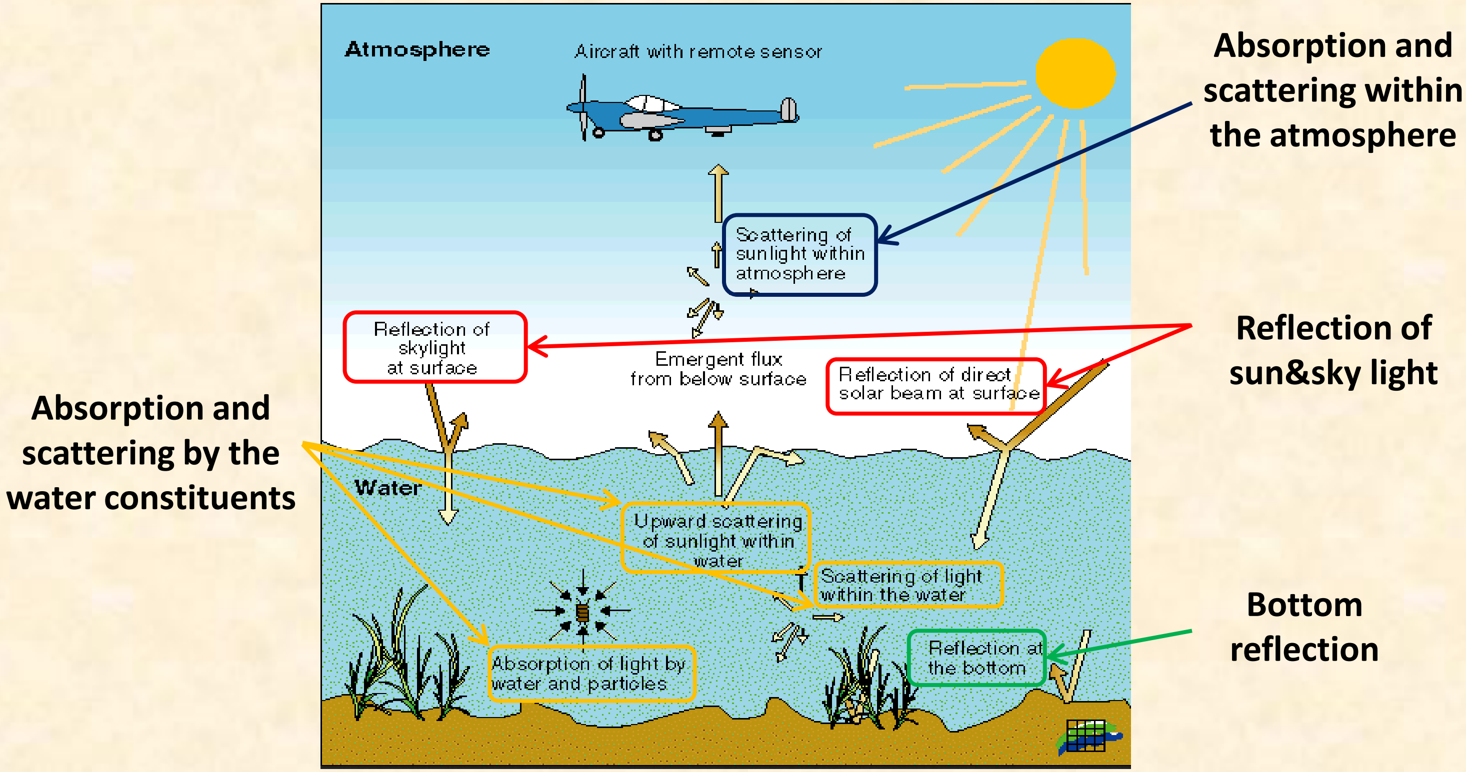
Hyperspectral remote sensing of coral reefs by semi-analytical model inversion
-
Comparison of inversion schemes

Tristan Petit [a], Touria Bajjouk [a], Pascal Mouquet [b], Sebastien Rochette [a], Benoit Vozel [c], Christophe Delacourt [b]

[a] Ifremer, DYNECO, Brest, France

[b] Université de Bretagne Occidentale, UMR CNRS 6538, Brest, France

[c] Université de Rennes 1, IETR UMR CNRS 6164, Lannion, France



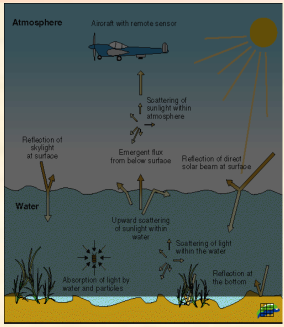
Bertels et al., 2008

GOAL : Retrieve **bottom depth** and **seabed types** from the sub-surface reflectance (i.e. after atmospheric and sea-surface corrections)

METHOD :

1. **Build a direct model** expressing the sub-surface reflectance as a function of the environmental conditions
2. **Inverse the direct model** so as to retrieve the desired bio-physical quantities

Direct model – Bottom reflectance



- **Linear mixing of four known endmembers**

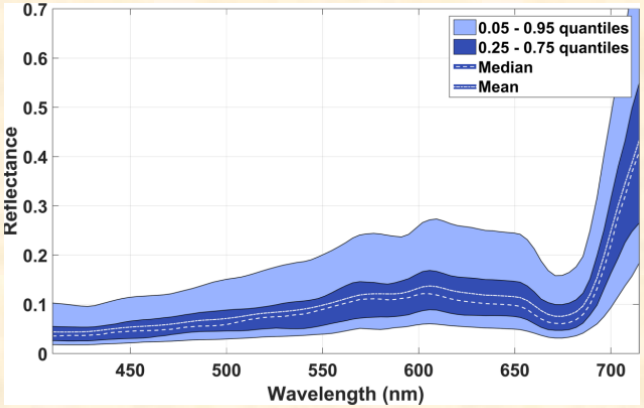
$$\boldsymbol{\rho}_B = [\boldsymbol{\rho}_{coral} \quad \boldsymbol{\rho}_{algae} \quad \boldsymbol{\rho}_{segrass} \quad \boldsymbol{\rho}_{sand}].\mathbf{x} = \mathbf{E}.\mathbf{x}$$

$\boldsymbol{\rho}_B$: Bottom reflectance (n x 1)
E : Endmember matrix (n x 4)
x : Abundance vector (4 x 1)
n : Number of spectral bands

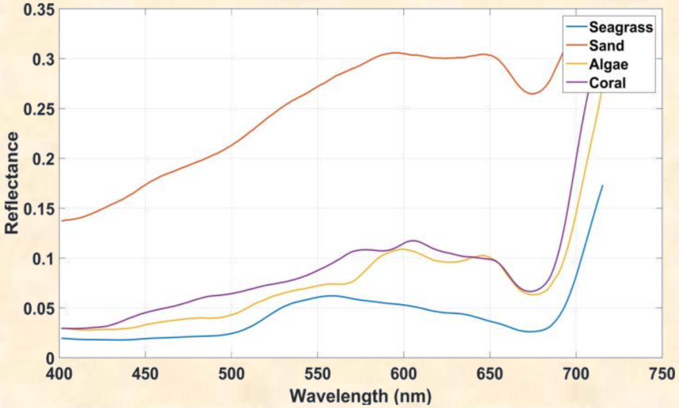
- **Endmember matrix construction**

1. ***In-situ* measurements enabled constituting a spectral library**
2. **Statistics were computed for each class of the spectral library**
3. **Mean spectrum of each class was retained as the corresponding endmember**

Reflectance measurment of a *Porites sp.*



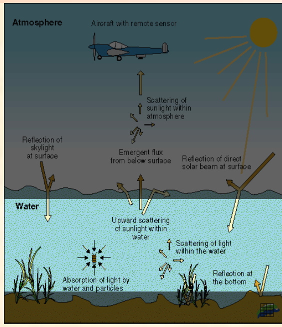
Submassive corals spectral statistics



Reflectances of the four retained endmembers

➡ **ρ_B expressed as a function of 4 unknowns, which are the abundances of coral, algae, seagrass and sand.**

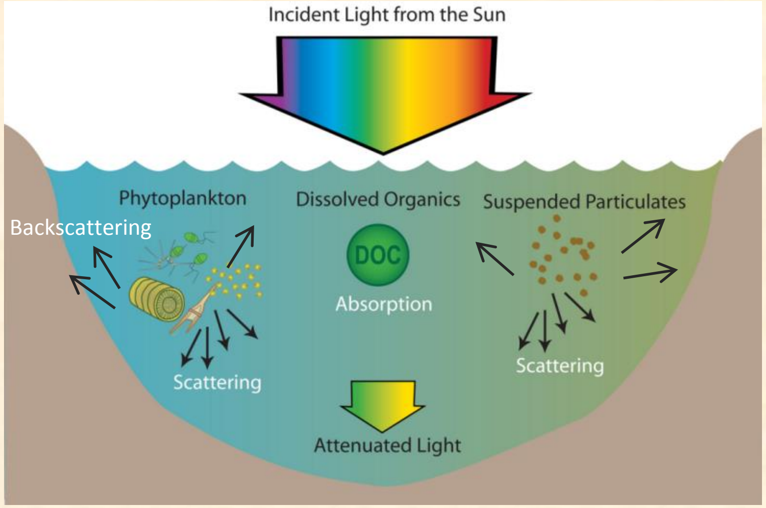
Direct model – Water column



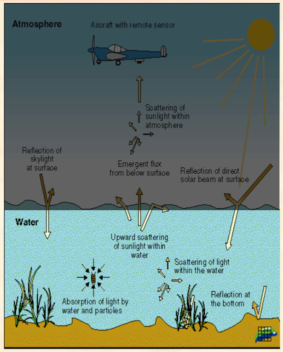
- **Four kinds of « optically active » water constituents**
  - Pure water
  - Colored dissolvec ordganic matter (CDOM)
  - Phytoplankton (phy)
  - Non algal particles (NAP)

  Concentration vector : $\mathbf{C} = [C_{phy} \quad C_{CDOM} \quad C_{NAP}]$

- **Two kinds of quantities modeled according to *Brando et al., 2009***
  - Water reflectance : $r_{rs}^{dw} = f_1(\lambda, \mathbf{C})$
  - Water diffuse attenuation : $\begin{cases} k_d = f_2(\lambda, \mathbf{C}) \\ k_u^C = f_3(\lambda, \mathbf{C} \\ k_u^b = f_4(\lambda, \mathbf{C}) \end{cases}$



Water column reflectance and diffuse attenuation coefficients expressed as functions of 3 unknowns, namely the concentrations of phytoplankton, CDOM and NAP



- **Surface reflecance model** (Lee et al., 1998)

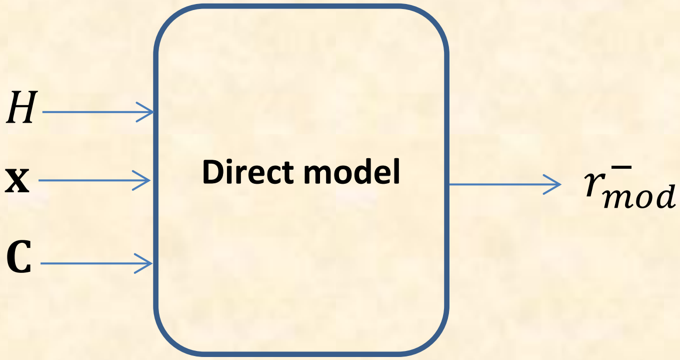
$$r_{mod}^{-}(\lambda) = r_{rs}^{dw}(\lambda)\left[1 - e^{-\left(k_d(\lambda)+k_u^C(\lambda)\right)H}\right] + \frac{1}{\pi}\rho_B(\lambda)e^{-\left(k_d(\lambda)+k_u^B(\lambda)\right)H}$$

r_{mod}^{-}: Modeled subsurface reflectance
H : Bottom depth

- ***A priori* inclusion**

$$r_{mod}^{-}(\lambda, H, \mathbf{x}, \mathbf{C}) = f_1(\lambda, \mathbf{C})\left[1 - e^{-(f_2(\lambda,\mathbf{C})+f_3(\lambda,\mathbf{C}))H}\right] + \frac{1}{\pi}\sum_i E_i(\lambda).x_i.e^{-(f_2(\lambda,\mathbf{C})+f_4(\lambda,\mathbf{C}))H}$$

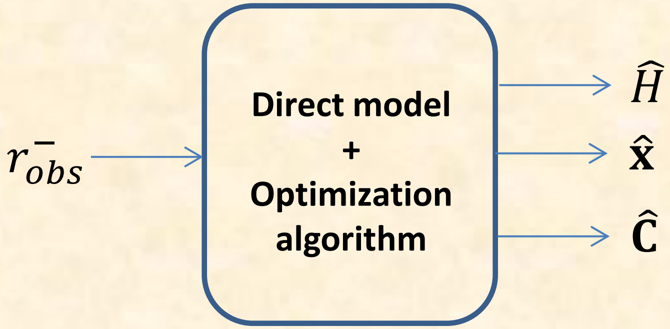
- **Direct model synoptic**



Subsurface reflectance expressed as a function of 8 scalars : bottom depth (H), four seabed abundances (x) and three water column constituent concentrations (C)

Model inversion – global formulation + counfounding factors

- **Inverse model synoptic**



- **Mathematical formulation**

$$[\hat{H} \quad \hat{\mathbf{x}} \quad \hat{\mathbf{C}}] = arg \min_{\mathbf{C},\mathbf{x},H} c\left(\bar{r}_{obs} ; \bar{r}_{mod}(H, \mathbf{x}, \mathbf{C})\right)$$
$$s.t \text{ some constraints}$$

Need to define a proper cost function c as well as relevant constraints on $\mathbf{C}$, $\mathbf{x}$ and H.

- **Issues that should be taken into account when choosing the cost function & optimization constraints :**
  - **Residual sun&sky sea surface reflections (low frequency additive noise)**
  - **Residual atmospheric effects (low frequency additive&multiplicative noise)**
  - **Amplitude variability of the seabed endmembers (flat multiplicative noise)**

Model inversion - Parametrization

- **Cost function**

  - **Least squares** ($c_{LS}(a;b) = \|a-b\|_2$)

    Most natural cost function for curve fitting but very sensitive to non zero-mean noise

  - **Spectral angle mapper** ($c_{SAM}(a;b) = \frac{\langle a,b \rangle}{\|a\|_2 . \|b\|_2}$)

    Robust to multiplicative low-frequency noise, but loses part of the information

  - **Least squares on first spectral derivative** ($c_{LSD}(a;b) = \left\|(a-b) * sg_{3,7}^{1}\right\|_2$; sg : savitsky-golay filter)

    Robust to additive low-frequency noise, but loses part of the information

- **Constraints on seabed abundances (x vector)**

  - **Abundance sum-to-one constraint (ASC: $\|\mathbf{x}\|_1 = 1$)**

    Strictly respects the physics of the problem under ideal conditions (perfect endmembers and linear mixture)

  - **Relaxed abundance sum-to-one constraint (RASC: $0.5 < \|\mathbf{x}\|_1 < 2$)**

    Can take into account part of the amplitude variability of the endmembers

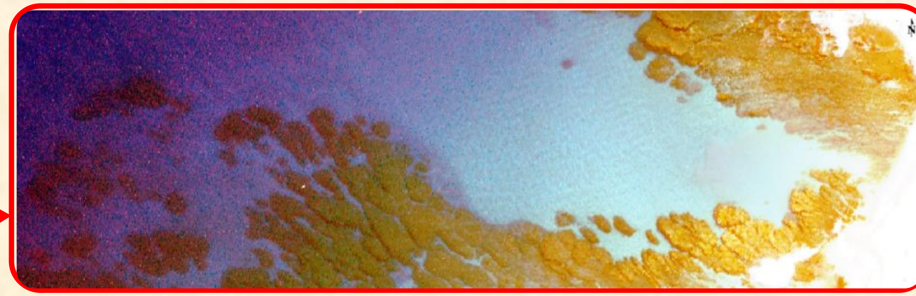
➡ **3 cost functions x 2 seabed constraints = 6 inversion schemes to be assessed**

Study sites

Indian Ocean Litto3d cruise : Flight lines of hyperspectral acquisitions over La Réunion

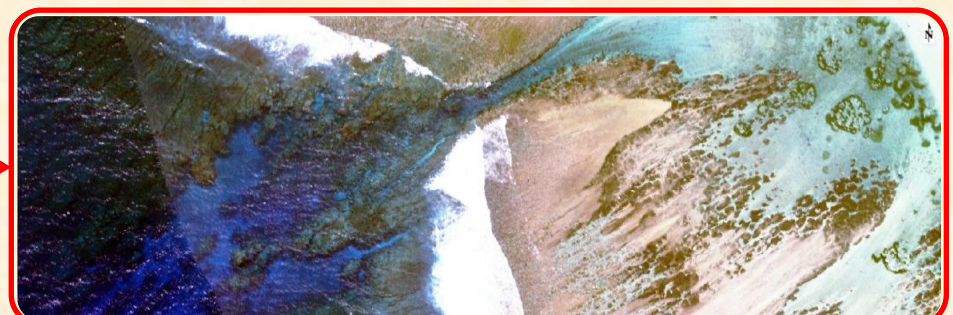
Flight lines over Saint-Gilles coastline

Boucan



- Homogeneous seabed
- Low bathymetric gradient

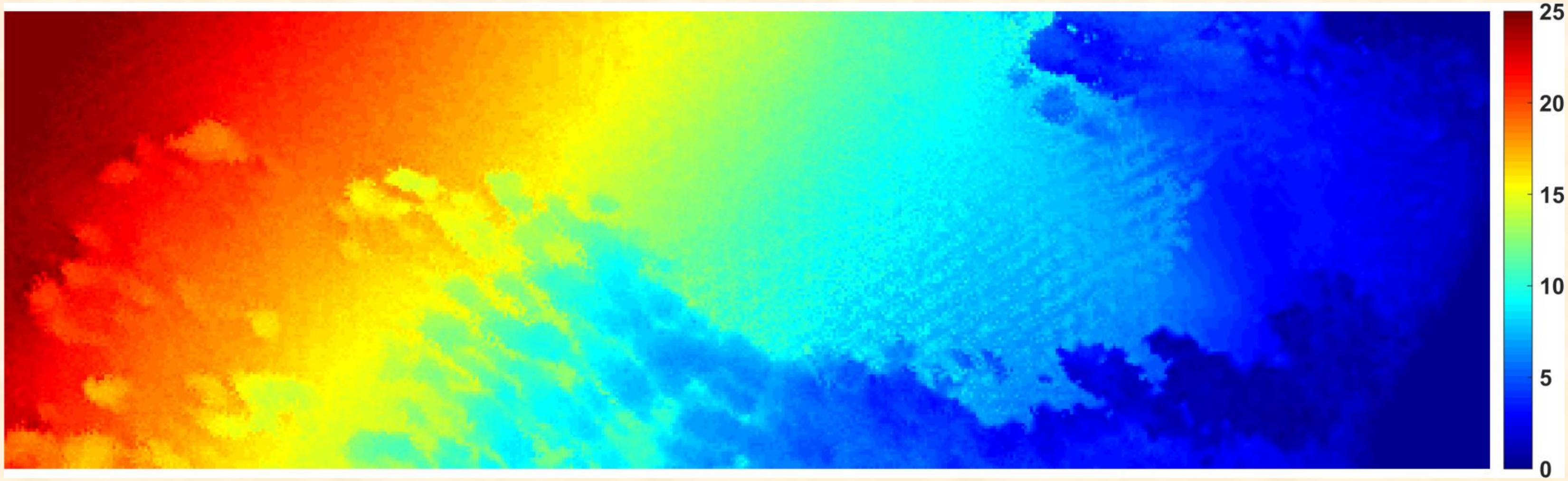
Ermitage



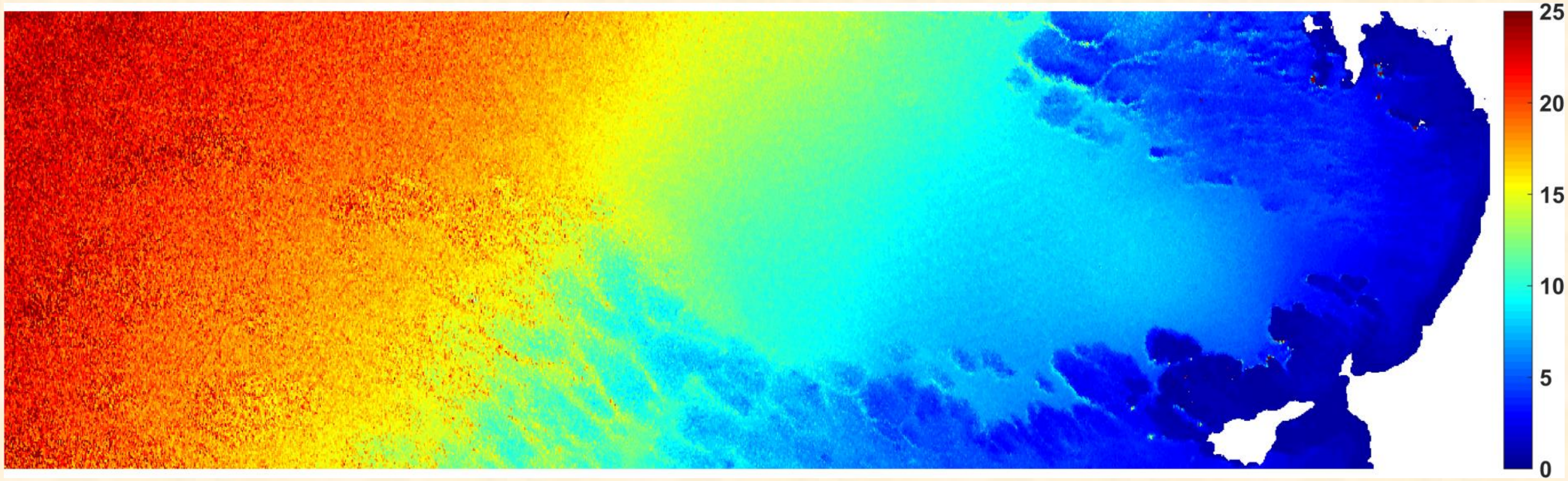
- Heterogeneous seabed
- Inner vs Outer reef

Results – Bathymetry on Boucan

- **Result example**
  - **LIDAR bathymetry**

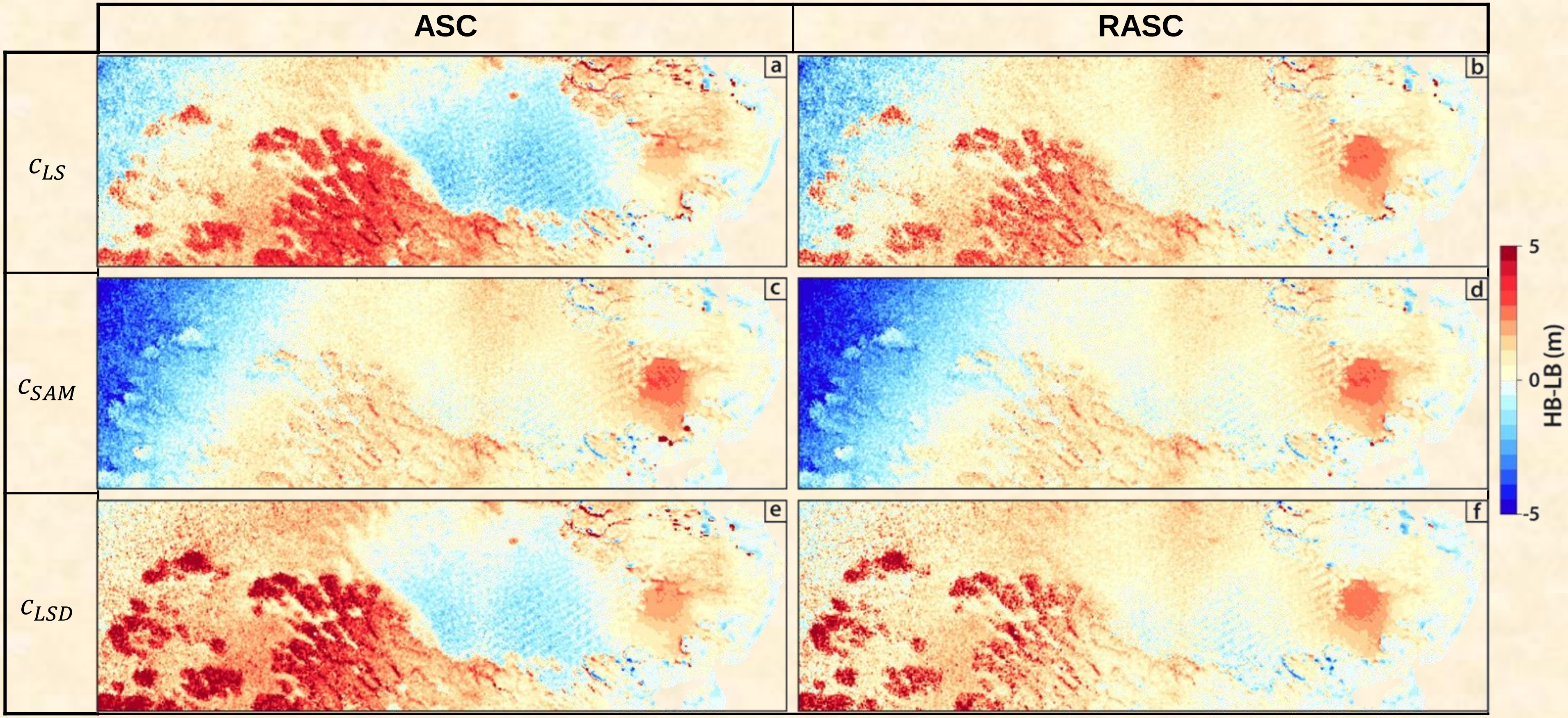


  - **Hyperspectral bathymetry (RASC-LS based inversion)**



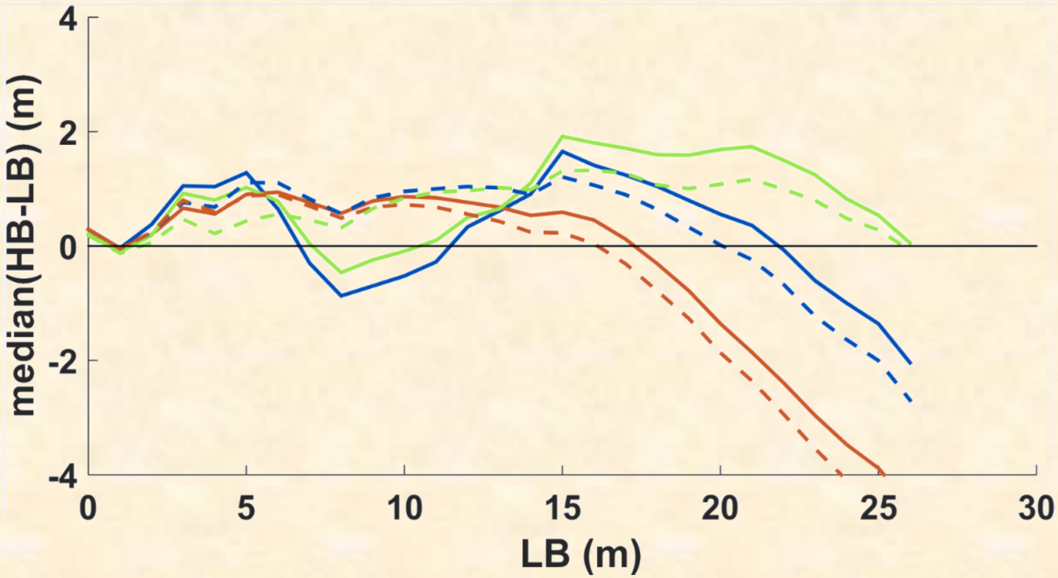
Results – Bathymetry on Boucan

- **Differential maps between hyperspectral and Lidar bathymetry (HB and LB)**



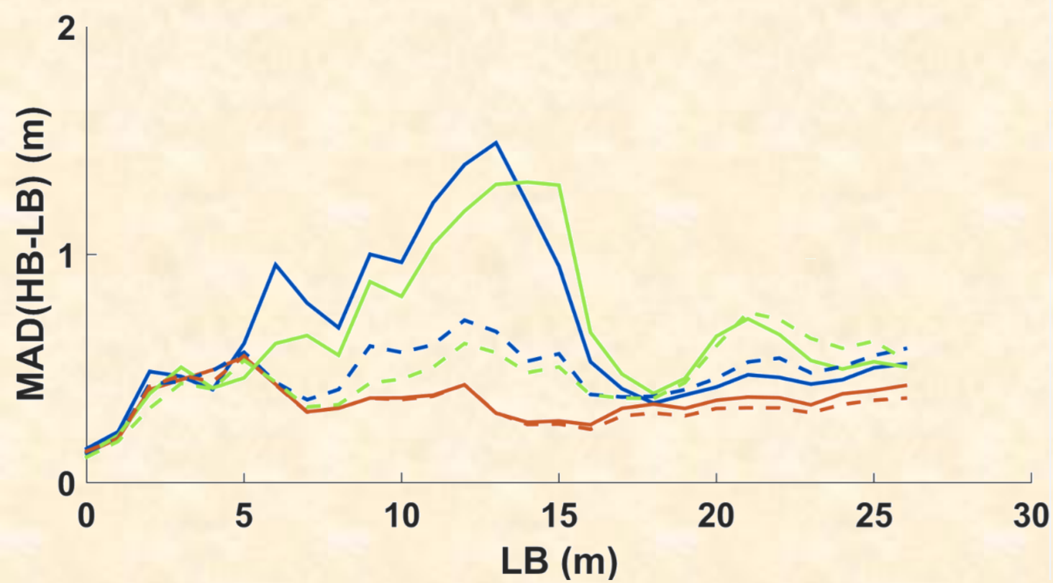
Results – Bathymetry on Boucan

- **Median estimation error**



- ➢ Interest of using LSD at high depths
- ➢ More stable estimation with RASC for LS&LSD cost functions

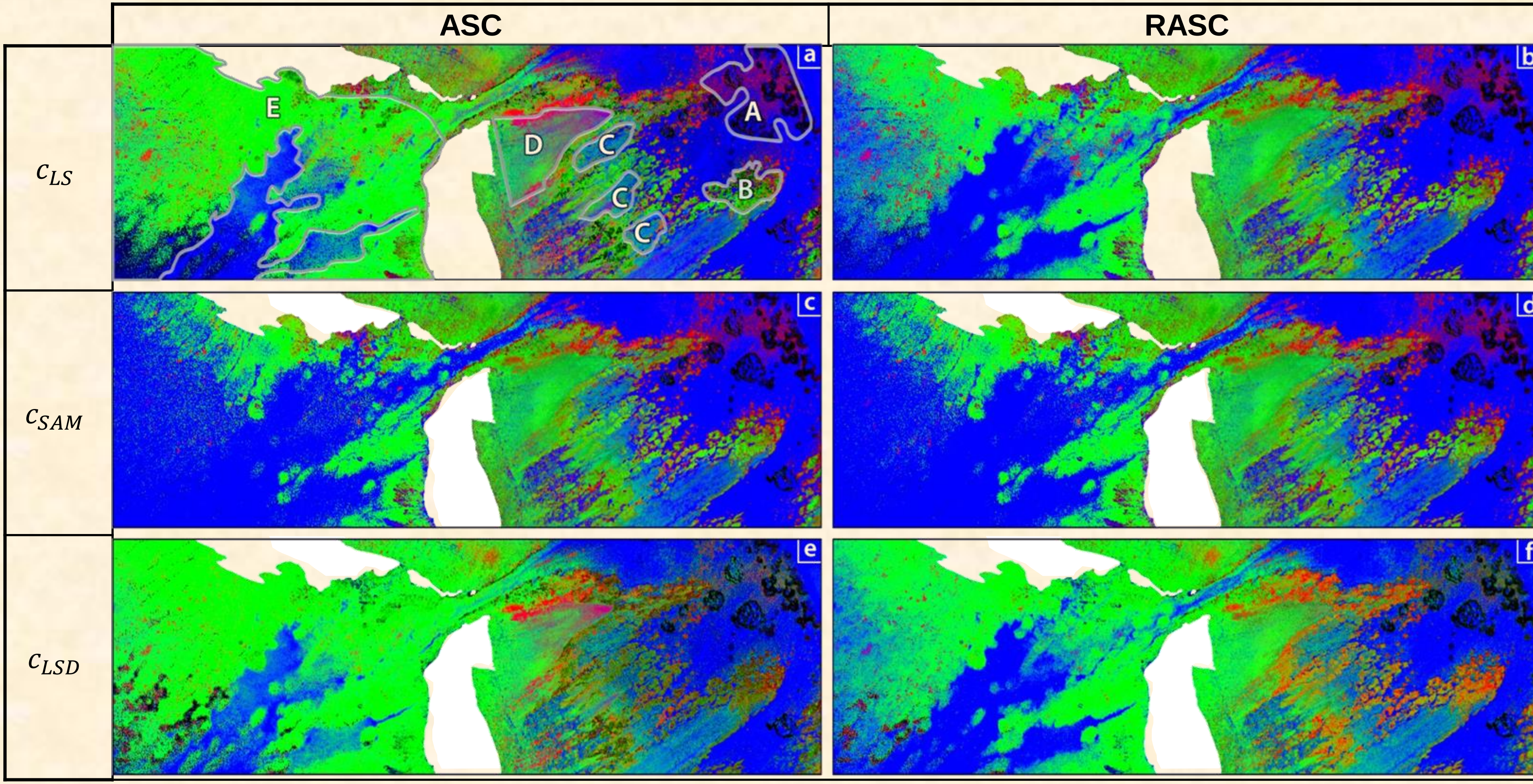
- **Median absolute deviation**



- ➢ SAM shows the lowest dispersion
- ➢ Very positive impact of RASC for LS&LSD cost functions

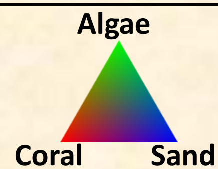
Results – Seabed type retrieval on Ermitage

- **Composite abundance maps (R=coral; G=algae; B=sand; darkness=seagrass)**



Outer reef (left part of the study site) :

- ASC enables differentiating seabed types deeper than RASC
- Inefficiency of SAM for mapping seabed in deep areas
- Instability issues with LSD in deep areas

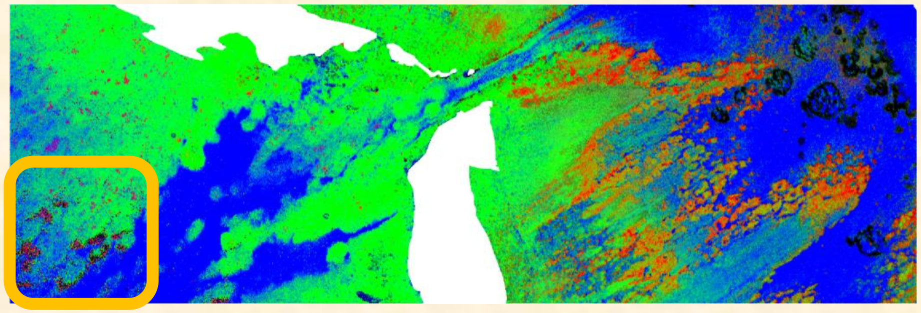


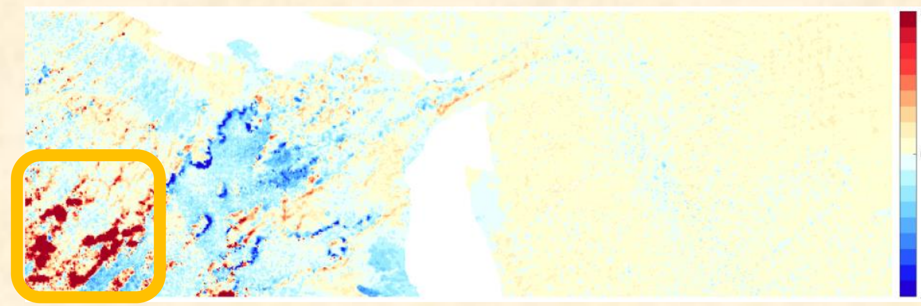
Inner reef (right part of the study site):

- Algae surrounding seagrass (zone A) correctly identified by LSD-based inversion schemes
- Enhancement of coral detection with RASC-LSD (e.g. zone B)

On the potential benefit of regularization...

- **Instability issue with RASC-LSD on deep area**





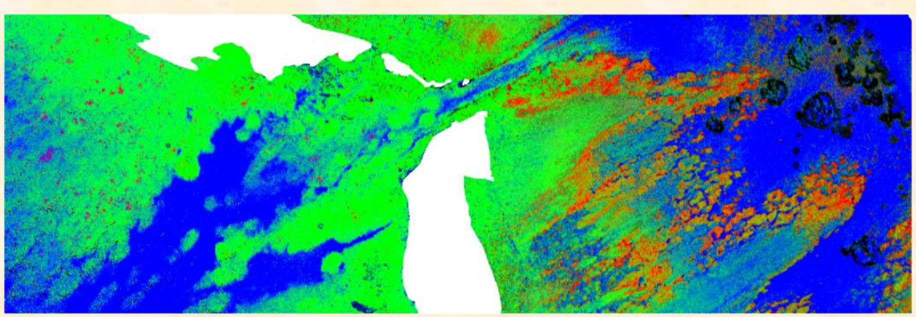
ill-conditioned problem ?

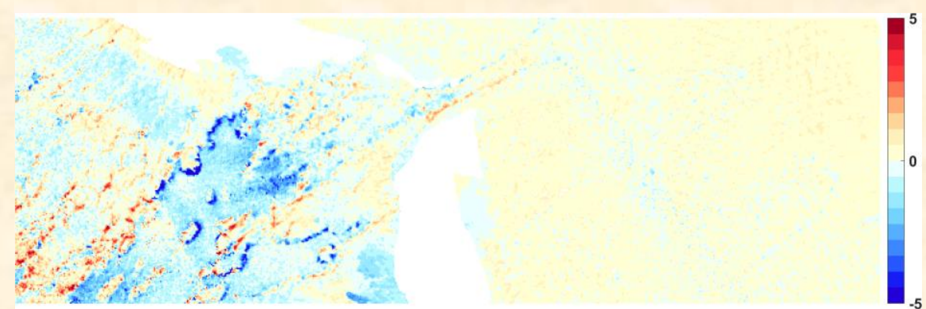
- **Addition of a regularization term to the cost function (*Jay&Guillaume, 2016*)**

$$c_{LSD}\left(r_{obs}^{-}; r_{mod}^{-}(H, \mathbf{x}, \mathbf{C})\right) = \left\|\left(r_{obs}^{-} - r_{mod}^{-}(H, \mathbf{x}, \mathbf{C})\right) * sg_{3,7}^{1}\right\|_2$$

$$c_{LSDR}\left(r_{obs}^{-}; r_{mod}^{-}(H, \mathbf{x}, \mathbf{C})\right) = \left\|\left(r_{obs}^{-} - r_{mod}^{-}(H, \mathbf{x}, \mathbf{C})\right) * sg_{3,7}^{1}\right\|_2 + \lambda . H$$

- **Results obtained with RASC-LSDR ($\lambda = 10^{-5}$)**





Conclusion

- Bathymetry
  - Great potential of hyperspectral imaging for predicting bathymetry down to 15-20 m depth
  - SAM was the least sensitive cost function to changes in seabed type
  - LSD cost function gave the best results at high depths
  - Use of RASC decreased error dispersion compared to ASC
- Seabed types
  - Very accurate results at low depths (<2 m) with RASC-LSD algorithm
  - SAM was not able to differentiate seabed types from ~5 m depth
  - ASC-LS provided the most consistent results at high depths
  - LSD-based inversion schemes suffered from instability issues at high depth

➡ **There is no optimal inversion scheme for estimating all the parameters at all the depths.**

➡ **Future work should focus on the formalization of prior knowledge into relevant regularization terms.**

Merci pour votre attention