lambda} - b^*_{b,p,\lambda} 0.07\left[1 - \frac{R(0-,\lambda)}{f}\right], \frac{R(0-,\lambda)}{f} a^*_{NAP,\lambda} - b^*_{b,p,\lambda}\left[1 - \frac{R(0-,\lambda)}{f}\right]$$

and

$$y_\lambda = -a_{w,\lambda} \cdot \frac{R(0-,\lambda)}{f} + b_{b,w,\lambda}\left[1 - \frac{R(0-,\lambda)}{f}\right] \quad \text{with } \lambda = 1,\ldots,m \quad \text{and } x = \begin{bmatrix} CDOM \\ CHL \\ NAP \end{bmatrix}$$

The SIOPs used in the analytical approach were based on in-situ measurements as well as literature values for the North Sea. a_w was taken from (ix) and b_{bw} is given by (x). Following the methods of (xi, xii, xiii). The a^*_{ph}, a^*_{NAP} were determined from seawater samples taken from station 230 one day after the CASI flight. The average specific scattering coefficient for the North Sea given by (xiv) was used. To determine the specific backscattering $b^*_{b,p}$ a backscattering to total scattering ratio of 0.02 derived from the Petzold's volume scattering function was used. For $\tilde{a}_{CDOM}$ the average value derived from water samples taken at station 130 and 230 during cruises in April and May 2004 was used.

RESULTS AND DISCUSSION

Water quality maps were calculated with the different algorithms (Fig. 1 and 2). Areas with negative values haven been flagged (black colour). Adjacent flight lines are not acquired successively in time and time difference between the neighbouring lines ranges from 15 minutes to almost one hour. This explains the shifts visible in the concentration of the water constituents between overlapping flight lines.

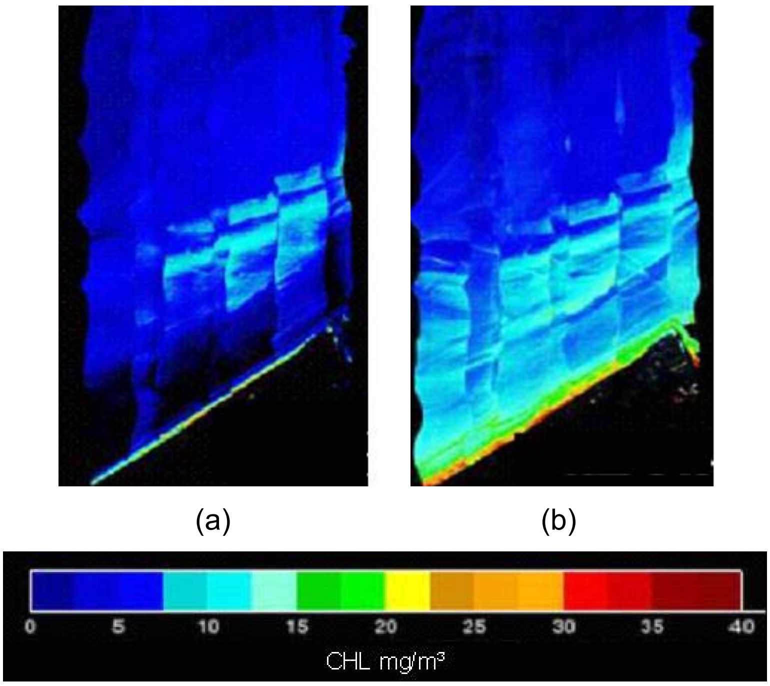
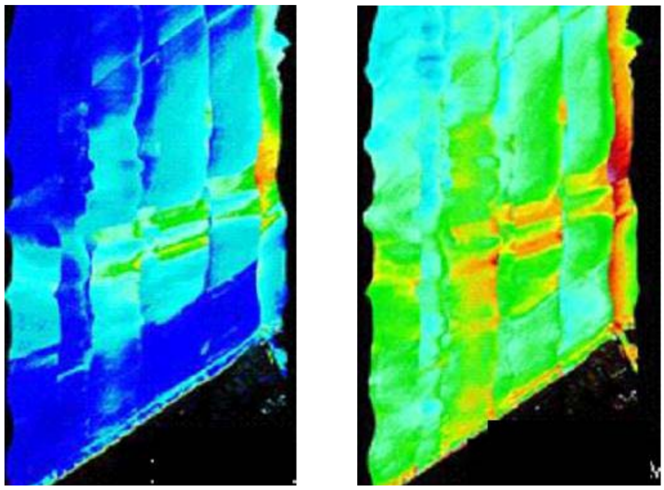


Figure 1 : Distribution maps of Chl-a calculated with least square inversion approach (a) and Gons algorithm (b).

In the offshore area the chlorophyll-a concentrations derived with the Gons algorithm and with the least square approach are in good agreement. Closer to the coast the least square approach underestimates strongly the chlorophyll-a concentration. It was also noticed that the least square inversion of the bio-optical model was quite sensitive to the spectral wavelength range chosen. In essence only three wavelengths would be sufficient to retrieve the 3 water constituents. In case sufficient ground truth points are available the optimal bands can be determined by iteratively changing the spectral bands until the retrieved concentration agreed well with the measured concentrations. It was decided not to apply this procedure since there were only two points where water samples were taken to determine the concentrations and furthermore significant differences were observed in the concentrations measured by two independent teams.

The problem of negative values concentrations can be avoided by using a constraint minimization technique. In this approach the concentrations of the 3 water constituents are derived from each image reflectance spectrum by finding those concentrations for which the deviation between the computed spectrum described by equation (6) and the image spectrum is minimized, taken into account that the concentrations are subjected to constraints. A minimization technique which gives good results in escaping from local minima and which searches within a bounded range of the parameters is the simulated annealing approach. A drawback of this method is the higher computation time required to retrieve the concentrations.



(a) (b)

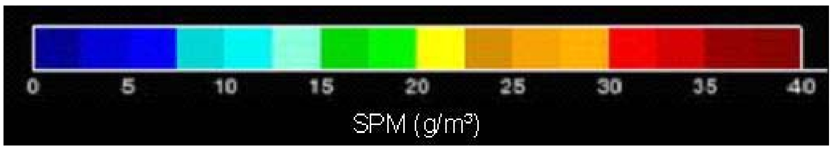


Figure 2 : Distribution maps of NAP calculated with least square inversion approach (a) and SPM derived with the MUMM-SPM algorithm (b).

The relative spatial distribution of the tripton concentration (NAP) derived with the least square approach and the SPM concentration calculated with the MUMM-SPM algorithm are similar (fig. 2), but the absolute values differ strongly. The specific scattering value was taken from the literature and may not be accurate for the water composition at the time of recording. A second possible explanation for this is the difference in product terminology. The MUMM-SPM algorithm was calibrated against SPM concentration measured at 3 m depth while the NAP concentration derived from the least square approach is more representative for the surface layer.

CONCLUSIONS

Different algorithms were applied to atmospherically corrected CASI data to produce water quality maps of the Belgian coastal waters. Since there are only two in-situ stations within the area it is difficult to assess the exact accuracy of water quality maps, however the spatial variability of Chl-a in the offshore area correspond well with the fluorescence measurements. Some problems (negative values, strong dependency of the result on wavelengths chosen) were encountered with the least square inversion technique. It is expected that significant improvements in the simultaneous retrieval of all constituents can be achieved by (1) applying a constraint optimization technique and (2) by using more appropriate SIOPs for the Belgian coastal waters.

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