# COMPARISON FOR CHLOROPHYLL -A REMOTE SENSING RETRIEVAL ALGORITHMS BASED ON STANDARD LABORATORY PROCEDURES AND ON *IN-SITU* ABSORPTION MEASUREMENTS

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**_ABSTRACT_**

Water quality monitoring is vital to guaranty endless water resources to the human population. In that sense, orbital remote sensing can be a significant tool for large scale monitoring. However, the retrieval of water parameters that could inform about water quality depends on the reliability of the algorithms. This work aims on testing the suitability of an algorithm for retrieving the in-situ Chla absorption peak in 676 nm ($a_\varphi(676)$) as a proxy of Chla concentration for Amazon floodplain lakes. This way $a_\varphi(676)$ could be used as a surrogate of Chlorophyll-a (Chla) concentration. Results show that, for the receding period, $a_\varphi(676)$ instead of Chla can be more suitable for a better understanding of Chla dynamic in Amazon floodplain lakes. This approach also encourages the use of *in-situ* absorption data to support Remote Sensing retrievals of Chla.

***Key words —*** Chlorophyll-a, Remote Sensing, Amazon Floodplain Lakes, Absorption Spectra.

## 1. INTRODUCTION

Water quality monitoring is essential for ensuring safe water resources to an ever-growing human population. The global scope of water monitoring demands versatile tools to capture quick changes in the aquatic system state. For that, monitoring systems with high temporal resolution and able to provide fast response to managers are needed so as prompt mitigation strategies can be implemented. Those monitoring systems, however, are still missing.

In that sense, orbital remote sensing data can be used to monitor inland water in a temporal resolution higher than the present monitoring system (every two months, at maximum). Italso improves the spatial representativity and provides a synoptic view of the area, allowing to identify probable factors controlling changes in water quality. The orbital remote sensing technology can be even more suitable to monitor lakes with large dimensions, usually poorly represented by sampling field campaigns due to both cost and time constraints. In that sense, Amazon floodplain lakes are a fit as a focus of studies to develop remote sensing technics.

One of the main focus of orbital remote sensing to monitor water quality in inland water is the retrieval of Chlorophyll-a (Chla) concentration. Chla concentration is one of the most relevant parameters to grasp the biological processes within the aquatic system, since it can be related to a series of biological indicators, acting as a proxy for primary productivity [1,2] and trophic level state [3,4].

Several research efforts [5,6,7,8], in the past few years, made available a series of empirical algorithms for retrieving Chla concentration based on orbital remote sensing images. There are, however, accuracy issues related to errors introduced by the measurement of Chla concentration in laboratory such as, sampling, transportation and even the adequacy of current measurement protocols.

To overcome this problem, *in-situ* absorption measurements may be an alternative for isolating the response of Chla pigment without the sampling issues previously described. Moreover, *in-situ* absorption measurements are more reliable in describing the phytoplankton characteristics at the very moment in which radiometric measurements are been performed.

This study focused on testing the accuracy of empirical algorithms, originally developed to retrieve Chla concentration from remote sensing reflectance, by comparing their retrieval accuracy when using *in-situ* phytoplankton absorption coefficient at 676 nm ($a_\varphi(676)$). *In-situ* $a_\varphi(676)$ measurements were carried out using field spectrophotometry and concurrent field radiometry which was then applied to simulate Sentinel -2 MSI spectral bands The comparison between Chla concentration and $a_\varphi(676)$ retrievals was performed for each field campaign in all hydrograph phases .

## 2. MATERIAL AND METHODS

**Study Area**

The Lago Grande de Curuai (LGC) floodplain is located on the southern margin of the Amazon River, near Óbidos city (Brazil), about 900km upstream from the Atlantic Ocean (between 56.10°W and 55.00˚W from upstream to downstream, and 2.3°S and 1.9°S) and covers ≈ 3500 km$^2$. It is a complex system of about 30 shallow interconnected lakes with spatially and temporally variable hydraulic connectivity among themselves and with the Amazon River.

During the hydrological year, the floodplain landscape presents savannahs, shrubs and alluvial forest and in at the maximum flooding height it is bounded by the ``terra firme'' forest which is not flooded [9,10].

**Field Campaigns**

Five field campaigns were carried out in different phases of the hydrograph: February 2013, August 2013, September 2013, April 2014 and June 2015. In each field campaign radiometric measurements, spectroradiometric and laboratory Chla concentration measurements were performed.

**In-Situ Remote Sensing Reflectance ($R_{rs}$)**

Above water Irradiance and Radiance measurements were carried out with a set of three inter-calibrated TRIOS sensors in the wavelength range of 350-950 nm with a sampling interval of approximately 3.3 nm. All measurements were carried out from 9:30 a.m. to 3:00 p.m. local time, avoiding large solar zenith angles.

Above water leaving radiance ($L_T(0^+)$) measurements were performed with a sensor-viewing geometry of 45° zenith angle and approximately 137˚ azimuth angle taking the Sun direction as reference [11]. Unfortunately, it was not possible to measure the Sky Radiance (following [11] to correct for skylight surface reflection) in all field campaigns and therefore the method proposed by [12] was used. The above water remote sensing reflectance was calculated as $R_{rs}(0^+) = L_T(0^+)/E_{s,}$.

To simulate the Sentinel-2 MSI spectral bands the Spectra Response Function was used to weight the in-situ $R_{rs}(0^+)$ following equation (1:

$$R_{rs-Sent2} = \frac{\sum_{i=liminf}^{limsup} R_{rs}(0^+)(\lambda_i)\cdot\sigma(\lambda_i)}{\sum_{i=liminf}^{limsup}\sigma(\lambda_i)} \qquad (1)$$

where $\sigma$ is the Sentinel-2 MSI Spectral Response Function taken between the lower limit (*liminf*) and upper limit (*limsup*).$\lambda$ is the wavelength.

**Chlorophyll-a Parameters**

*In-situ Absorption Measurements (ACS)*

An optical package containing a 10cm WetLabs AC-S \ and a SeaBird SBE-37SI CTD were used to provide concurrent profiles of the absorption and attenuation coefficients, temperature and pressure respectively. At each station, the optical package was lowered to allow instrument acclimation, warm up period (6 to 8 min) and to help remove air bubbles. Prior to each field campaign, an AC-S air calibration was performed following manufacturer factory specifications. The repeatability stabilization factory recommendation values ($\approx$ 0.01 $m^{-1}$) was not reached but was below $\approx$ 0.05 $m^{-1}$.

For AC-S processing, firstly, the instrument's ``pure water file'' (AC-S device file) was applied to all vertical profiles and a 10 cm median moving window was used to filter spikes in the data. Temperature correction was made based on standard procedures and salinity in Curuai Lake was measured and considered negligible, which lead to no salinity correction. To reach reliable absorption and scattering, AC-S measurements were subjected to corrections for the scattering effect in the absorption tube. For details see Sander de Carvalho [13].

The absorption line height at 676 nm ($a_\varphi(676)$) was calculated as in [14], replacing the particulate absorption coefficient ($a_p$) for particulate *plus* Colored Dissolved Organic Matter (CDOM) absorption coefficient ($a_{p+cdom}$).

$$a_\phi(676) = \left[a_{(\mathrm{ap\,+\,cdom})}(676) - \frac{39}{65}a_{(\mathrm{ap\,+\,cdom})}(650) - \frac{26}{65}a_{(\mathrm{ap\,+\,cdom})}(715)\right](m^{-1}) \qquad (2)$$

*Laboratory Chlorophyll-a Concentration*

Water samples were taken and kept in dark and cold for a maximum of three hours before filtration. 47-mm Whatman GF/F pore size filters were used for Chla and the concentration measurements were identical to methods described in [13].

**Empirical Models**

Four empirical models originally designed to retrieve Chla concentration were tested to retrieve $a_\varphi$ (676), as follows::

- TBR - Two Band Model Ratio – [5,6].

$$Chla \propto \left(\frac{1}{R_{rs-Sent2}(665)} - \frac{1}{R_{rs-Sent2}(705)}\right)\cdot R_{rs-Sent2}(740) \qquad (3)$$

- TBS - Three Band Model Ratio – [5,6].

$$Chla \propto \left(\frac{1}{R_{rs-Sent2}(665)} - \frac{1}{R_{rs-Sent2}(705)}\right)\cdot R_{rs-Sent2}(740) \qquad (4)$$

- NDCI - Normalized Difference Chlorophyll Index – [8].

$$Chla \propto \frac{R_{rs-Sent2}(705) - R_{rs-Sent2}(665)}{R_{rs-Sent2}(705) + R_{rs-Sent2}(665)} \qquad ((5)$$

- FBS – Four Band Model – [7].

$$Chla \propto \frac{\left(\frac{1}{R_{rs-Sent2}(560)} - \frac{1}{R_{rs-Sent2}(665)}\right)}{\left(\frac{1}{R_{rs-Sent2}(705)} - \frac{1}{R_{rs-Sent2}(740)}\right)} \qquad ((6)$$

To reach the best set of algorithms to retrieve both, Chla concentration and $a_\varphi$ (676) separately, half of the samples were used to calibrate the model and half to validate the models. The MAPE (Mean Absolute Percentage Error) was used to evaluate the best model and to compare the Chla concentration and $a_\varphi$ (676) retrievals (Table 1).

**Table 1 – Field Campaigns and samples for Calibration and Validation for the empirical algorithms testing.**

| Field Campaign | Number of Samples (N) | Samples for Calibration | Samples for Validation |
|---|---|---|---|
| All | 120 | 61 | 59 |
| Feb 2013 | 23 | 12 | 11 |
| Aug 2013 | 30 | 15 | 15 |
| Sep 2013 | 26 | 13 | 13 |
| Apr 2014 | 25 | 13 | 12 |
| Jun 2015 | 16 | 8 | 8 |

## 3. RESULTS

Regarding Chla concentration, when the entire set of samples was applied (*All* samples) for both, model calibration and validation the results indicate poor estimates with MAPE varying from 88 % for the NDCI to 101 % for the TBR (Table 2).When Chla measurements were split according to each campaign, the best result was achieved by TBR for Apr 2014. However, considering each tested empirical model, the best result was achieved for Sep 2013 because although the FBS presents a MAPE of ≈ 78%, the remaining models (TBR, TBS and NDCI) present a MAPE under 30 %.

**Table 2- MAPE for empirical algorithms applied to retrieve Chla concentration.**

| (%) | TBR | TBS | NDCI | FBS |
|---|---|---|---|---|
| All | 101.07 | 100.50 | 88.60 | 92.74 |
| Feb 2013 | 54.90 | 47.99 | 54.13 | 82.83 |
| Aug 2013 | 96.35 | 261.26 | 128.48 | 87.29 |
| Sep 2013 | 27.38 | 27.26 | 27.83 | 78.77 |
| Apr 2014 | 24.98 | 71.78 | 62.30 | 89.76 |
| Jun 2015 | 64.30 | 36.45 | 38.31 | 66.51 |

Regarding the MAPE for empirical algorithms applied to retrieve $a_\varphi$ (676), Table 3 shows that, similar to Table 2, the strategy of grouping all station did not succeed, showing even higher MAPE values. It is noticeable that the FBS algorithm did not fit to any field campaign to retrieve $a_\varphi$ (676), which differs from the retrieval of Chla concentration.

**Table 3- MAPE for empirical algorithms applied to retrieve $a_\varphi$ (676).**

| (%) | TBR | TBS | NDCI | FBS |
|---|---|---|---|---|
| All | 161.58 | 133.06 | 97.95 | 3617.76 |
| Feb 2013 | 49.63 | 47.31 | 49.37 | 1230.95 |
| Aug 2013 | 34.75 | 26.74 | 37.58 | 1289.39 |
| Sep 2013 | 43.06 | 33.56 | 33.94 | 543.24 |
| Apr 2014 | 28.38 | 87.92 | 66.34 | 2773.45 |
| Jun 2015 | 393.22 | 305.18 | 440.49 | 16743.32 |

Assuming that a MAPE of ≈ 35% is acceptable for to retrieving Chla concentration from orbital remote sensing, all empirical algorithms presented acceptable results in Sep 2013, except for the FBS. For April 2014, only TBR presented acceptable results and for Jun 2015 only TBS. Regarding the retrieval of $a_\varphi$ (676), TBR and TBS presented acceptable results for Aug 2013. For Sep 2013, only TBS presented acceptable results and for Apr 2014 only TBS.

It is important to point out the differences between the retrievals of $a_\varphi$ (676) and Chla concentration presented in Table 2 and Table 3. Despite the higher MAPE found for Sep 2013, Apr 2014 and particularly Jun 2015 in Table 3, for Feb 2013 and Aug 2013 the MAPE values are lower when compared to those of Table 2, which shows that the empirical algorithms designed to retrieve Chla are also suitable to retrieve $a_\varphi$ (676). However, that for neither of retrievals (Chla concentrations or $a_\varphi$(676)) results were acceptable s (MAPE < 35%) for Feb 2013.

## 4. DISCUSSION

The results presented above shows that it is possible to use empirical algorithms originally designed to retrieve Chla concentration for retrieving $a_\varphi$ (676). The results shows that, depending on the set of optically active components (OAC), it should be worth using the measurements of *in-situ* $a_\varphi$(676) instead of laboratory Chla concentration.

There are some reasons that explain the results obtained when retrieving *in-situ* $a_\varphi$ (676). The first is the error related to laboratory measurements of Chla concentration. The process of filtering, storing the filters and finally measuring the concentration of Chla pigment can be corrupted by different types of environmental and procedural errors.

The measurement of *in-situ* $a_{\varphi}(676)$ is, however, affected by different types of sediment (organic and inorganic fractions) and also by the amount of colored dissolved organic matter (CDOM). Although CDOM absorption decreases exponentially, reaching low values in the 676 nm region, the amount of CDOM in Amazon floodplain lakes can interfere by increasing the overall absorption, what directly impacts the empirical algorithms. Sediment concentration also increases the overall absorption coefficient but interferes directly in ACS measurements, however, the nature of the effects are quite different from that of CDOM [13] .

Particularly, the results of MAPE under 35% for Feb 2013 might be related to the very high inorganic load during this hydrograph phase. The higher load of inorganic material masks the Chla response in the Remote Sensing Reflectance, being the probable reason for the high MAPE in all algorithms tested for both Chla concentration and $a_{\varphi}(676)$.

However, compared to the problems found in laboratory measurements of Chla concentration, the errors for *in-situ* might be lower, what should encourage the retrieval of $a_{\varphi}(676)$. To reach Chla concentration, a robust relation between $a_{\varphi}(676)$ and Chla concentration can be build and the retrieval of $a_{\varphi}(676)$ could be a step for a better Chla retrievals.

## 5. CONCLUSIONS

The empirical algorithms originally built to retrieve Chla concentration from orbital remote sensing, particularly Sentinel 2 MSI sensor, can be used to retrieve *in-situ* aφ(676) in Amazon floodplain lakes, depending on the hydrograph phase. The retrieval of $a_{\varphi}(676)$ could be used as both, a surrogate of Cha concentration or a step for Chla concentration in order to lessen the errors introduced by laboratory measurements, depending on the type of optically active components that are part of the water body in a particular period.

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