LabISA - Instrumentation
Laboratory for Aquatic Systems and Brazilian inland water bio-optical dataset

Cláudio Barbosa
claudio@dpi.inpe.br

Earth Observation General Coordination - OBT
Remote Sensing of inland waters research group

The history timeline activities (two periods)

- Above water measurements & empirical algorithms (2001-2010)
  - Focused in the seasonal dynamics of volume and water composition in the Amazon floodplain lakes.

- Water column profiles measurements & semi analytical algorithms
  - Focused in bio-optics characterization and the seasonal dynamics of bio-optics properties
First period: Above water measurements (2001-2010)

In 2001, we began studies focused on the development of methodologies integrating remote sensing data, spectroradiometric data and empirical algorithms to understand the dynamics of water circulation in the Amazon floodplain lakes.

Up to 2007 nearly 10 field campaigns measuring above water reflectance, limnological variables as well as bathymetry of some lakes.

After 2007 we also started to make measurements in hydroelectric reservoirs.

Built a database integrating all available radiometric and limnological data.
2001 to 2010

Above water measurements in the amazon floodplain Lakes
Study sites in the Amazon floodplain (three sites)

Site 1 ➔ 900 km upstream from the Amazon River mouth.
Diversity of Amazonian water types

Black water (Negro River)

Organic dissolved matter

Chlorophyll concentration 500-800μg/liter

White water (Amazon River)

High inorganic matter

Clear Water (Tapajós River)

Manaus

Santarém

Cláudio Barbosa
Dynamics of flooding in terms of water level fluctuation

Annual flooding amplitude: 7 meters

Inter-annual fluctuations: 2 meters

Daily water stage records

[Graph showing daily water stage records from 1993 to 2002, with arrows indicating fluctuations and a 400 Km scale below the image.]
The flood pulse leads to a complex mixture of water composition seasonally.

1999

- Igarapés
- Clear water rivers

2002
Effect of food pulse on the water composition

### Mean concentration values

<table>
<thead>
<tr>
<th>Variável</th>
<th>Média</th>
<th>Rio Amaz.</th>
<th>Mínimo</th>
<th>Máximo</th>
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<tbody>
<tr>
<td><strong>pH</strong></td>
<td>7,72</td>
<td>6,5</td>
<td>6,10</td>
<td>9,30</td>
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<td></td>
<td>6,75</td>
<td>6,5</td>
<td>4,70</td>
<td>7,50</td>
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<td></td>
<td>7,27</td>
<td>6,6</td>
<td>5,90</td>
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<td>7,53</td>
<td>6,6</td>
<td>6,01</td>
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<td></td>
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<td>124</td>
<td>5,00</td>
<td>90,00</td>
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<td></td>
<td>66,13</td>
<td>27,5</td>
<td>5,46</td>
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<tr>
<td><strong>TSS</strong> (mg/l)</td>
<td>462,71</td>
<td>60</td>
<td>12,74</td>
<td>1137,75</td>
</tr>
<tr>
<td></td>
<td>98,7</td>
<td>161</td>
<td>36,75</td>
<td>359,42</td>
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<td>58</td>
<td>5,68</td>
<td>34,90</td>
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<td></td>
<td>68,78</td>
<td>4,15</td>
<td>5,61</td>
<td>350,00</td>
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<tr>
<td></td>
<td>33,4</td>
<td>2</td>
<td>0,80</td>
<td>87,86</td>
</tr>
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<td></td>
<td>8,2</td>
<td>2</td>
<td>0,21</td>
<td>25,79</td>
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<tr>
<td><strong>Clorof. (µg/l)</strong></td>
<td>28,85</td>
<td>0,7</td>
<td>1,16</td>
<td>131,28</td>
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<td></td>
<td>8,37</td>
<td>5,11</td>
<td>4,20</td>
<td>31,52</td>
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<td></td>
<td>6,04</td>
<td>4,83</td>
<td>1,03</td>
<td>11,38</td>
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<td></td>
<td>5,56</td>
<td>4,47</td>
<td>2,81</td>
<td>11,25</td>
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<tr>
<td></td>
<td>6,73</td>
<td>8,32</td>
<td>4,38</td>
<td>15,29</td>
</tr>
</tbody>
</table>

- **TSS** = 3 $10^{-4}$ turb$^2$ + 0.38 turb - 0.4
- $R = 0.98$ valor $p < 10^{-4}$
Effect of food pulse on the water spectral response

How changes on water composition affect both:

Amplitude and Shape of the spectra
Spectra shaped by water composition

High chlorophyll concentration

Dissolved organic matter

High inorganic suspended solid concentration
Intensive sampling in different water level stage (2003-2010)
Field infrastructure
Field infrastructure
Visual intercomparison of spectral shape

Reflectance at each in situ sample station was extracted from MERIS image for all MERIS spectral bands.

In situ spectra were resampled to MERIS spectral resolution bands (SimMERIS)

Clorophyll = 26 ug/l

Clorophyll = 61 ug/l
Visual intercomparison of spectral shape

**six day time delay.**

- **Meris**
- **Continuous**
- **Simulated**

June, 19 - sample 94

**one day time delay**

- **Meris**
- **Continuous**
- **Simulated**

June, 14 - sample 22

**satellite overpass**

- **Meris**
- **Continuous**
- **Simulated**

June, 13 - sample 45

June, 13 - sample 43
Water masses characterization (decline water) Clustering based on (SAM)

<table>
<thead>
<tr>
<th>Classe</th>
<th>TURB</th>
<th>TSS</th>
<th>TSI</th>
<th>TSO</th>
<th>TSO/TSS</th>
<th>TSO/TSI</th>
<th>CLORO</th>
<th>cloro/TSS</th>
<th>CID</th>
<th>COD</th>
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<tbody>
<tr>
<td>C1</td>
<td>202</td>
<td>87.52</td>
<td>56.69</td>
<td>30.84</td>
<td>0.35</td>
<td>0.54</td>
<td>204.30</td>
<td>2.33E-03</td>
<td>15.04</td>
<td>6.56</td>
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<tr>
<td>C2</td>
<td>87</td>
<td>39.30</td>
<td>23.82</td>
<td>15.48</td>
<td>0.39</td>
<td>0.65</td>
<td>89.75</td>
<td>2.28E-03</td>
<td>10.29</td>
<td>4.74</td>
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<tr>
<td>C3</td>
<td>205</td>
<td>95.08</td>
<td>76.81</td>
<td>18.27</td>
<td>0.19</td>
<td>0.24</td>
<td>63.31</td>
<td>6.66E-04</td>
<td>11.46</td>
<td>6.04</td>
</tr>
<tr>
<td>C4</td>
<td>161</td>
<td>65.17</td>
<td>54.38</td>
<td>10.79</td>
<td>0.17</td>
<td>0.20</td>
<td>25.57</td>
<td>3.92E-04</td>
<td>12.18</td>
<td>5.25</td>
</tr>
<tr>
<td>C5</td>
<td>124</td>
<td>52.69</td>
<td>35.59</td>
<td>17.10</td>
<td>0.32</td>
<td>0.48</td>
<td>91.86</td>
<td>1.74E-03</td>
<td>10.75</td>
<td>4.75</td>
</tr>
<tr>
<td>C6</td>
<td>151</td>
<td>55.08</td>
<td>40.41</td>
<td>14.66</td>
<td>0.27</td>
<td>0.36</td>
<td>61.62</td>
<td>1.12E-03</td>
<td>8.33</td>
<td>5.20</td>
</tr>
</tbody>
</table>
**Chlorophyll concentration (empirical models)**

- **Graph (A)**: Chlorophyll concentration as a function of the ratio of bands (R708/R684) with equation:
  \[ \text{Chlorophyll} = 79.25 \times (R708/R684) - 62.59 \]
  \( R = 0.96, \ \text{value} \ p < 10^{-4} \)
  \( n = 71 \)

- **Graph (B)**: Chlorophyll concentration as a function of the difference of bands (R708-R684) with equation:
  \[ \text{Chlorophyll} = 2210.7 \times (R708-R684) + 17.64 \]
  \( R = 0.92, \ \text{value} \ p < 10^{-4} \)
  \( n = 65 \)

- **Graph (C)**: Chlorophyll concentration as a function of the first derivative at 690 nm with equation:
  \[ \text{Chlorophyll} = 48400 \times (D690) + 14.499 \]
  \( R = 0.89, \ \text{value} \ p < 10^{-4} \)
  \( n = 65 \)

- **Graph (D)**: Chlorophyll concentration as a function of the second derivative at 715 nm with equation:
  \[ \text{Chlorophyll} = -2006 \times (D715) + 5.7 \]
  \( R = 0.69, \ \text{value} \ p < 10^{-4} \)
  \( n = 65 \)
mapping water masses

State 2 = low
State 1 = high
State 3 rising
State 4 decline
Site 2 An extension of site 1 - nearly 1000 km
Site 2 An extension of site 1 - nearly 1000 km

Seasonal changes in chlorophyll distributions in Amazon floodplain lakes derived from MODIS images (Novo et al., 2006 Limnology (2006) 7:153-161)
Chl (Images MODIS, empirical model)

Seasonal changes: 2002 & 2003

Some master dissertation and PhD Thesis

- Remote Sensing of water circulation dynamics in the Curuai floodplain/Amazon River

- Spectral Library: References for water types classification in Amazon wetlands

- Fluorometric and Spectral data applied to estimate chlorophyll concentration in freshwater environments

- Empirical models for suspended sediments concentration estimative in white water amazon rivers from LANDSAT 5 images
Some master dissertation and PhD Thesis

- Integration between MODIS images and census data to assessment of livestock impact in aquatic systems on the lower amazon

- Mapping the Amazon river floodplain using object based classification with SRTM-DEM and HAND-DEM Data

- Occurrence and removal of sunglint effects in hyperspectral and high spatial resolution images from the Spectrir sensor
Reference spectra to classify Amazon water types
Lobo at all 2012 - IJRS Vol. 33, No. 11

A spectral database (392 spectra) were compiled into spectral library
⇒ resulting in 10 reference spectra, that describe four limnological characteristics

Result of SAM algorithms: overall accuracy of 86%

![MERIS](image1.png) ![Hyperion](image2.png)

- **Clear water** - low concentrations of OAC
- **Black water** - rich in CDOM
- **Water dominated by inorganic suspended solids**
- **Water dominated by chlorophyll-a**
Mapping potential cyanobacterial bloom using Hyperion data in Patos Lagoon estuary - Brazil

Spectral angle mapping using two spectral library:

- analytical (Kutser, 2004)
- empirical

Hyperion image

Lobo et al. 2009
Acta Limnol. Bras
vol. 21, no. 3

88% of similarity
**Project:** Spatio-temporal evaluation of inland aquatic system’s eutrophication in response to sugarcane expansion

**Airborne Hyperspectral Imaging**

*SpecTIR V-S: Flight lines*

357 spectral bands

- Affected by sunglint
- Sunglint removal

*Phyto bloom*
First period: Above water measurements (2001-2010)

- Allowed characterizing patterns of spatio-temporal dynamics of water masses composition without however characterizing the spectral composition of the underwater light field.

  ➔ key information to support primary productivity studies.
Second period: Water column measurements (2011-2016)

In 2010, we moved towards to measure the *Inherent and Apparent Optical Properties in water column in order to do:

- the *spectral characterization* of the underwater light field,
- the *bio-optical characterization* of lakes and reservoirs
- Use *semi analytical algorithms* to retrieve constituents.

*Why?* ➔ *semi analytical algorithms have time frame coverage*
Second period: Water column measurements (2011-2016)

The history timeline (two periods)

- Above water measurements & empirical algorithms (2001-2010)
  - Focused in the seasonal dynamics of volume and water composition in the Amazon floodplain lakes.

- Water column profiles measurements & semi analytical algorithms
  - Focused in bio-optics characterization and the seasonal dynamics of bio-optics properties
Motivation

MODIS
Motivation
Second period: Water column measurements (2011-2016)

It took us nearly three years and be involved in six projects to acquire the whole set of instruments

- ANEEL
- Three FAPESP Projects
- FUNDO AMAZONAS
- CNPq UFC
- FAPESP - mamiraua
Some of the Projects that funded instruments

- Modeling human impacts on ecological properties of wetland and aquatic ecosystems of central Amazon floodplain.

- Spatio-temporal evaluation of inland aquatic system’s eutrophication in response to sugarcane expansion using remote sensing images

- Emissions of Greenhouse Gases in Hydroelectric Reservoirs
Instrumentation Laboratory for Aquatic Systems (LabISA)

Two AC-S (10 and 25 cm)

CTD

UV-VIS-2600 Shimadzu

LISST-Portable

10AU Field and Laboratory Fluorometer

HydroScat-6P

ECO BB9

http://www.dpi.inpe.br/labisa/index_en.html

Six RAMSES radiometer

ASD HandHeld 2: VNIR

ADP- Acoustic Doppler Profiler
Course "Radiative Transfer Theory, Optical Oceanography, and Hydrolight" (Curtis Mobley, INPE, 2013)
Examples of recent results
(2012 - 2015)
Sampled sites (six reservoirs and lakes at Amazonian floodplain)

Selected for accomplishing the goals of the projects that funded the instruments.

**Goals:** providing support for

- Effects of climate change in the Amazon region
- Environmental impacts and the net carbon budget in Brazilian reservoirs.

<table>
<thead>
<tr>
<th>Sampled sites</th>
<th>Site</th>
<th>Area (Km²)</th>
<th>Biome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Itaipu</td>
<td>1.350</td>
<td>Atlantic Tropical Forest</td>
</tr>
<tr>
<td>2</td>
<td>Três Marias</td>
<td>1.040</td>
<td>Brazilian Savana (Cerrado)</td>
</tr>
<tr>
<td>3</td>
<td>Funil</td>
<td>40</td>
<td>Atlantic Tropical Forest</td>
</tr>
<tr>
<td>4</td>
<td>Ibitinga</td>
<td>114</td>
<td>Atlantic Tropical Forest</td>
</tr>
<tr>
<td>5</td>
<td>Tucuruí</td>
<td>2.430</td>
<td>Amazon</td>
</tr>
<tr>
<td>6</td>
<td>Curuai</td>
<td>2000</td>
<td>Amazon</td>
</tr>
<tr>
<td>7</td>
<td>Açude Orós</td>
<td>190</td>
<td>Semi-arid Caatinga</td>
</tr>
</tbody>
</table>
Optical and limnological data were gathered along 13 field campaigns between 2012 and 2015.

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (Km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curuai</td>
<td>1.350</td>
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<tr>
<td>Funil</td>
<td>190</td>
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<tr>
<td>Orós</td>
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<tr>
<td>Três Marias</td>
<td>1.040</td>
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<tr>
<td>Ibitinga</td>
<td>40</td>
</tr>
<tr>
<td>Itaipú</td>
<td>114</td>
</tr>
</tbody>
</table>
Measured variables:

Defined taking as reference the ones listed on NASA document that describes key *in situ* variables to be measured for satellite ocean color sensor validation, algorithm development and algorithm validation.

Sampling stations were defined based on homogeneous spectral response mapped from an unsupervised classification.
Measured variables:
Profiles of Apparent Optical Properties (AOP)

Six inter-calibrated spectroradiometers

Downward & Upward irradiances /radiances
\[ E_s, E_d, L_w, L_u, E_u, E_{sky} \text{ (320 to 950nm)} \]
Measured variables:
Profiles of Inherent Optical Properties (IOP) & Probe

**Attenuation & Absorption & Backscattering**

**4 Hz sampling rate**

Reservoirs

Amazonian floodplain

**Probe (Tu, Te, Co, pH, DO)**

**Specific coefficients (a\textsubscript{ph}*, a\textsubscript{NAP}*, a\textsubscript{TP}*)**

**OAC (Chl-a, TSS, TSI, TSO, DOC, DIC, CDOM)**

Due to remoteness during Amazonian campaigns, the team stay all time onboard.
Pre-processing

Some data has to be submitted to correction protocols

- Absorption measurements ➔ be corrected for scatter absorption tube
- Backscattering ➔ have be corrected for attenuation in optical path
- AOP measurements ➔ have be normalized for sunlight changes

Algorithms were developed and tested for case I waters

- Have to be assessed since efficiency is related to water composition
- Assessments were made for Amazonian lakes water.

(Carvalho et al, 2015 special edition on inland waters of RSE).
**Descriptive statistics of some bio-optical properties of Brazilian inland aquatic systems**

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Tucuruí</th>
<th>Itaipú</th>
<th>Três Marias</th>
<th>Curuai</th>
<th>Ibitinga</th>
<th>Funil</th>
<th>Orós</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z_{eu\text{-19%}}) [m]</td>
<td>Mean/Median</td>
<td>4.84/6.87</td>
<td>3.17/3.26</td>
<td>6.57/7.54</td>
<td>1.18/1.38</td>
<td>5.61/7.42</td>
<td>2.45/3.11</td>
</tr>
<tr>
<td></td>
<td>Min/Max</td>
<td>1.14/9.39</td>
<td>1.89/4.18</td>
<td>2.19/13.14</td>
<td>0.35/2.72</td>
<td>2.66/9.20</td>
<td>1.02/4.51</td>
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<tr>
<td>(K_{d}) (PAR) ([m^{-1}])</td>
<td>Mean/Median</td>
<td>0.95/0.67</td>
<td>1.45/1.41</td>
<td>0.70/0.61</td>
<td>3.90/3.33</td>
<td>0.82/0.62</td>
<td>1.88/1.48</td>
</tr>
<tr>
<td></td>
<td>Min/Max</td>
<td>0.49/4.03</td>
<td>1.10/2.44</td>
<td>0.35/2.10</td>
<td>1.69/13.30</td>
<td>0.50/1.73</td>
<td>1.02/4.50</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>0.75</td>
<td>0.31</td>
<td>0.37</td>
<td>1.72</td>
<td>0.36</td>
<td>1.00</td>
<td>-</td>
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<tr>
<td>(C(450)) ([m^{-1}])</td>
<td>Mean/Median</td>
<td>4.51/2.89</td>
<td>-</td>
<td>3.66/2.72</td>
<td>20.08/19.44</td>
<td>4.75/4.39</td>
<td>6.44/5.62</td>
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<tr>
<td></td>
<td>Min/Max</td>
<td>1.47/16.04</td>
<td>-</td>
<td>1.40/15.35</td>
<td>12.47/37.95</td>
<td>2.49/8.10</td>
<td>3.26/12.80</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>4.11</td>
<td>-</td>
<td>2.99</td>
<td>-</td>
<td>1.84</td>
<td>3.13</td>
<td>-</td>
</tr>
<tr>
<td>(a_{	ext{sec}}(440)) ([m^{-1}])</td>
<td>Mean/Median</td>
<td>-</td>
<td>0.66/0.41</td>
<td>2.16/2.13</td>
<td>0.88/0.90</td>
<td>0.56/0.56</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Min/Max</td>
<td>-</td>
<td>0.19/4.3</td>
<td>1.70/2.66</td>
<td>0.78/0.99</td>
<td>0.36/0.67</td>
<td>-</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>-</td>
<td>0.81</td>
<td>0.23</td>
<td>0.09</td>
<td>0.1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>Mean/Median</td>
<td>3.12/1.45</td>
<td>7.86/8.50</td>
<td>2.87/0.90</td>
<td>20.88/21.70</td>
<td>10.52/7.20</td>
<td>8.77/6.10</td>
</tr>
<tr>
<td></td>
<td>Min/Max</td>
<td>0.10/17.0</td>
<td>3.60/10.70</td>
<td>0.10/24.10</td>
<td>8.10/33.20</td>
<td>1.00/45.40</td>
<td>3.60/33.80</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>4.41</td>
<td>2.09</td>
<td>5.28</td>
<td>5.72</td>
<td>10.52</td>
<td>7.63</td>
<td>13.18</td>
</tr>
<tr>
<td>Chl-(\alpha) ((\mu g/L))</td>
<td>Mean/Median</td>
<td>7.19/5.01</td>
<td>1.61/1.12</td>
<td>5.47/4.67</td>
<td>18.41/11.74</td>
<td>41.9/20.65</td>
<td>38.00/13.08</td>
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<tr>
<td></td>
<td>Min/Max</td>
<td>2.75/39.53</td>
<td>0.59/04.81</td>
<td>1.17/13.22</td>
<td>0.90/92.06</td>
<td>3.72/180.40</td>
<td>1.39/242.86</td>
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<tr>
<td>Std. deviation</td>
<td>7.10</td>
<td>1.21</td>
<td>3.33</td>
<td>18.82</td>
<td>53.90</td>
<td>64.15</td>
<td>16.23</td>
</tr>
<tr>
<td>TSS ((mg/L))</td>
<td>Mean/Median</td>
<td>3.43/1.92</td>
<td>1.77/1.61</td>
<td>4.34/3.33</td>
<td>32.37/15.72</td>
<td>7.02/5.20</td>
<td>5.67/5.00</td>
</tr>
<tr>
<td></td>
<td>Min/Max</td>
<td>0.26/20.41</td>
<td>0.63/3.77</td>
<td>1.33/11.93</td>
<td>0.53/161.85</td>
<td>0.80/30.80</td>
<td>0.87/18.60</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>4.26</td>
<td>0.74</td>
<td>2.54</td>
<td>34.93</td>
<td>7.35</td>
<td>4.50</td>
<td>15.25</td>
</tr>
<tr>
<td>DOC ((mg/L))</td>
<td>Mean/Median</td>
<td>2.32/1.98</td>
<td>2.17/2.06</td>
<td>1.95/1.90</td>
<td>2.11/7.74</td>
<td>3.63/3.44</td>
<td>3.41/3.32</td>
</tr>
<tr>
<td></td>
<td>Min/Max</td>
<td>1.45/7.03</td>
<td>1.73/4.09</td>
<td>0.93/2.71</td>
<td>4.14/7.74</td>
<td>2.72/4.91</td>
<td>2.80/5.22</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>1.12</td>
<td>0.62</td>
<td>0.37</td>
<td>1.05</td>
<td>0.63</td>
<td>0.62</td>
<td>1.85</td>
</tr>
</tbody>
</table>
Range of values

✓ In reservoirs, the chlorophyll-a ranged from 0.6 to 243 µg/L while in Amazonian lakes ranged from 0.90 to 92 µg/L.

✓ In reservoirs the highest Total Suspended Solids (TSS) was 30 mg/L while at the Amazonian lakes was as high as 160 mg/L.

✓ The median value of beam attenuation coefficient (450 nm) reaches 5 m\(^{-1}\) in reservoirs and 19 m\(^{-1}\) at the Amazonian lakes.

✓ The Kd (PAR)** reaches 1.5 m\(^{-1}\) in reservoirs and 3.3 at the Amazonian lakes.
Spectral composition of normalized downwelling irradiance relative to surface incoming light (incident irradiance $E_s(\lambda)$)

Underwater light field:

Red curves are the depth of euphotic zone, and white curves are the attenuation depth (the thickness of the layer from which 90% of the signal recorded by satellite sensor originates).
Conclusion

Main difficulty faced ➔ The huge amount of data of each campaign

✓ Developing an interactive toolbox for processing and analyzing

➢ We are building a dataset which is the first and most comprehensive bio-optical information available for the Brazilian inland waters.
Some master dissertation and PhD Thesis

- Optical models and in situ data collected in Funil (RJ) reservoir used to aid researches on remote sensing of continental waters

- Optical and dissolved organic carbon characterization in Três Marias/MG reservoir

- Temporal characterization of the bio-optical properties of the Ibitinga/SP reservoir

- Bio-optical models to support the retrieval of optically active constituents in Amazon floodplain lakes
Obrigado