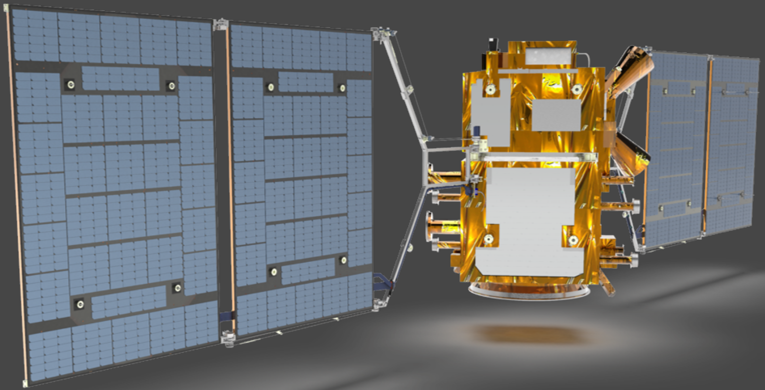
MISSION CRITICAL DESIGN REVIEW



SABIA-Mar Project

SECTION: 07B

L1, L2 & L3 Algorithm Description

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L1 Algorithm Overview

L1 product	**Input**	**Output**	**Auxiliary Data**
Georeference	Orbit Data	Pixel Latitude/Longitude	Geometric Coefficients
Angular Geometry	Attitude Data	Sensor and Solar Angles	Geometric Coefficients
Band to Band Corregistration	Pixel Latitude/Longitude Data	Band referenced	Geometric Coefficients
Radiometric	Raw Science Data	Physical TOA radiance	Radiometric Coefficients

L1B Processing Algorithms

Georeference:
Each pixel latitude and longitude are obtained with a interpolation process over the orbit data

Angular Geometry:
For each pixel the sensor and solar angles are compute for that we use on board attitude measurements

Band To Band Corregistration:
To accomplish the corregistration a linear interpolator algorithm is applied to the longitude, latitude dataset of the band to be correlated.

Radiometric:
For each pixel and for all bands a transformation is aplied to converts the raw science data to physical Top-of-Atmosphere (TOA) radiance values.

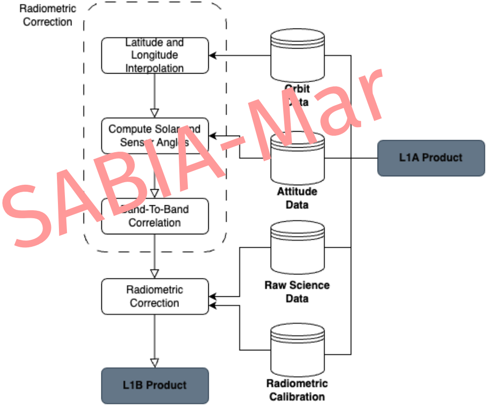


Figure: L1B Processing Overview

Contents

Related documentation

- Atmospheric corrections and L_w:
  - **SB-04050501050000-NT-00001-A**, Simplified Atmospheric Correction For SABIA-Mar,
  - **SB-04050501000000-RP-00001-A**, Report: SABIA-Mar simulated TOA Radiances and L2 products,
  - **SB-04050501050000-RP-00001-A**, L2 Processor Prototype Description,
  - **SB-04040208000000-NT-00001-A**, Cloud Mask Algorithm for SABIA-Mar,
  - **SB-04040201000000-NT-00002-B**, ATBD: Normalized Water Leaving Radiance $[L_w]_N$,
- Chl-a concentration
  - **SB-04040202000000-NT-00001-C**, Algorithm Theoretical Bases Document: Chlorophyll-a concentration Chl-a

Related documentation

- Diffuse attenuation coefficient, Kd490
  - **SB-0404020300000-NT-00002-B**, Algorithm Theoretical Bases Document: Kd490.
- PAR
  - **SB-0404020400000-NT-00002-B**, Algorithm Theoretical Bases Document: Daily Mean PAR.
  - **SB-0405050109000-IA-00001-A**, Implementation of Daily Mean PAR
- Turbidity
  - **SB-0404020500000-NT-00001-B**, Algorithm Theoretical Bases Document: Turbidity.
- Night boats detection
  - **SB-0404020600000-NT-00001-A**, ATBD: Night boat detection
- L3 binning and mapping method
  - **SB-0404030000000-NT-00001-A**, ATBD: Level 3 products

Key requirements

Uncertainties requirements for L2 products

Product	Uncertainty
Normalized Water Leaving Radiance (L_w)	It shall be less than 5% at bands B0, B1, B2, B3, and less than 15% at bands at B4, in oligotrophic deep case 1 waters.
Chlorophyll-a concentration (Chl_a)	It shall be less than 40% in oligotrophic deep case 1 waters.
Diffuse Attenuation coefficient at 490nm (Kd490)	It shall be less than 25% in oligotrophic deep case 1 waters.
Daily mean Photosynthetic Available Radiation (PAR)	It shall be 20%.
Turbidity (T)	It shall be 35% in turbid waters.

Key requirements

Temporal and Spatial resolutions for L3 products

		Binned & Mapped
Variables		$[L_w]_N$ & R_{sr}, Chl-a, FLH, Turbidity, K_d, PAR
Temporal Resolution	Global	Daily, 8-day, monthly, seasonal, annual
	Regional	Daily, 8-day, monthly, seasonal, annual
Spatial Resolution	Global	2.32km, 4.64km
	Regional	0.46km

	Binned		**Mapped**		
	0.46 km	**2.32 km**	**0.46 km**	**2.32 km**	**4.64 km**
Daily	Regional	Global	Regional	Global	Global
8-Days	Regional	Global	Regional	Global	Global
Monthly	Regional	Global	Regional	Global	Global
Seasonal	Regional	Global	Regional	Global	Global
Annual	Regional	Global	Regional	Global	Global

Summary of bands and algorithms for L2 products

L2 product	Algorithm	Bands	
		L2 product	Atm Corr
$[L_w]_N$ & R_{sr}	NASA Global	412, 443, 490, 510, 555, 620, 665, 680, 710	750, 865
	Regional	+ 865	750, 765, 1044, 1240, 1610
Chl-a	OC4 & OCI	L_W@443, 490, 510, 555	
FLH	Abbot&Lettelier	L_W@665, 680, 710	
Turbidity	Dogliotti's	L_W@665 (Global) L_W@665, 865 (Regional)	
Daily mean PAR	Frouin's	L_{TOA}@412, 443, 490, 510, 555, 620, 665	
$K_d(490)$	KD2S	L_W @ 490, 555	
Night lights	Elvidge's	Panchromatic @ 450 nm to 800 nm	

$[L_w]_N$ & R_{sr} and $Chl - a$ are the main mission variables, being **L_w the fundamental** one.
Turbidity, $K_d(490)$ and PAR are OC derived variables from main cameras.
Night lights is secondary camera derived variable.
FHL is a complementary OC variable.

Auxiliary data

Auxillary data	Uses	Source
Ozone O_3	Transmittance	OMI/EPTOMS, TOAST
Nitrogen dioxide NO_2	Transmittance	SCIAMACHY/OMI/GOME
Atmospheric pressure P_0	$\rho_r(\lambda_i)$	NCEP/GMAO MERRA-2
Wind Speed W	$\rho_r(\lambda_i)$, $\rho_g(\lambda_i)$, $\rho_{wc}(\lambda_i)$	NCEP/GMAO MERRA-2
Relative Humidity RH	Aerosol models ($\varepsilon(\lambda_i, \lambda_j)$)	NCEP/GMAO MERRA-2
Water Vapor H_2O	Transmittance	NCEP
Sea ice coverage	Masking	NSIDC/SHN
In situ Lw, Chl-a, Kd	Fit models	NOMAD

Atmospheric Corrections Physical Problem

The process to retrieve the water-leaving radiance is known as **Atmospheric Correction**.

The objective is to remove both atmospheric and surface effects from the signal measured by sensor.

It is a fundamental stage, as several products use the water-leaving radiance as input.

Radiative Transfer Equation

$$L_t(\lambda_i) = \left(L_r(\lambda_i) + L_a(\lambda_i) + L_{ra}(\lambda_i) + T_s T_v L_g(\lambda_i) + t_{dv} L_{wc}(\lambda_i) + L_w(\lambda_i) \right) t_{gv} t_{gs} \, f_p$$

- L_w: Water-leaving Radiance 🔴 (Unknown)
- L_t: Top of Atmosphere Radiance 🔵 (Measured by satellite)
- $L_r + L_a + L_{ra}$: Atmospheric Radiance (aerosols + molecules) 🟣 (Modeled)
- L_g: Sun glint radiance 🟢 (Masking and corrected)
- L_{wc}: Whitecaps radiance 🟠 (Modeled)
- f_p: Instrument polarization correction factor ⚪ (pre-launch)
- t_d, t_g, T: Rayleigh and aerosols diffuse transmittance, gaseous transmittance and direct transmittance, respectively.
- s: in sun direction, v: in satellite direction.

Normalized water-leaving radiance

$$L_{wn}(\lambda_i) = L_w(\lambda_i) / \left(\mu_s f_s \; t_{d_s} \; f_b(\lambda_i) \; f_\lambda(\lambda_i) \right)$$

- L_{wn}: Normalized water-leaving radiance.🔵 (Normalization applied to measurement)
- L_w: Water-leaving radiance 🟣 (Measured)
- $\mu_s f_s$: Normalization as if the sun were at its zenith and correction for the Earth-Sun distance.🟢 (Measured)
- t_{d_s}: Diffuse transmittance in the direction of the Sun. 🟠 (Modeled)
- f_b: BRDF correction of the ocean surface. 🔴 (Modeled)
- f_λ: Remainder Out-of-Band correction (only if needed). ⚪ (Modeled)

SABIA-Mar atmospheric correction algorithm

SABIA-Mar Atmospheric Correction (SMAC) algorithm considerations:

- Based on Gordon & Wang's work and NASA standard algorithm implementation (see Refs. [1] and [2]).
- Uses the black pixel assumption in NIR (for *global scenario*) and in SWIR (for *regional scenario*).
- Includes some modifications that take into account the unique geometrical configuration of SABIA-Mar cameras.

References:

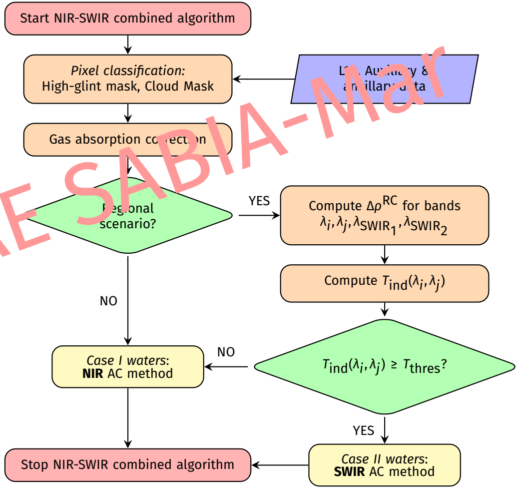
1. Gordon, H.R. and Wang, M. (1994). *Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm*. Appl. Optics, 33: 443-452.
2. The guidelines followed by the NASA OBPG group: Mobley, Curtis & Werdell, Jeremy & Franz, Bryan & Ahmad, Ziauddin & Bailey, Sean. (2016). *Atmospheric Correction for Satellite Ocean Color Radiometry*. 10.13140/RG.2.2.23016.78081.

SMAC high level flowchart

- Use of combined method that involves SABIA-Mar's NIR ($\lambda = 750, 865$ nm) and SWIR ($\lambda = 1044, 1610$ nm) bands.
- $\lambda_i = 750$ nm, $\lambda_j = 1240$ nm
  $\lambda_{SWIR_1} = 1240$ nm, $\lambda_{SWIR_2} = 1610$ nm
- The selection of SMAC bands to use is based on the calculation of turbidity index, $T_{\text{ind}}(\lambda_i, \lambda_j)$ and threshold value, $T_{\text{thres}} = 1.05$.

References:

1. W. Shi and M. Wang. *Detection of turbid waters and absorbing aerosols for the modis ocean color data processing*. Remote Sensing of Environment, 100:149–161, 2007.
2. Menghua Wang, Seunghyun Son, and Wei Shi. *Evaluation of modis swir and nir-swir atmospheric correction algorithms using seabass data*. Remote Sensing of Environment, 113:635–644, 03 2009b. doi: 10.1016/j.rse.2008.11.005.



Start NIR-SWIR combined algorithm

Pixel classification:
High-glint mask, Cloud Mask

L1 Auxiliary & ancillary data

Gas absorption correction

Regional scenario?

YES

Compute $\Delta\rho^{RC}$ for bands $\lambda_i, \lambda_j, \lambda_{SWIR_1}, \lambda_{SWIR_2}$

Compute $T_{\text{ind}}(\lambda_i, \lambda_j)$

NO

$T_{\text{ind}}(\lambda_i, \lambda_j) \geq T_{\text{thres}}$?

NO

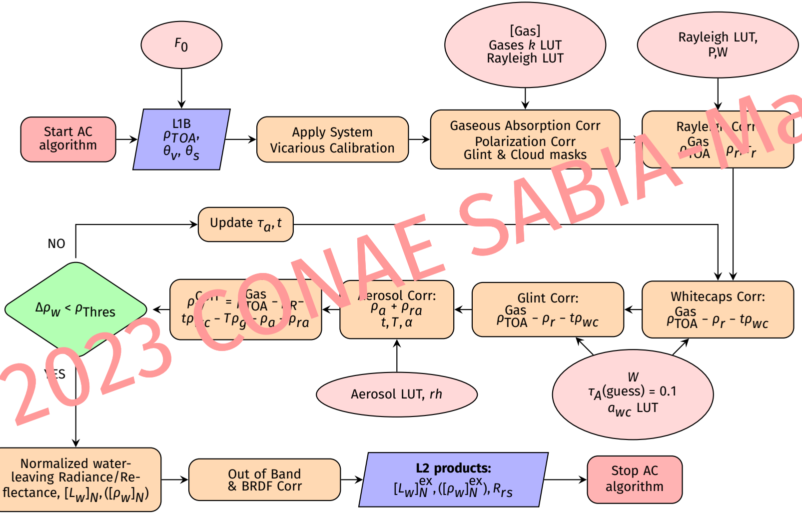
Case I waters:
NIR AC method

YES

Case II waters:
SWIR AC method

Stop NIR-SWIR combined algorithm

SABIA-Mar Atmospheric Correction flowchart



F_0

L1B
ρ_{TOA}, θ_v, θ_s

Start AC algorithm

Apply System Vicarious Calibration

[Gas]
Gases k LUT
Rayleigh LUT

Gaseous Absorption Corr
Polarization Corr
Glint & Cloud masks

Rayleigh LUT, P,W

Rayleigh Corr
$\rho_{TOA}^{Gas} - \rho_r, T_r$

Update τ_a, t

NO

$\Delta\rho_w < \rho_{Thres}$

$\rho_w^{Corr} = \rho_{TOA}^{Gas} - \rho_R - t\rho_{wc} - T\rho_g - \rho_a - \rho_{ra}$

Aerosol Corr:
$\rho_a + \rho_{ra}$
t, T, α

Glint Corr:
$\rho_{TOA}^{Gas} - \rho_r - t\rho_{wc}$

Whitecaps Corr:
$\rho_{TOA}^{Gas} - \rho_r - t\rho_{wc}$

YES

Aerosol LUT, rh

W
τ_A(guess) = 0.1
a_{wc} LUT

Normalized water-leaving Radiance/Reflectance, $[L_w]_N$, $([\rho_w]_N)$

Out of Band & BRDF Corr

L2 products:
$[L_w]_N^{ex}$, $([\rho_w]_N^{ex})$, R_{rs}

Stop AC algorithm

Masks algorithms

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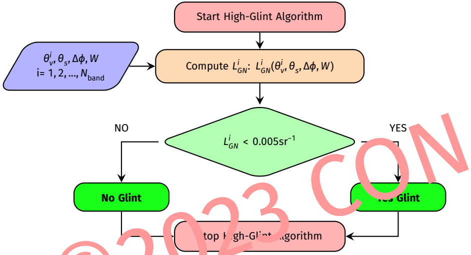
Application of masks *prior* to SMAC process:

High-glint mask algorithm flowchart [1]



Start High-Glint Algorithm

$\theta_v^i, \theta_s, \Delta\phi, W$
i= 1, 2, ..., N_{band}

Compute L_{GN}^i: $L_{GN}^i(\theta_v^i, \theta_s, \Delta\phi, W)$

$L_{GN}^i < 0.005\text{sr}^{-1}$

NO

YES

No Glint

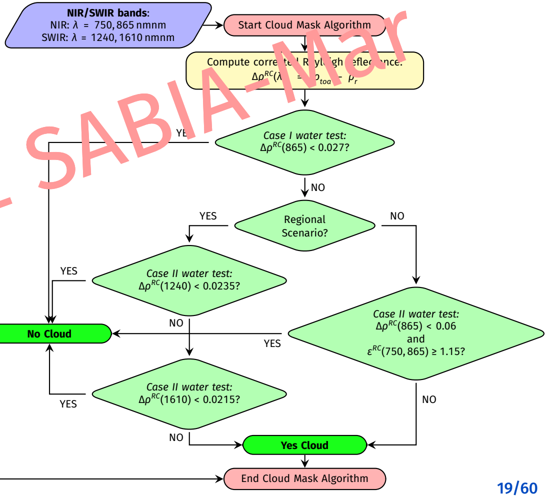
Yes Glint

Stop High-Glint Algorithm

References:

1. M Wang, SW Bailey (2001) *Appl Opt*, 40(27):4790-8.
2. M Wang, W Shi (2006) *IEEE Transactions on Geoscience and Remote Sensing*, 44(11), 3196–3105.

Cloud mask algorithm flowchart [2]



NIR/SWIR bands:
NIR: λ = 750, 865 nmnm
SWIR: λ = 1240, 1610 nmnm

Start Cloud Mask Algorithm

Compute corrected Rayleigh reflectance:
$\Delta\rho^{RC}(\lambda) = \rho_{toa} - \rho_r$

Case I water test:
$\Delta\rho^{RC}(865) < 0.027$?

YES

NO

Regional Scenario?

YES

NO

Case II water test:
$\Delta\rho^{RC}(1240) < 0.0235$?

YES

NO

Case II water test:
$\Delta\rho^{RC}(865) < 0.06$
and
$\varepsilon^{RC}(750, 865) \geq 1.15$?

YES

NO

No Cloud

Case II water test:
$\Delta\rho^{RC}(1610) < 0.0215$?

YES

NO

Yes Cloud

End Cloud Mask Algorithm

Gaseous Absorption

The gaseous absorption takes O_3 and NO_2 into consideration:

Ozone Correction, t_{O_3}

$$t_{O_3} = \exp\left(-\tau_{O_3} M\right)$$

- $\tau_{O_3} = [O_3] k_{O_3}$
- $[O_3]$: O_3 concentration (auxiliary data).
- k_{O_3}: absorption cross section.

Nitrogen Dioxide Correction, t_{NO_2}

$$t_{NO_2} = \exp\left(\alpha N' M\right)$$

- N': NO_2 concentration between an altitude of 200 m and TOA (auxiliary data).
- α: absorption cross section.

- M: **mass factor**

$$M = \frac{1}{\cos\theta_0} + \frac{1}{\cos\theta_v}$$

References:

1. H.R. Gordon and K.J. Voss. MODIS normalized water-leaving radiance (ATBD MOD18, v4). Ocean Color web page, (Mod 18):1–96, 1999. URL http://oceancolor.gsfc.nasa.gov/DOCS/atbdmod18.pdfhttp://oceancolor.gsfc.nasa.gov/DOCS/atbdmod18.pdf
2. C.D. Mobley, J. Werdell, B. Franz, Z. Ahmad, and S. Bailey. Atmospheric correction for satellite ocean color radiometry. TECHNICAL MEMORANDUM NASA/TM–2016-217551, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, Maryland 20771, 2016.

Polarization Correction Factor

Polarization correction factor, p_c

$$p_c = \frac{1}{1 - m_{12}[\cos(2\alpha)Q_t + \sin(2\alpha)U_t]/I_m - m_{13}[-\sin(2\alpha)Q_t + \cos(2\alpha)U_t]/I_m}$$

- Q_t, U_t are the Stokes components at TOA and I_m is the radiance measured by satellite.
- m_{12}, m_{13} are the Mueller coefficients.

References:

1. Gordon HR, Du T, Zhang T (1997). *Applied optics*, 36(27), 6938-6948.
2. Meister G, Kwiatkowska EJ, Franz BA, Patt FS, Feldman GC, McClain CR (2005). *Applied Optics*, 44(26), 5524-5535.

Rayleigh Correction Algorithm

Takes into account contribution of *molecules present in the atmosphere*:

Rayleigh radiance, L_r (for any atmospheric pressure P)

$$L_r(\tau_r(P,\lambda)) = L_r(\tau_r(P_0,\lambda))\frac{1-\exp\left[-C(\lambda,M)\tau_r(P,\lambda)M\right]}{1-\exp\left[-C(\lambda,M)\tau_r(P_0,\lambda)M\right]}$$

- $L_r(\tau_r(P_0,\lambda)) = L_r(\tau_r(P_0,\lambda),\theta_0,\theta_v,\sigma)$: **Rayleigh radiance at TOA**

  $$L_r = I_0 + I_1\cos\Delta\phi + I_2\cos 2\Delta\phi$$

  I_0, I_1,I_2: first components of Fourier Transform of Stokes I component. Obtained from LUTs that consider multiple values for σ and geometries (θ_0, θ_v, $\Delta\phi$). Values of σ, θ_0 and θ_v are interpolated for the case of interest.

- $\tau(P,\lambda) = \frac{P}{P_0}\tau_{r_0}(P_0,\lambda)$
  - $P_0 = 1013.25$ hPa,
  - $\tau_{r_0}(P_0,\lambda)$ given by Bodhaine table.
- $C(\lambda,M) = a(\lambda) + b(\lambda)\log(M)$
  - $a(\lambda) = -0.6543 + 1.608\tau_r(P_0,\lambda)$
  - $b(\lambda) = 0.8192 - 1.2541\tau_r(P_0,\lambda)$

References:

1. Gordon, H. R., Wang, M. (1992). *Applied optics*, 31(21), 4247-4260.

Whitecaps Correction Algorithm

Whitecaps reflectance, ρ_{wc}

$$\rho_{wc}(\lambda, W) = \begin{cases} 0, & W \leq 6.33\,\mathrm{m\,s^{-1}} \\ 1.925 \times a_{wc}(\lambda) \times 10^{-5}(W - 6.33)^3, & 6.33\,\mathrm{m\,s^{-1}} < W < 12\,\mathrm{m\,s^{-1}} \\ 1.925 \times a_{wc}(\lambda) \times 10^{-5}(12.0 - 6.33)^3, & W \geq 12\,\mathrm{m\,s^{-1}}, \end{cases}$$

- $a_{wc}(\lambda)$ is a factor in a file containing the normalized reflectance of whitecaps.

References:

1. Frouin R, Schwindling M, Deschamps PY (1996). *Journal of Geophysical Research: Oceans*, 101(C6), 14361-14371.

Sun Glint Correction Algorithm

Sun glint radiance, L_g

$$L_g(\theta_0, \theta_v, \phi_0, \phi_v, W, \lambda) = T(\theta_0, \theta_v, \lambda) F_0 L_{GN}$$

- Computed according to the *isotropic model* of Cox & Munk [1]
- $T(\theta_0, \theta_v, \lambda)$: **direct transmittance**
- F_0: **extraterrestrial solar irradiance**

- L_{GN} is the **normalized Sun glint radiance,**

$$\mathrm{L}_{GN}(\theta_0, \theta_v, \phi_0, \phi_v, W) = \frac{r \times g}{4\pi \cos(\theta_v)},$$

- r is *Fresnel reflectance*
- $g = \dfrac{\exp(-\tan^2(\theta_n)/\sigma^2)}{\sigma^2 \cos^4(\theta_n)}$
  - $\sigma^2 = 0.00512W + 0.003$ is the *rms* slope
  - θ_n is the *normal angle to the surface.*

References:

1. Cox C, Munk W (1954). *Josa*, 44(11), 838-850.

Aerosol Correction Algorithm

- The aerosol correction term is based on the *black pixel* assumption according to Gordon & Wang (1994) for $\lambda_s = 750\,\mathrm{nm}$ and $\lambda_l = 865\,\mathrm{nm}$, which means that $L_w(\lambda_s) = L_w(\lambda_l) \sim 0$ (or for reflectance).
- To calculate the aerosols radiance, precomputed LUTs are also needed.
- To get the aerosols reflectance implies to know the *single-scattering* radiance (L^{ss}) from *multi-scattering* radiance (L^{ms}).
- The multi-scattering radiance assuming black-pixel is:

$$L_a^{ms} = L_a + L_{ra} = L_t - L_r - L_g - L_{wc}. \tag{1}$$

Aerosol Correction Algorithm

- The radiances L_a^{ss} and L_a^{ms} are adjusted as follows:

$$\ln(L_a^{ms}) = c + b\log L_a^{ss} + a\log^2 L_a^{ss}, \tag{2}$$

where a, b and c are parameters which depends on the geometry, wavelength and aerosols model.

- The L_a^{ss} is obtained solving this second order equation and the single-scattering radiance is computed. This is solved for each aerosol model present in the LUTs and for λ_l.
- It is computed the *epsilon* parameter:

$$\varepsilon^M(\lambda_s,\lambda_l) = \frac{\hat{L}_a^{ss}(M;\lambda_s)}{\hat{L}_a^{ss}(M;\lambda_l)}, \tag{3}$$

where

$$\hat{L}_a^{ss}(\lambda) = \frac{F_0\omega_a(\lambda)\tau_a(\lambda)p_a(\theta_v,\phi_v;\theta_0,\phi_0;\lambda)}{4\pi\cos(\theta_v)}, \tag{4}$$

is the modeled single-scattering radiance. All the parameters in this equation are in the LUTs.

Aerosol Correction Algorithm

- Finding the models ε^{M_1} and ε^{M_2} with which to bound the average value, $\bar{\varepsilon}$, for all the models in the LUTs we can compute the $L_a^{ss}(\lambda)$:

$$\begin{cases} \tilde{L}_a^{ss}(M_1;\lambda) = \varepsilon^{M_1}(\lambda,\lambda_l)L_a^{ss}(M_1;\lambda_l), \\ \tilde{L}_a^{ss}(M_2;\lambda) = \varepsilon^{M_2}(\lambda,\lambda_l)L_a^{ss}(M_2;\lambda_l). \end{cases} \tag{5}$$

- The radiance $L_a^{ss}(\lambda)$ *measured* by the satellite is calculated as a weighted average:

$$L_a^{ss}(\lambda) = q\tilde{L}_a^{ss}(M_2;\lambda) + (1-q)\tilde{L}_a^{ss}(M_1;\lambda), \tag{6}$$

  where $q = (\bar{\varepsilon} - \varepsilon^{M_1})/(\varepsilon^{M_2} - \varepsilon^{M_1})$.

- Finally, using the expression of Eq. (2) is possible to find the multi-scattering radiance *measured* by the satellite for all λ:

$$\boxed{\mathrm{L}_a^{ms}(\lambda) = \exp\left[c + b\ln(L_a^{ss}(\lambda)) + a\ln^2(L_a^{ss}(\lambda))\right]} \tag{7}$$

The impact of the geometry

The term on the RTE which is affected by the geometry layout of SABIA-Mar is the corresponding to *aerosols reflectance* contribution due to the expression to compute the aerosols reflectance in the single-scattering model. This has the following consequences:

- The diffuse and direct transmittance are affected.
- The Sun glint and whitecaps reflectance also are affected due to the sum of aerosols and Rayleigh optical thickness.

Single-scattering Reflectance

$$\rho_{as} = \frac{\omega_a \tau_a p_a(\theta_v, \phi_v; \theta_0, \phi_0)}{4\cos(\theta_v)\cos(\theta_0)}$$

Epsilon parameter

$$\varepsilon(\lambda^1, \lambda^2) = \frac{\rho^1_{as}(\lambda^1)}{\rho^2_{as}(\lambda^2)}$$

The impact of the geometry

Single Viewing Angle

$$\varepsilon(\lambda^1,\lambda^2) = \frac{\omega_a^1 \tau_a^1 p_a^1(\theta_v^1,\phi_v^1;\theta_0^1,\phi_0^1)}{4\cos\theta_v^1\cos\theta_0^1} \times \frac{4\cos\theta_v^2\cos\theta_0^2}{\omega_a^2\tau_a^2 p_a^2(\theta_v^2,\phi_v^2;\theta_0^2,\phi_0^2)}$$

$$= \frac{\omega_a^1\tau_a^1}{\omega_a^2\tau_a^2} \times \frac{p_a^1(\theta_v,\phi_v;\theta_0,\phi_0)}{p_a^2(\theta_v,\phi_v;\theta_0,\phi_0)} \times 1,$$

where $\theta_v^1 := \theta_v^2 = \theta_v$ and $\phi_v^1 := \phi_v^2 = \phi_v$

Multi Viewing Angle

$$\varepsilon(\lambda^1,\lambda^2) = \frac{\omega_a^1 \tau_a^1 p_a^1(\theta_v^1,\phi_v^1;\theta_0^1,\phi_0^1)}{4\cos\theta_v^1\cos\theta_0^1} \times \frac{4\cos\theta_v^2\cos\theta_0^2}{\omega_a^2\tau_a^2 p_a^2(\theta_v^2,\phi_v^2;\theta_0^2,\phi_0^2)}$$

$$= \frac{\omega_a^1\tau_a^1}{\omega_a^2\tau_a^2} \times \frac{p_a^1(\theta_v^1,\phi_v^1;\theta_0,\phi_0)}{p_a^2(\theta_v^2,\phi_v^2;\theta_0,\phi_0)} \times \frac{\cos\theta_v^2}{\cos\theta_v^1},$$

where $\theta_v^1 \neq \theta_v^2$ and $\phi_v^1 \neq \phi_v^2$

Near Real Time (NRT)

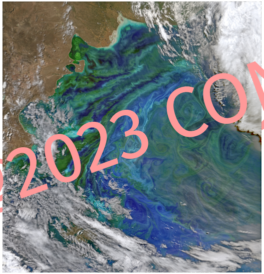
Types of $[L_w]_N$ that will be generated:

- **Near Real Time (NRT)**: climatological, meteorological, ozone auxiliary data (e.g., monthly, seasonal, annual aggregations) and predicted attitude and ephemeris data files will be used, which will be replaced when real orbit data are available. For the L2 products derived from $[L_w]_N$, such as Chlorophyll-*a* concentration, the NRT version will be produced from NRT $[L_w]_N$ product which will be replaced when real orbit data are available.
- **Refined products**: coincident meteorological and ozone will be used from corresponding actualized databases. Will be produced from the refined version of water leaving radiance

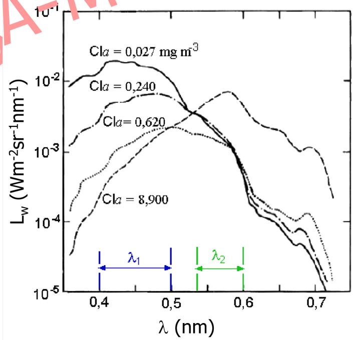
The used algorithm is the same for both types of products. Concerning to LuT and the procedures and algorithms involved, both NRT and refined versions are valid. There are no differences between the procedures applied in both cases.

Chlorophyll-a concentration [Chl-a].

- An essential climate variable that can be estimated from ocean color sensors.
- Great importance since it is a proxy of phytoplankton biomass in the seas and oceans.
- Estimation based on the different water leaving radiance in the green and blue region according to pigment concentration.



Source: MODIS



Dogliotti (2007)

SABIA-Mar [Chl-a] algorithm

OC4

Fourth-order polynomial relationship between a ratio of R_{rs} and [Chl-a]:

$$\log_{10}([\text{Chl-a}]) = \sum_{i=0}^{4} a_i log_{10}\left(\frac{R_{rs}(\lambda_b)}{R_{rs}(\lambda_g)}\right)^i$$

a_i: obtained by adjustment between R_{rs} ratio and [Chl-a].

Color Index

For low CI, there is a strong relationship between CI and [Chl-a] that was modeled as:

$$[\text{Chl-a}]_{\text{CI}} = 10^{a+b\text{CI}}$$

a and *b*: obtained by adjustment of *in situ* data.

$$\text{CI} = \text{R}_{rs}(\lambda_g) - \left[R_{rs}(\lambda_b) + \frac{\lambda_g-\lambda_b}{\lambda_r-\lambda_b}(R_{rs}(\lambda_r) - R_{rs}(\lambda_b))\right]$$

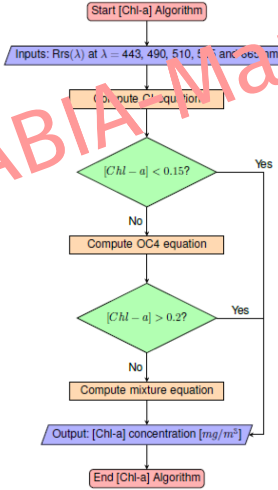
SABIA-Mar bands: $\boxed{?}_r = 665nm, \lambda_g = 555nm, \lambda_b = \max(443, 490, 510)nm$

References: OCx (O'Reilley et al 1998) and CI (Hu et al 2012)

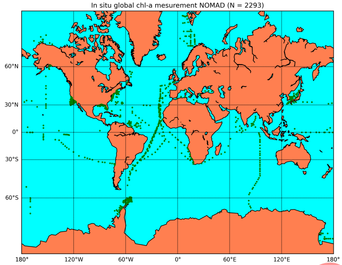
SABIA-Mar [Chl-a] algorithm

- The algorithm proceeds as follows:
  1. $[Chl - a]$ is calculated using CI algorithm ($[Chl - a]_{CI}$)
  2. $[Chl - a]$ is calculated using OC4 algorithm ($[Chl - a]_{OC4}$)
  3. For [Chl-a] < 0.25 mg m-3, the CI algorithm is used.
     For [Chl-a] > 0.35 mg m-3, the OCx algorithm is used.
     In between these values, the CI and OCx algorithm are blended using a weighted approach where:

$$[Chl\text{-}a] = \frac{[Chl - a]_{CI}(t_2 - [Chl - a]_{CI})}{t_2 - t_1} + \frac{[Chl - a]_{OCx}([Chl - a]_{CI} - t_1)}{t_2 - t_1}$$



SABIA-Mar model



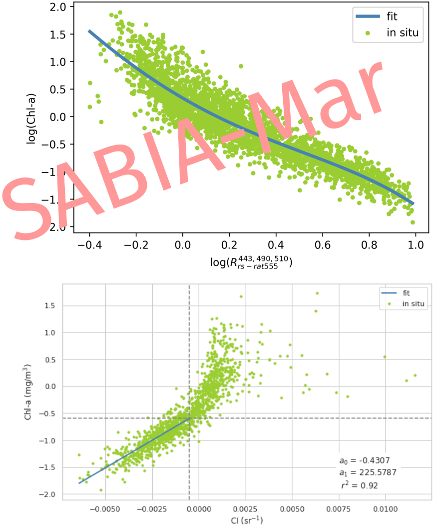
NOMAD Database (Werdell & Bailey, 2005, NASA OBPG):

- SABIA-Mar coefficients:

Algorithm	a_0	a_1	a_2	a_3	a_4
OC4	0.[illegible]3	[illegible]2.45	1.46	−0.56	−0.41
CI	-0.43	225.58	-	-	-

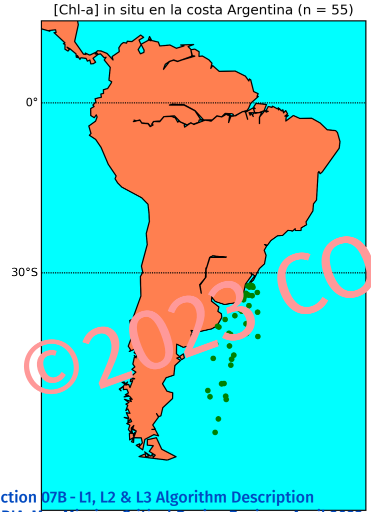
- Stastistics:

N	**R^2**	**RMS**	**slope**	**Interc**
2482	0.909	0.1017	0.8671	-0.05



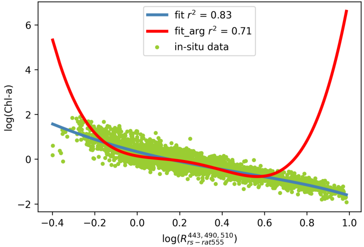
OC4 (on top) and **Color Index** (bottom)

Regional Scenario case



[Chl-a] in situ en la costa Argentina (n = 55)

- In regional scenario we do not have enough data.
- Blue line is the one already shown and red line is the regional fitted.
- We have over-fitting problem due to the scarce amount of data.



Alternative Algorithm: Non Parametric approach

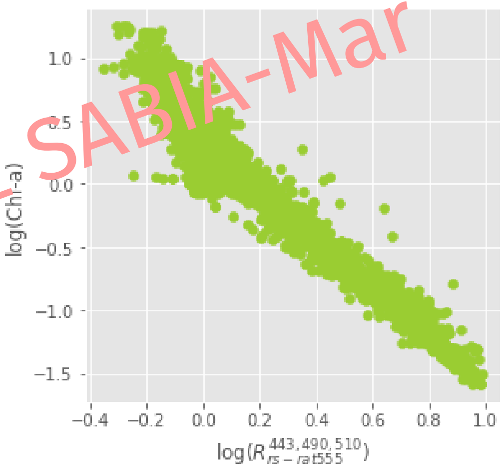
K-NN Algorithm

- Given (X_i, Y_i), an integer k and a new value X, find the k nearest observations of $X_1, \ldots, X_n$.
- Average the k corresponding $Y_1, \ldots, Y_n$. to define the estimate:

$$\boxed{\hat{m}_n(X) = \frac{1}{k}\sum_{i=1}^{k} Y_{(i)}}$$

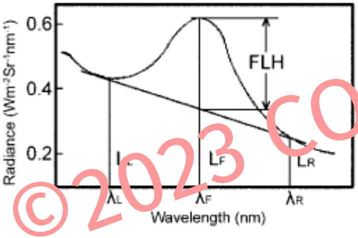
- Statistic metrics with the SABIA-Mar bands:

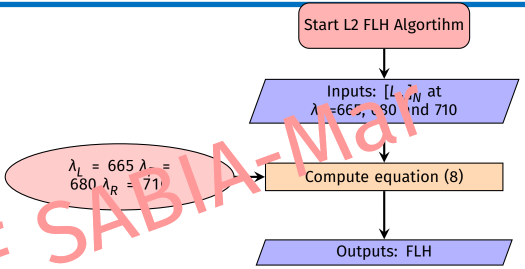
N	RMSE	R^2	slope	intercept
2482	0.26	0.87	0.83	-0.06



Chl-a fluorescence line height FLH

- It will be generated as an complementary product of Chl-a concentration.
- Useful HABs and blooms detection, as fluorescent signals are mainly attributed to Chl-a.
- $FLH = k + \frac{b*[Chla]}{1+a*[Chla]}$





$$FLH = L_F - \left[L_R + \frac{\lambda_R - \lambda_F}{\lambda_R - \lambda_L}(L_L - L_R) \right] \qquad (8)$$

References:

1. Xiao-Gang Xing, Dong-Zhi Zhao, Yu-Guang Liu, Jian-Hong Yang, Peng Xiu, and Lin Wang. An overview of remote sensing of chlorophyll fluorescence. Ocean S, 42(1):49–59, 2007.

Diffuse attenuation coefficient $K_d(490)$

- Describe light penetration in aquatic systems and predict light availability at various water depths.
- Understanding underwater ecological health impacts physical processes:
  - heat transfer in the upper layer of the ocean,
  - photochemical reactions,
  - biological processes such as phytoplankton photosynthesis in the euphotic zone.

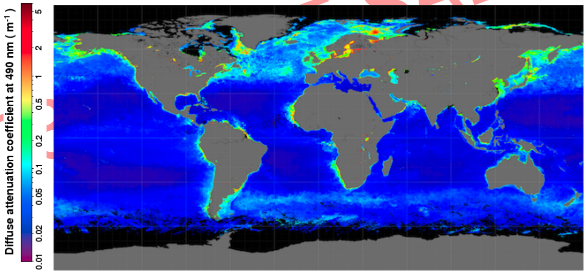


Figure: MODIS Aqua L3 image of the Kd_{490} variable at a 2014 station.

Physics fundamentals

- Attenuation equation for downward spectral irradiance attenuation:

$$\boxed{E_d(\lambda, z) = E_d(\lambda, 0^-)e^{-K(\lambda,z)z},} \tag{9}$$

- The diffuse attenuation coefficient at wavelength λ can be found as:

$$K(\lambda) = z_{90}^{-1}. \tag{10}$$

References:

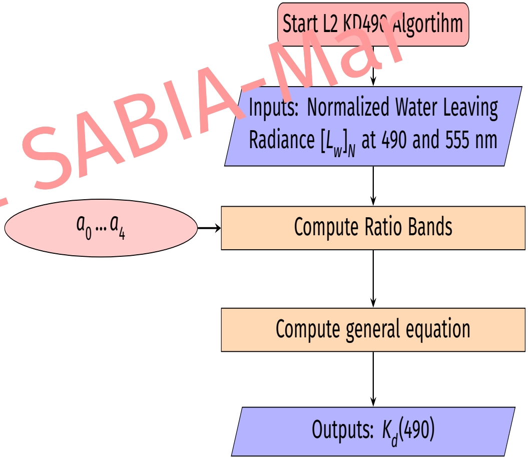
1. J.L. Mueller. Seawifs algorithm for the diffuse attenuation coefficient k(490) using water-leaving radiances at 490 and 555nm. DRAFT SeaWiFS Postlaunch Calibration and Validation Analyses 3, Center for Hydro-Optics and Remote Sensing/SDSU, San Diego, California, 2000
2. H.R. Gordon and W.R. McCluney. Estimation of the depth of sunlight penetration in the sea for remote sensing. Applied Optics, 14:413–416, 1975.

Algorithm for SABIA-Mar

$$\boxed{K_d(490) = K_{dbio}(490) + 0.0166}$$

$$\log_{10}(K_{dbio}(490)) = \sum_{i=0}^{4} a_i \log_{10}^i \left(\frac{R_{rs}(\lambda_b)}{R_{rs}(\lambda_g)} \right) \quad (11)$$

$$\boxed{\textbf{For SABIA-Mar:} \; \lambda_b = 490, \lambda_g = 555}$$


Start L2 KD490 Algortihm

Inputs: Normalized Water Leaving Radiance $[L_w]_N$ at 490 and 555 nm

$a_0 \ldots a_4$

Compute Ratio Bands

Compute general equation

Outputs: $K_d(490)$

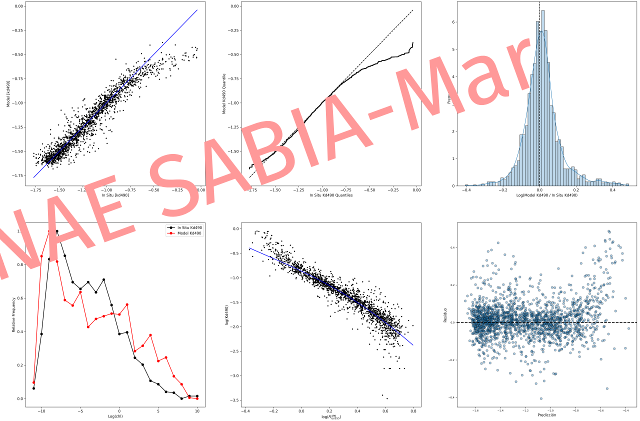
SABIA-Mar Kd(490)

- SABIA-Mar coefficients for KD2 algorithm:

a_0	a_1	a_2	a_3	a_4
-0.85	-1.83	1.87	-2.44	-1.07

- Statistics:

N	**R^2**	**RMS**	**slope**	**Bias**
1828	0.91	0.10	0.87	0.96



Photosynthetically Available Radiation (PAR)

- PAR: *Photosynthetically Available Radiation*
- Incident solar energy flux on the ocean surface, in the spectral interval [400,700]nm:

$$E_{\mathrm{PAR}} = \int_{400\ \mathrm{nm}}^{700\ \mathrm{nm}} E_d(\lambda) d\lambda$$

- Wavelengths involved in the chemical reactions of photosynthesis.
- Regulates the composition and evolution of marine ecosystems by controlling the growth of phytoplankton.
- It is very important to know the *spatial* and *temporal* distribution of PAR in the oceans.
- *Daily mean* PAR

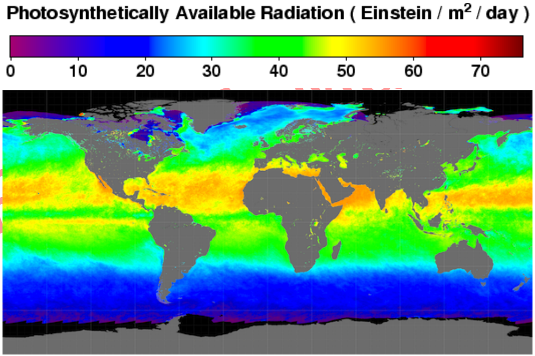


Figure: PAR for spring 2014 (MODIS Aqua)

PAR Theoretical Bases

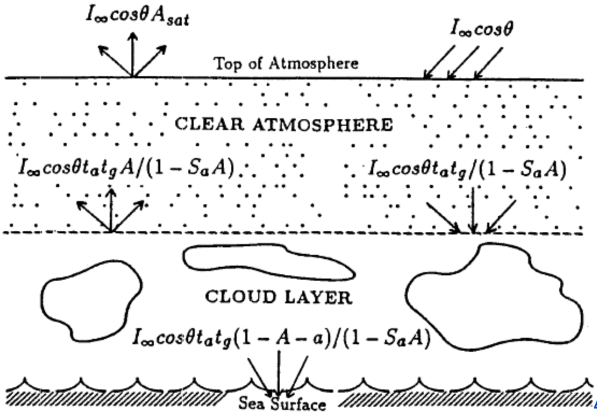
Asummptions:

- Plane-parallel theory
- Isotropy of radiance reflected by clouds and surface
- Effects of clouds can be decoupled from the effects of the clear atmosphere

Expression for Daily Mean PAR, $\overline{E}_s$:

$$\overline{E}_s = \overline{E}_0 \int_{\text{day}} \frac{\cos\theta_0\,\overline{t}_d\,\overline{t}_g(1-\overline{A})}{(1-\overline{A}_s)(1-\overline{S}_a\overline{A})}\,dt$$

Figure: R Frouin *et al* (1992) *Journal of Applied Meteorology and Climatology*, 31(9):1056–1066



PAR Theoretical Bases

Ministerio de Ciencia, Tecnología e Innovación

Gaseous transmittance:

$$\boxed{\bar{t}_{g\lambda} = \prod_i t_{i\lambda} = \prod_i \exp\left[-\alpha_{i\lambda}\left(\frac{U_i}{\cos\theta}\right)^{\beta_{i\lambda}}\right]}$$

Diffuse transmittance:

$$\boxed{t_{d\lambda} = \exp\left(\frac{\alpha\tau_{r\lambda} + \beta_\lambda\tau_{a\lambda}}{\cos\theta}\right)\exp\left(-\frac{\tau_\lambda}{\cos\theta}\right)}$$

Spherical albedo:

$$\boxed{S_{a\lambda} = \left(\alpha'\tau_{r\lambda} + \beta'_\lambda\tau_{a\lambda}\right)\exp\left(-\tau_\lambda\right)}$$

$\alpha_o = 0.052, \beta_o = 0.99, \alpha_v = 0.002, \beta_v = 0.87$

$\alpha = 0.52, \alpha' = 0.92, \beta_\lambda = 0.83, \beta'_\lambda = 0.33$

Cloud+system albedo:

$$\boxed{\overline{A} = F\left(\overline{\rho} - \overline{A_s}\right) + \overline{A_s}}$$

- F: simple bidirectional reflectance factor
- $\overline{A_s}$: obtained from LUTs
- $\rho = (\rho' - \rho_a)[t_d(\theta_s)t_d(\theta_v) + S_a(\rho' - \rho_a)]^{-1}$: cloud+system reflectance
  - ρ': correction for gaseous absorption
  - ρ^*: radiance converted into reflectance
  - ρ_a: instrinsic atmospheric reflectance

$$\boxed{\rho = \rho(L^*, \theta_s, \theta_v, U_o, \tau_{\text{mol}}, \tau_{\text{aer}}, P_{\text{mol}}, P_{\text{aer}}, \omega_{\text{aer}})}$$

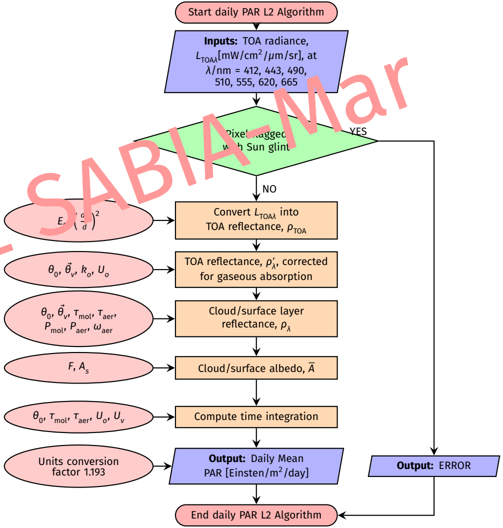
References:

1. R Frouin *et al* (1989) *Jour. of Geoph. Res.: Oceans*, 94(C7):9731–9742
2. D Tanré *et al* (1979) *Applied optics*, 18(21):3587–3594
3. R Frouin *et al* (2007) *Journal of oceanography*, 63(3):493–503, 2007

SABIA-Mar PAR algorithm

SABIA-Mar PAR algorithm

- Bands:
  - B7: 412 nm
  - B2: 443 nm
  - B4: 490 nm
  - B1: 510 nm
  - B3: 555 nm
  - B11: 620 nm
  - B8: 665 nm
- Modifications:
  - FORTRAN 77 → Python
  - 1 pixel → granule N × M
  - $\theta_v \rightarrow (\theta_v^{B0}, \theta_v^{B1}, \theta_v^{B2}, \theta_v^{B3}, \theta_v^{B4}, \theta_v^{B5}, \theta_v^{B6})$
  - $\phi_v \rightarrow (\phi_v^{B0}, \phi_v^{B1}, \phi_v^{B2} \phi_v^{B3}, \phi_v^{B4}, \phi_v^{B5}, \phi_v^{B6})$
  - Part of L2 Proccesor



Start daily PAR L2 Algorithm

Inputs: TOA radiance, $L_{TOA\lambda}$[mW/cm^2/μm/sr], at λ/nm = 412, 443, 490, 510, 555, 620, 665

Pixel flagged with Sun glint

YES

NO

$E_\lambda \left(\frac{d_0}{d}\right)^2$ → Convert $L_{TOA\lambda}$ into TOA reflectance, ρ_{TOA}

θ_0, $\vec{\theta}_v$, k_o, U_o → TOA reflectance, ρ'_λ, corrected for gaseous absorption

θ_0, $\vec{\theta}_v$, τ_{mol}, τ_{aer}, P_{mol}, P_{aer}, ω_{aer} → Cloud/surface layer reflectance, ρ_λ

F, A_s → Cloud/surface albedo, $\bar{A}$

θ_0, τ_{mol}, τ_{aer}, U_o, U_v → Compute time integration

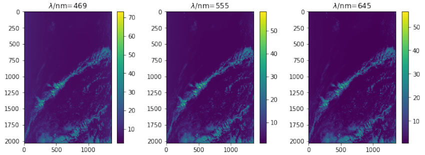
Units conversion factor 1.193 → **Output:** Daily Mean PAR [Einsten/m^2/day]

Output: ERROR

End daily PAR L2 Algorithm

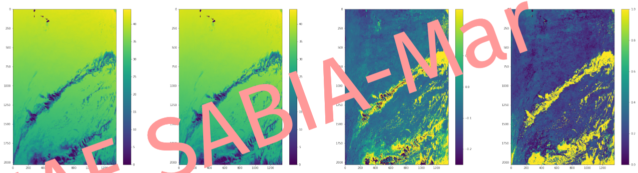
Pre-launch validation

Input: $L_{TOA\lambda}$ [mW/cm^2/μm/sr] (λ/nm = 469, 555, 645)



MODIS image (2030×1354= 2748620 pixels), obtained the 30/12/2021 at 15 hs. Includes latitudes and longitudes in ranges [13.53, 34.32] and [-43.44, -16.20] degrees.

Output: $PAR_{SABIA\text{-}Mar}$ and PAR_{SeaDAS}



$PAR_{SABIA\text{-}Mar}$, PAR_{SeaDAS}, ΔPAR, ΔPAR(%)

Statistic metrics:

	Bias	Median	σ	$p_{25\%}$	$p_{75\%}$
ΔPAR	-0.02	-0.07	0.32	-0.08	-0.02
ΔPAR(%)	-0.41	-0.19	6.27	-0.24	-0.07

Turbidity

Generalities

- Optical property of a liquid related to the *dispersion suffered by light due to the presence of suspended particles*: the greater the intensity of scattered light, the greater the turbidity
- Indirect indicator of the *concentration of suspended solids in water* and is measured in FNU (*Formazin Nephelometric Units*)
- Parameter used to monitor *water quality*:
  - high concentrations of particulate matter can affect the penetration of light and therefore, the habitat of aquatic fauna
  - particles provide sites to attach contaminants such as metals and bacteria

La Plata River case

It is estimated that the amount of sediment transported by the **La Plata River** varies between *80 and 160 million tons per year*, making it one of the **most turbid rivers in the world** with SPM values of between 10 and 500 mg/l.

Dogliotti’s empirical model

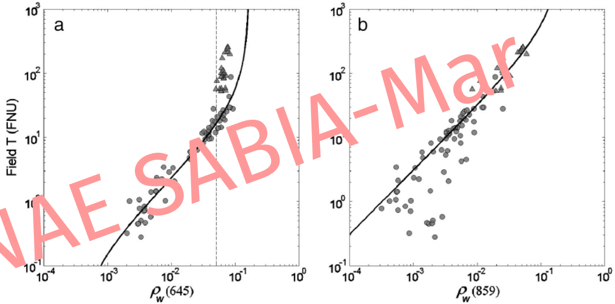
General Idea:
use specific bands for high and low turbid waters cases

Turbidity	**λ/nm**
High	859
Low	645

$$\boxed{T_\lambda = \frac{A_T^\lambda \rho_w(\lambda)}{1 - \rho_w(\lambda)/C^\lambda} [\mathrm{FNU}]}$$

- C^λ: determined only for particle type (IOPs)
- A_T^λ: obtained with non-linear regression of in situ measurements.

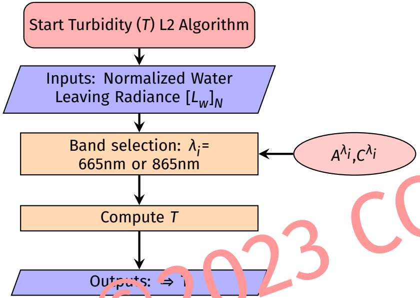
Northern Sea 2007-2010 (◦) y Scheldt estuary 2010 ()



$$T_\lambda = \begin{cases} T_{645} & \rho_w(645) \leq 0.05 \\ T_{859} & \rho_w(645) \geq 0.07 \\ (1-w)T_{645} + wT_{859} & 0.05 < \rho_w(645) < 0.07 \end{cases}$$

$$w = 50\left(\rho_w(645) - 0.05\right)$$

SABIA-Mar Turbidity algorithm



Start Turbidity (*T*) L2 Algorithm

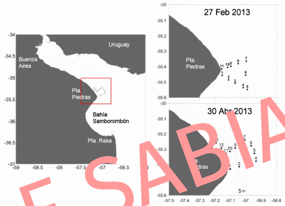
Inputs: Normalized Water Leaving Radiance $[L_w]_N$

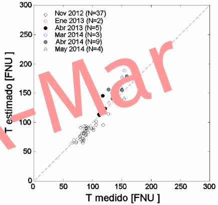
Band selection: λ_i= 665nm or 865nm

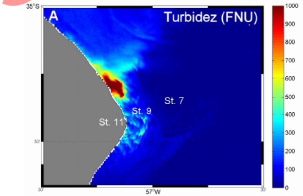
$A^{\lambda_i}, C^{\lambda_i}$

Compute *T*

Outputs: ⇒ T





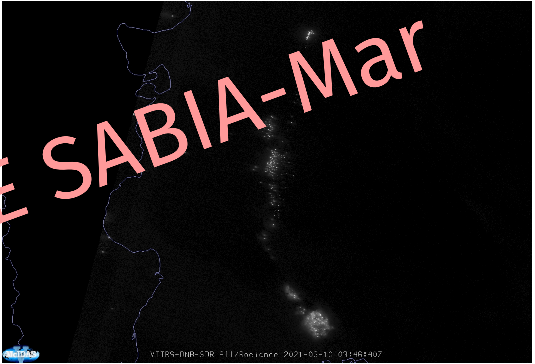


MODIS-A 27 Feb 2013

Preliminary evaluation of the algorithm with in situ measurements in Muelle de los Pescadores (CONAE-IAFE) for the determination of calibration coefficients A_T^λ y C^λ.

Night boats detection: Problem statement

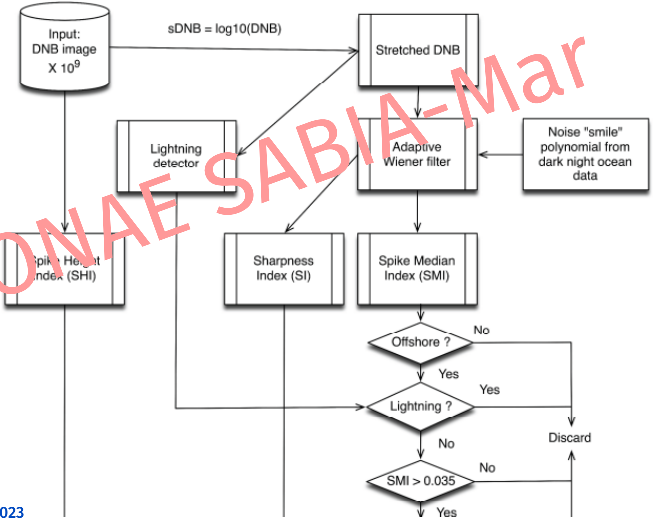
- One of the objectives of the SABIA-Mar Mission is to provide information and value-added products for studies related to management of fishery resources, with special focus in the Argentinian sea.
- Fishing boats are mainly between 50–60 m of longitude, and carry 120–150 incandescent lamps (2 kW) at both sides of the deck, which amount for 240-300 kW.
- This information is collected by sensors that measure low light imaging data in spectral bands covering emissions generated by electric lights



Images S-NPP from 11/03/2021 of the Argentine sea

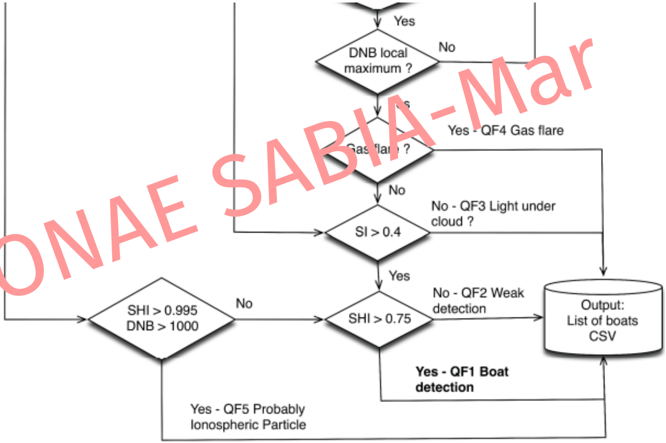
Flowchart

- The algorithm receives a HSC image data.
- There are three pre-processing steps
  1. Multiply the HSC radiances by a billion (nanowatts).
  2. Improve the contrast of features by taking the logarithm of the HSC radiances
  3. Flatten noise levels across the swath using an adaptive Weiner filter.
- Calculate Spike Median Index (SMI)
- Calculate Sharpness Index (SI)
- Calculate Spike Height Index (SHI)



Flowchart

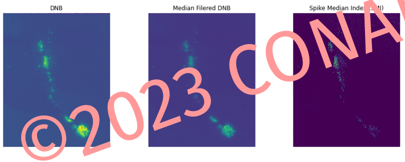
- Use thresholding to select a value of threshold for SMI.
- For each detection, the algorithm returns date, time, latitude/longitude, radiance, SMI, SHI and SI values. Each detection has a ”quality flag” rating: strong detections, weak detections, fuzzy detections, gas flares and energetic particles.



Example

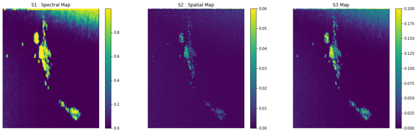
$$\boxed{SMI = RadLog - RadLogMedFilt}$$

- RadLog is the original image with a preprocessing applied.
- RadLogMedFilt is a filter by the median of each pixel in a 3x3 range.



Images S-NPP from 11/03/2021 of the Argentine sea

- **SI** is an index calculated following the algorithm described in the work of Vu (2009) ”S3: A Spectral and Spatial Sharpness Measure”



Images S-NPP from 11/03/2021 of the Argentine sea

SABIA-Mar L3 products

Temporal and Spatial resolutions for L3 products

		Binned & Mapped
Variables		$[L_w]_N$ & R_{sr}, Chl-a, FLH, Turbidity, K_d, PAR
Temporal Resolution	Global	Daily, 8-day, monthly, seasonal, annual
	Regional	Daily, 8-day, monthly, seasonal, annual
Spatial Resolution	Global	2.32km, 4.64km
	Regional	0.46km

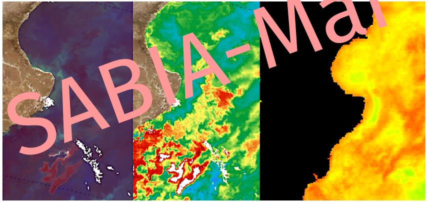
	Binned		**Mapped**		
	0.46 km	**2.32 km**	**0.46 km**	**2.32 km**	**4.64 km**
Daily	Regional	Global	Regional	Global	Global
8-Days	Regional	Global	Regional	Global	Global
Monthly	Regional	Global	Regional	Global	Global
Seasonal	Regional	Global	Regional	Global	Global
Annual	Regional	Global	Regional	Global	Global

SABIA-Mar L3 products

The Level 3 data products

- Are defined in concordance of CEOS and NASA's definition: derived geophysical variables that have been aggregated/projected onto a well-defined spatial grid over a well-defined time period. For each L2 product, two kind of L3 products shall be generated.

Brazil-Malvinas Confluence zone

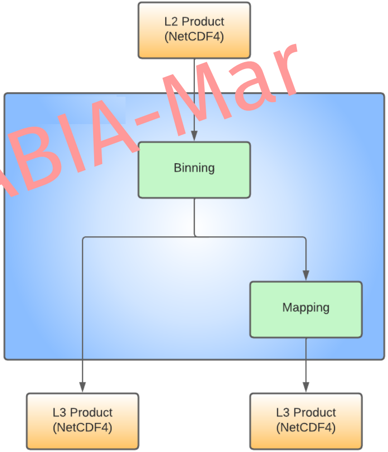


This image of the Brazil-Malvinas Confluence zone is a combined image displaying the dynamic biological and physiological oceanographic processes occurring off the coast of Argentina and Uruguay. Extracted from: Ocean Color website.

SABIA-Mar L3 products flowchart

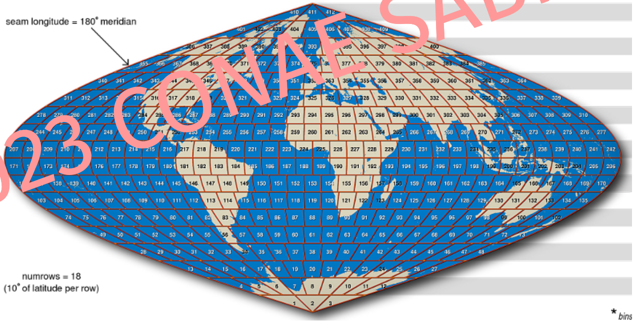
Data products

- Binned: accumulated data for all Level-2 products in a product suite, for the specified instrument and resolution, corresponding to a period of time (e.g. daily, 8 days, monthly, etc.) and stored in a global, nearly equal-area, integerized sinusoidal grid.
- Mapped: the Standard Mapped Image (SMI) products are created from the corresponding Level-3 binned products. Each SMI file contains a Plate Carreé, pixel-registered grid of floating-point values (or scaled integer representations of the values) for a single geophysical parameter.



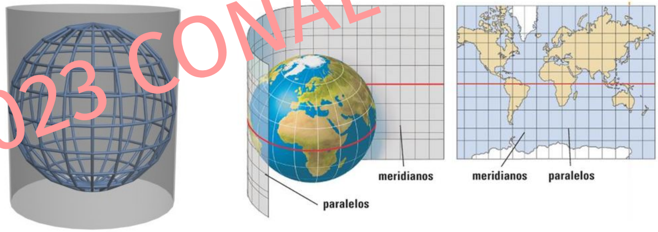
L3: binning method

This method is based on a sinusoidal map projection which is a pseudocylindrical equal-area map projection, sometimes called the Sanson–Flamsteed or the Mercator equal-area projection. A modification of it is used to divide the Earth into bins of roughly **equal area**. The area of the bin is chosen depending on the characteristics of the data set. The binning scheme has to accomplish with some basic features:



L3: mapping method

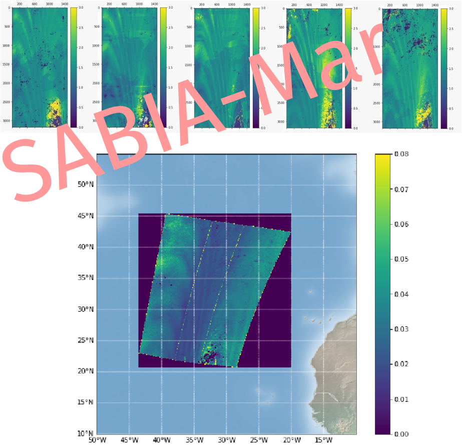
The Level-3 standard mapped image (SMI) products or mapped L3 products, are image representations of binned data products. The data in each SMI product represents an image of the parameter specified by the global attribute Parameter. This object is a two-dimensional array, which usually uses Equidistant Cylindrical (also known as Plate Carrée) projection of the globe where each rectangular bin has the **same size, shape, and area**.



SABIA-Mar L3 products algorithm

Steps

- Divide the earth into squares (bins)
- Choose squares of 4 x 4 km (spatial resolution)
- For each bin statistics are accumulated.
- Two types of level 3 data are generated:
  - **binned:** spatial and temporal
  - **mapped:** created from the corresponding Level 3 binned products. Each SMI file contains a Plate Carreé, pixel-registered grid of floating-point values for a single geophysical parameter.



Chlorophyll-a concentration, binned and mapped products.

QUESTIONS?