How is Remote Sensing used to observe the oceans?

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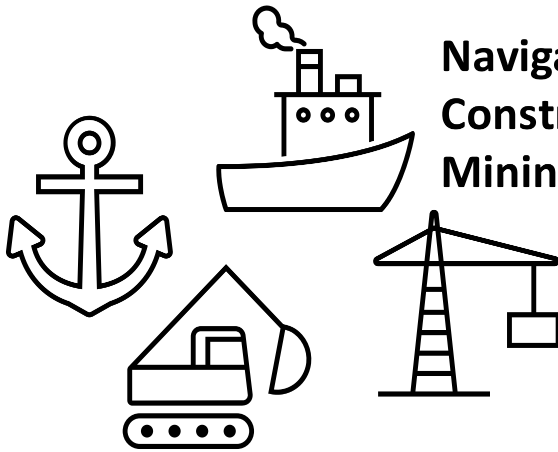
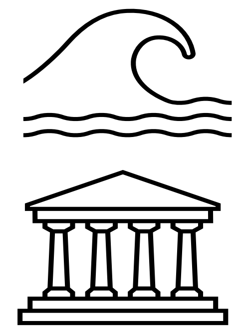
RSiM

RS platforms can "see the sea" in ways that are otherwise impossible

Why?



Navigation
Constructions
Mining

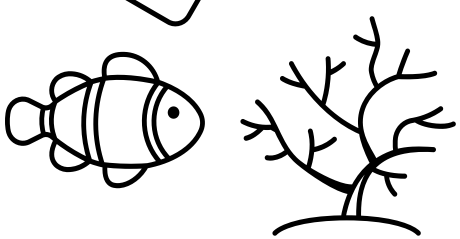


Cultural Heritage

Tourism

Marine litter detection

Support action for climate



Map/monitor marine animal forests

RSiM

What kind of platforms and data?

Satellites, occupied airborne or unoccupied airborne (drones)

- RGB+MS imagery
- LiDAR
- SAR Radar Altimeter
- Other special payload instruments (radiometers etc.)

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- **RGB+MS imagery**
- LiDAR
- SAR Radar Altimeter
- Other special payload instruments (radiometers etc.)

How can we get this information?

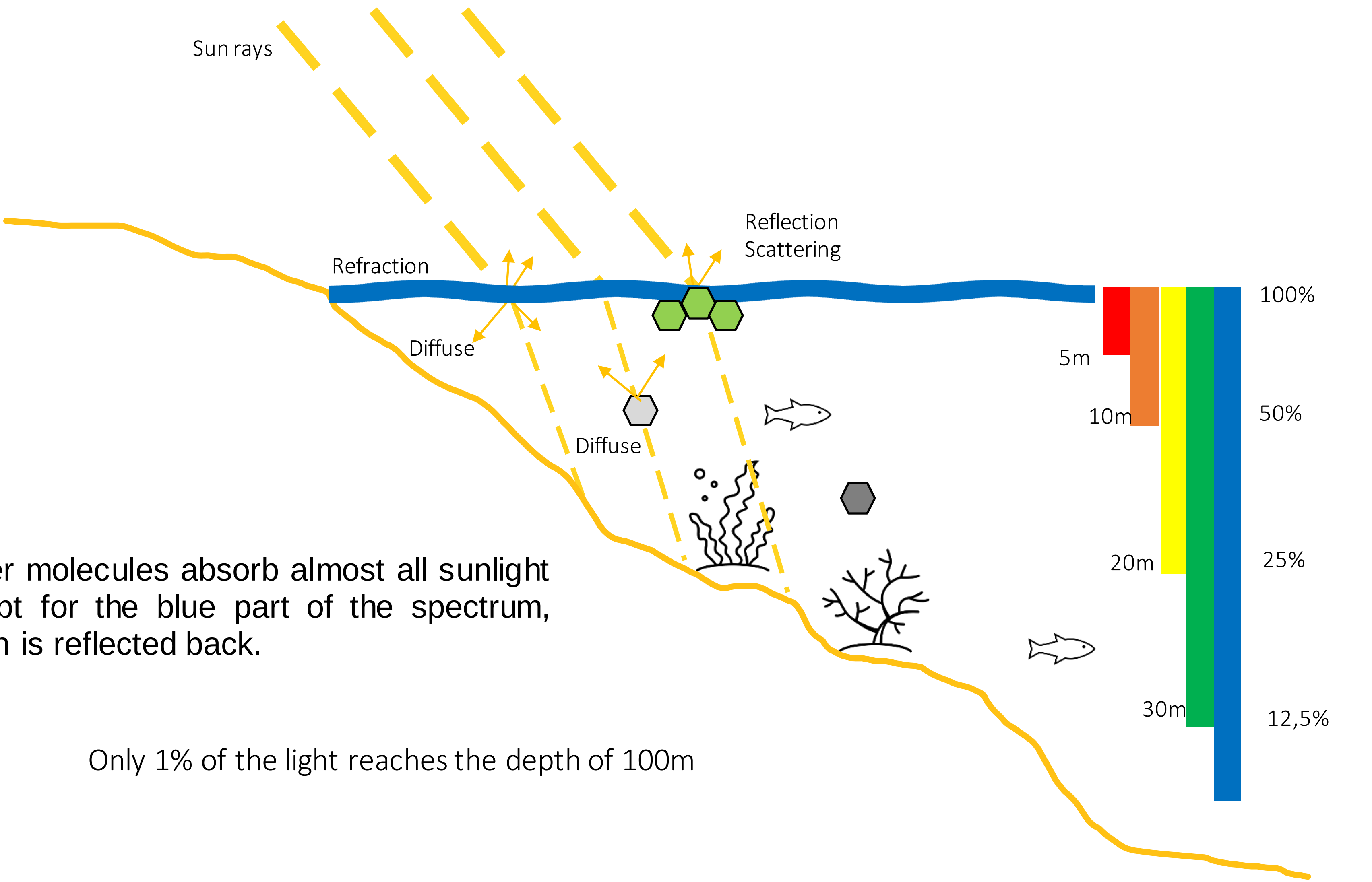
- **Exploiting the RADIOMETRIC information of the scenes**

- **Exploiting the GEOMETRIC information of the scenes**

What info can we get using RGB and MS Remote Sensing Ocean data?

- Biogeochemical indices (chlorophyll, nitrates)
- Sea ice coverage and state
- Sea surface temperature
- Marine debris detection/ tracking
- Pollution/ oil spill detection/ tracking
- Shallow water bathymetry
- Shallow seabed cover maps

Light absorption in water column



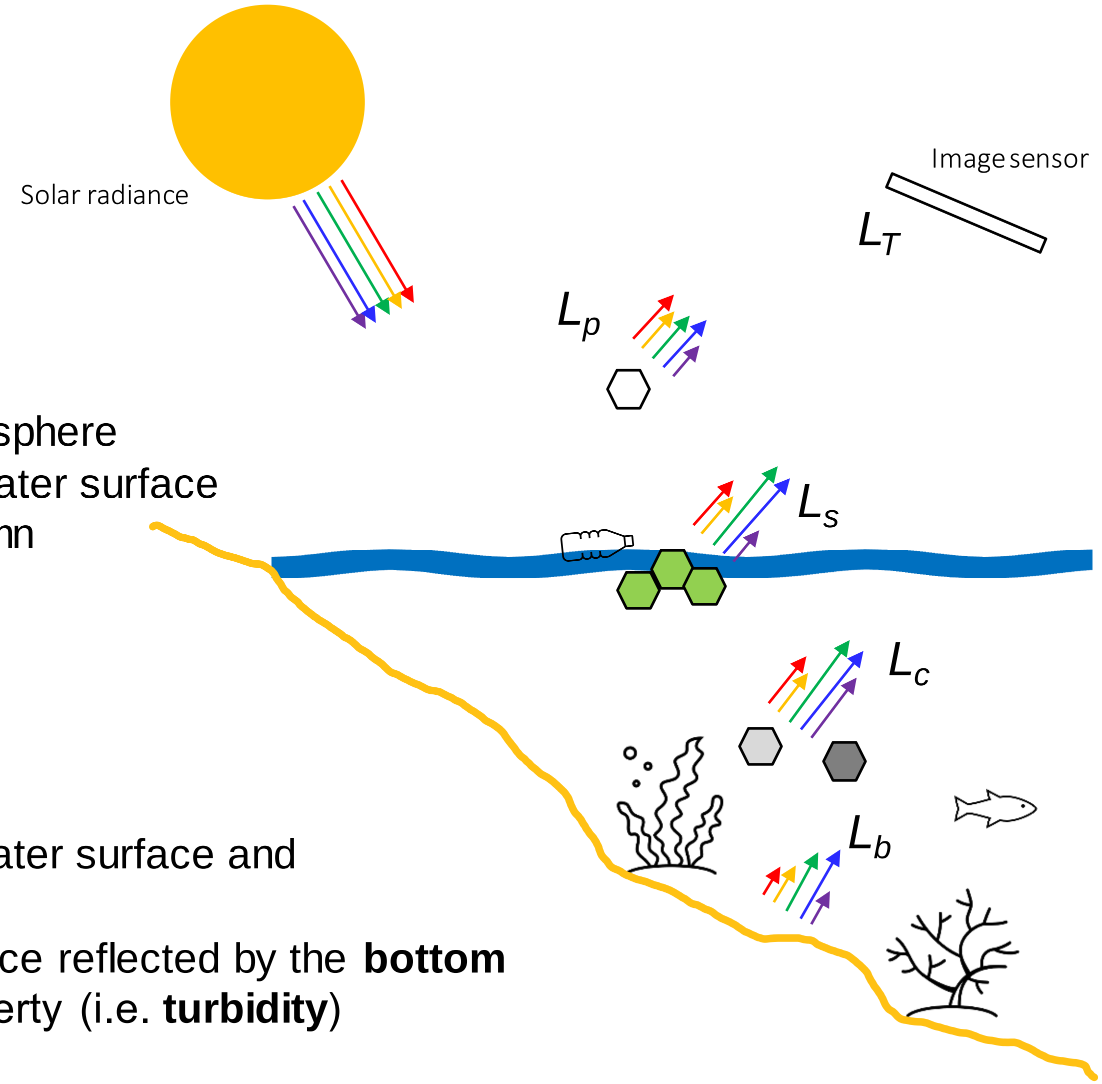
Water molecules absorb almost all sunlight except for the blue part of the spectrum, which is reflected back.

Only 1% of the light reaches the depth of 100m

Basics of Spectral-based methods

$$L_T(\lambda)=L_p(\lambda)+L_s(\lambda)+L_c(\lambda)+L_b(\lambda)$$

L_T is the total upwelling radiance
L_p are the contributions from the atmosphere
L_s is the radiance reflected from the water surface
L_c is the radiance from the water column
L_b is the bottom-reflected radiance



L_s depends on the roughness of the water surface and sun position (**sun glint**)
L_b is related to **depth** and is the radiance reflected by the **bottom**
L_c is related to the water's optical property (i.e. **turbidity**)

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Biogeochemical indices

$$L_T(\lambda)=L_p(\lambda)+L_s(\lambda)+L_c(\lambda)+L_b(\lambda)+\boldsymbol{L(\lambda)}$$

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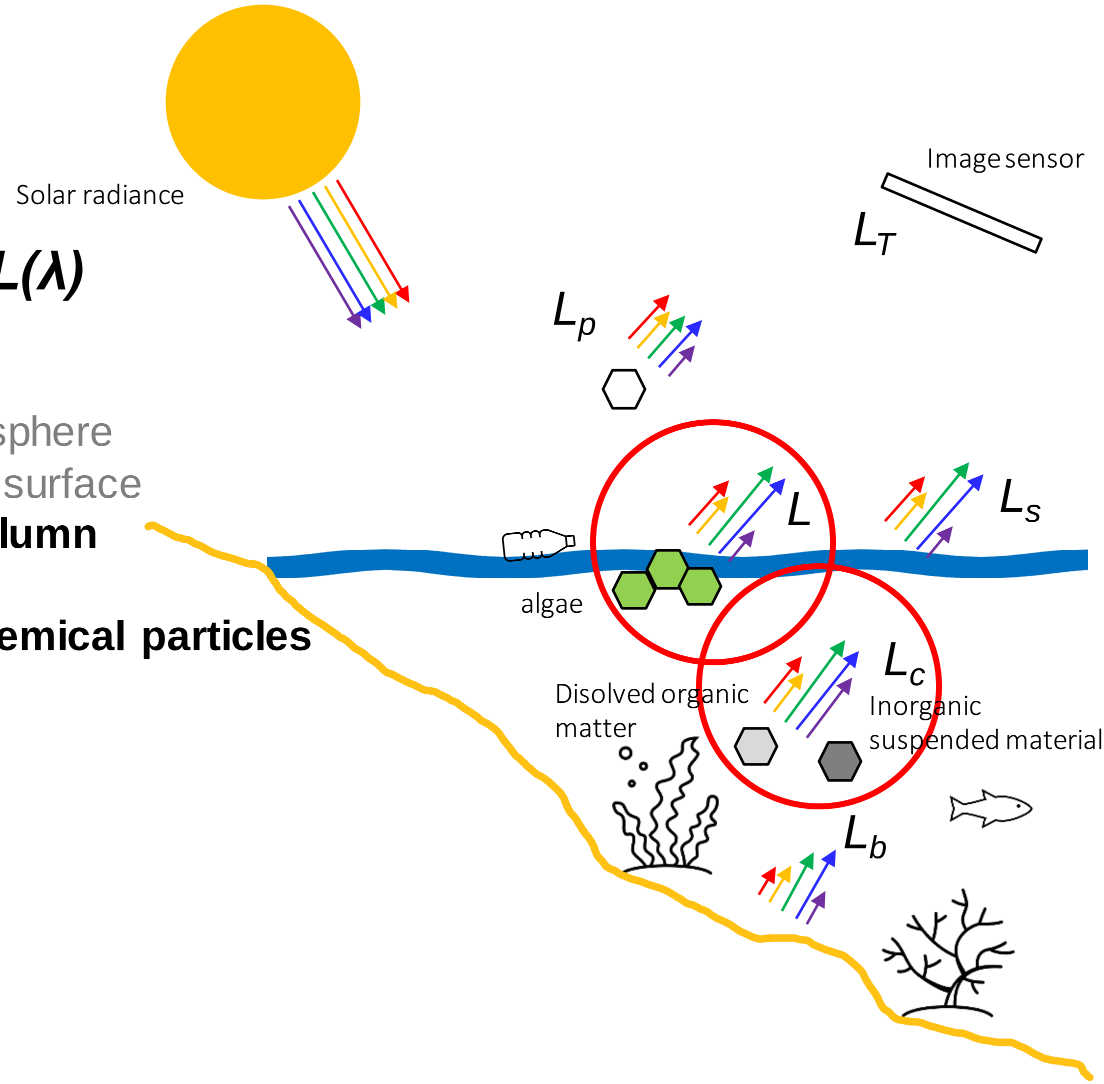
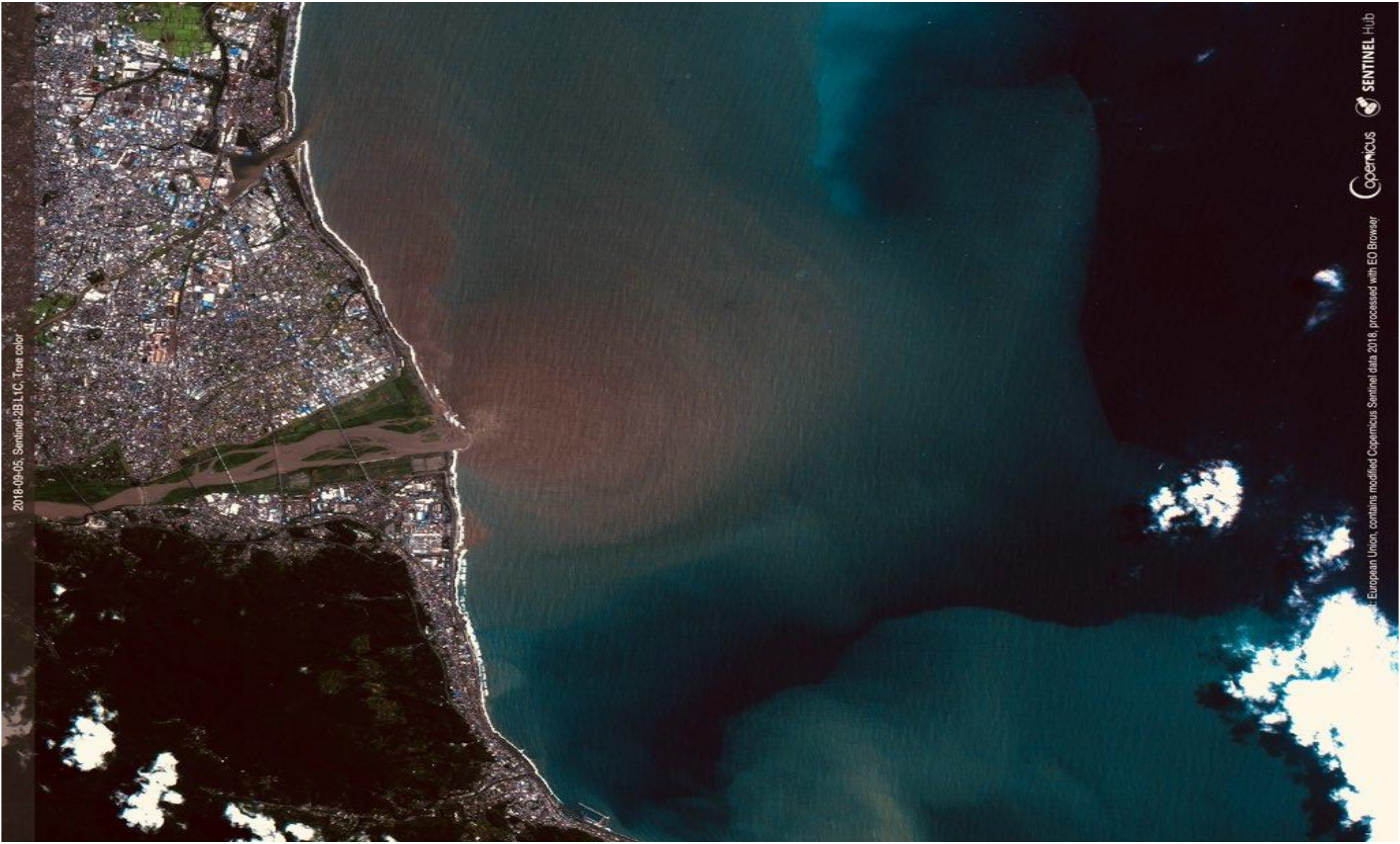
L_b is the bottom-reflected radiance
L is the radiance from the biogeochemical particles



Chlorophyll (algae)

Suspended matter (turbidity)



Get biogeochemical indices

How?

Empirical algorithms

Statistically relate measurements of i.e. chlorophyll (CHL) or suspended matter and reflectance through regression, polynomial expressions or **Artificial Neural Networks**

Widely used bands:

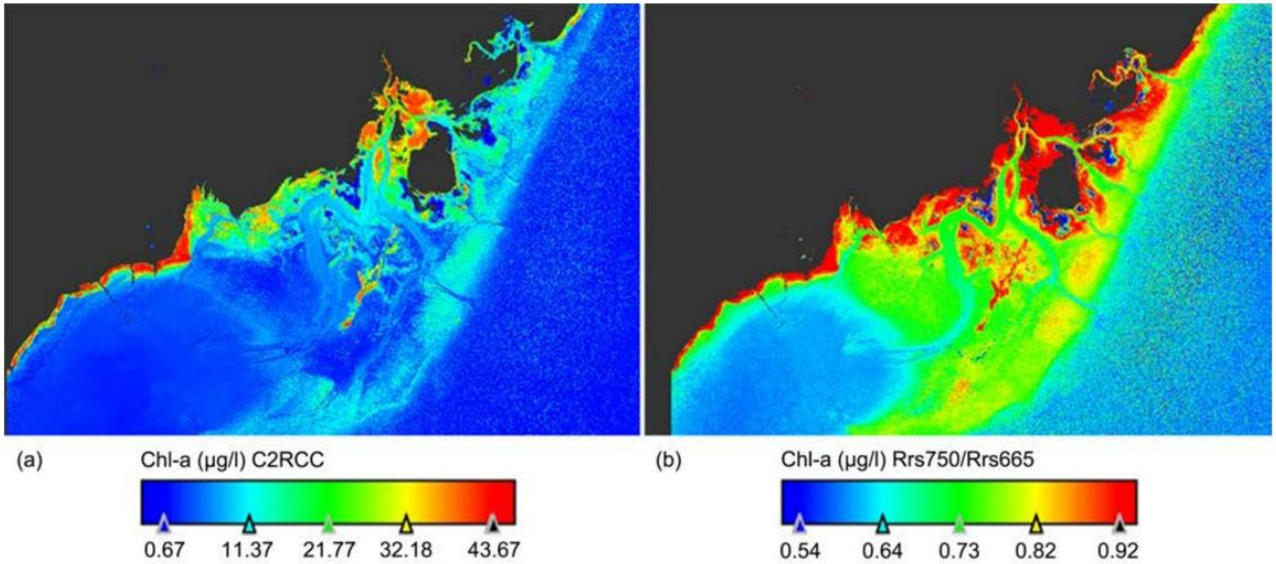
- Chlorophyll: Red, green and visible and near infrared (VNIR) bands
- Suspended matter: Red band

Semi-analytical algorithms

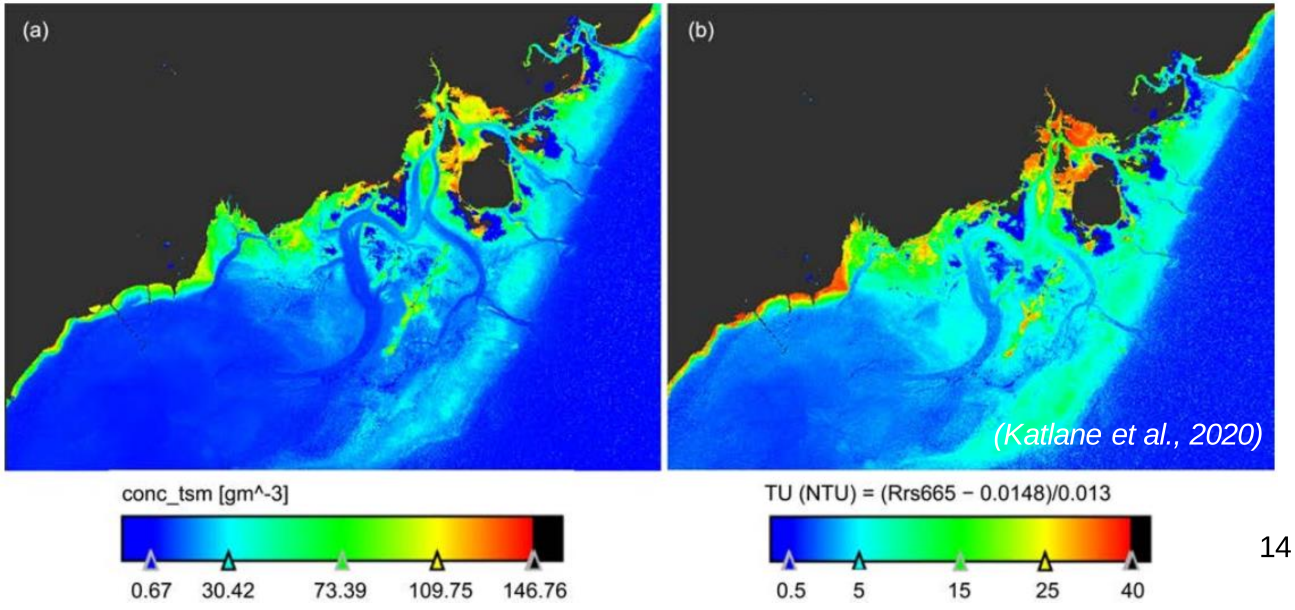
Estimate CHL via spectral absorption of phytoplankton, spectral backscattering by particles & the combined absorption by non-algal particles and colored dissolved organic material *(O'Reilly et al., 2019)*

Examples

Chlorophyll



Suspended matter



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Sea ice

$$L_T(\lambda)=L_p(\lambda)+L_s(\lambda)+L_c(\lambda)+L_b(\lambda)+\mathbf{L(\lambda)}$$

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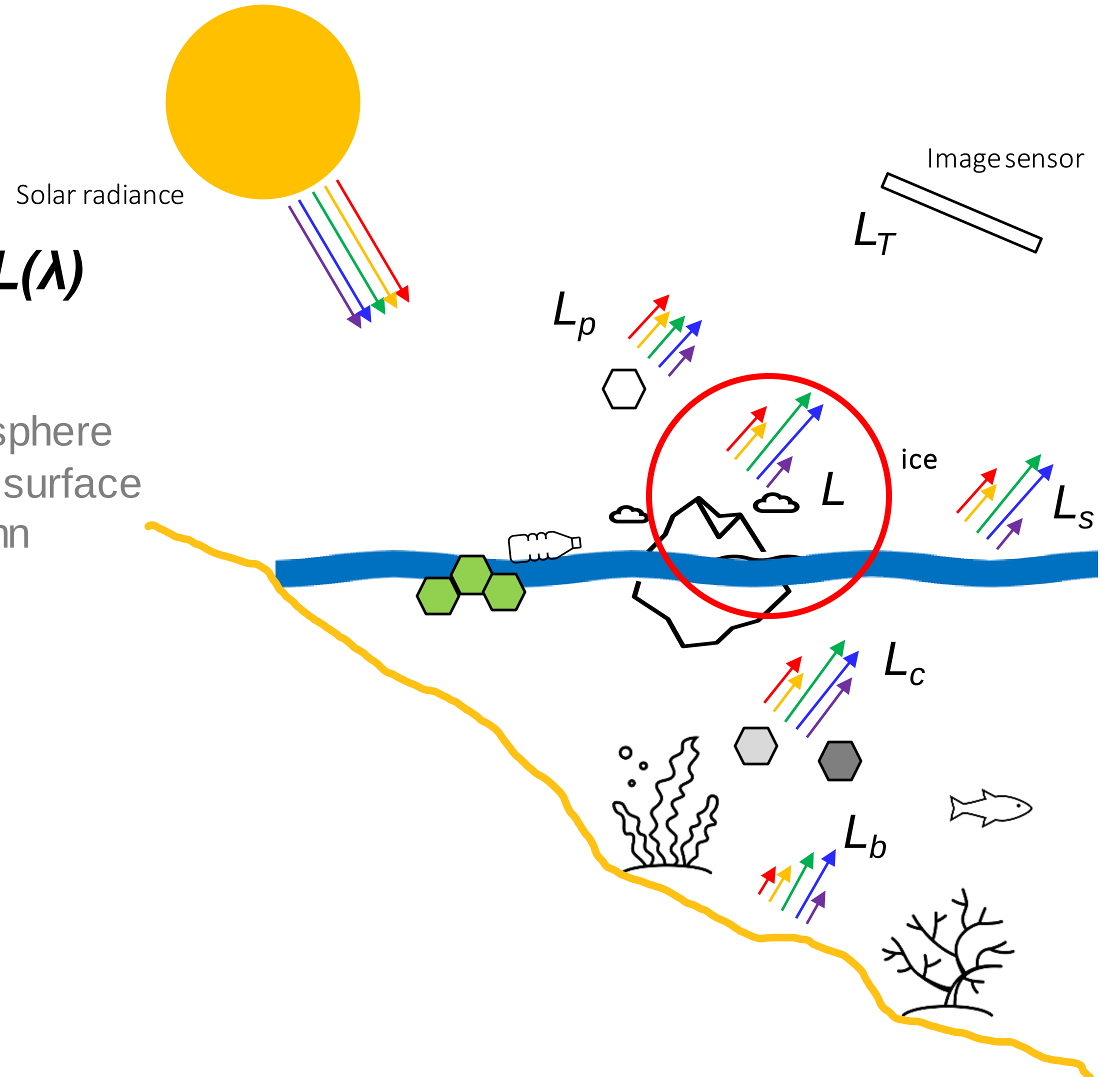
L_b is the bottom-reflected radiance
L is the ice-reflected radiance



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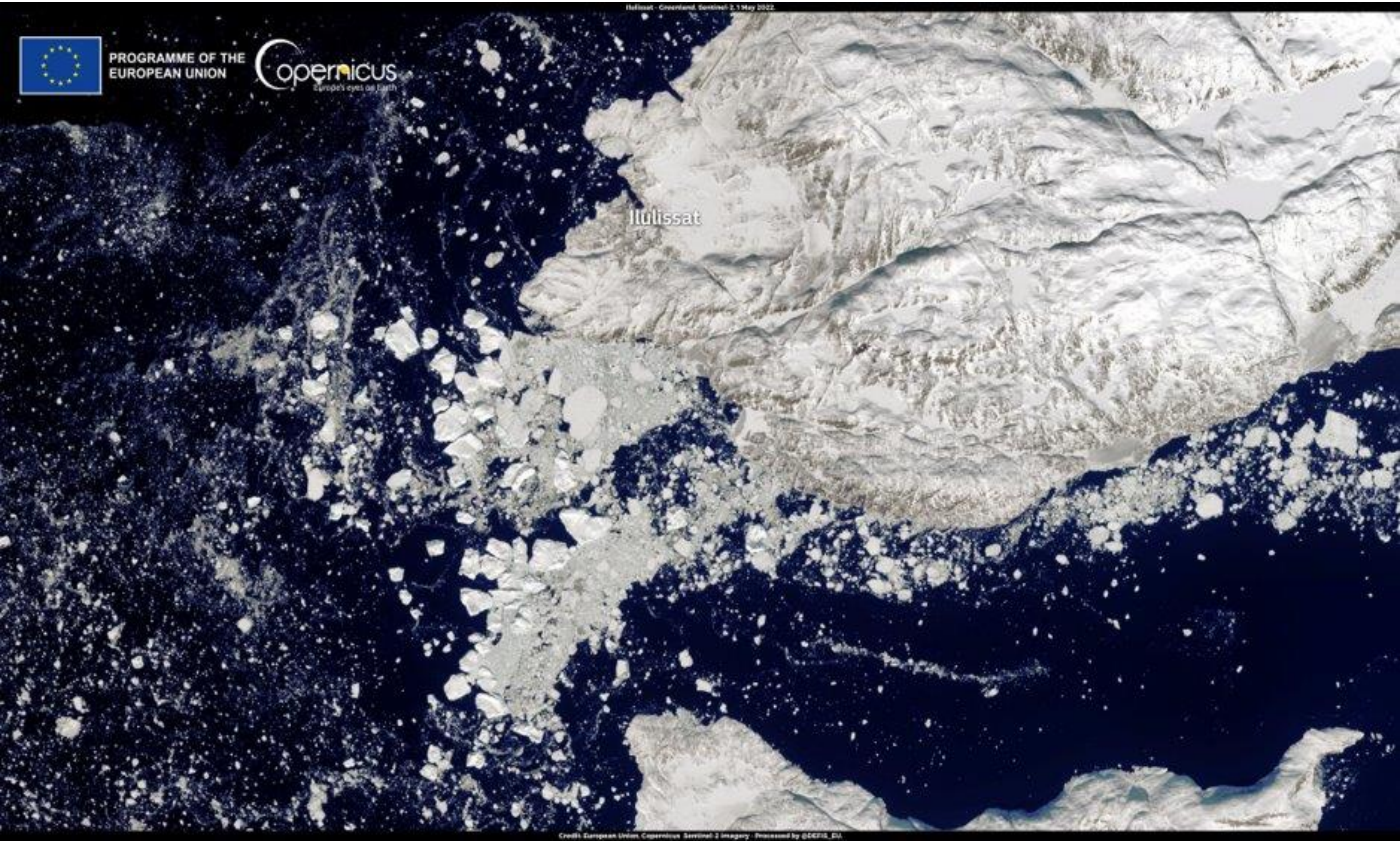
Sea ice



Sea ice

How?

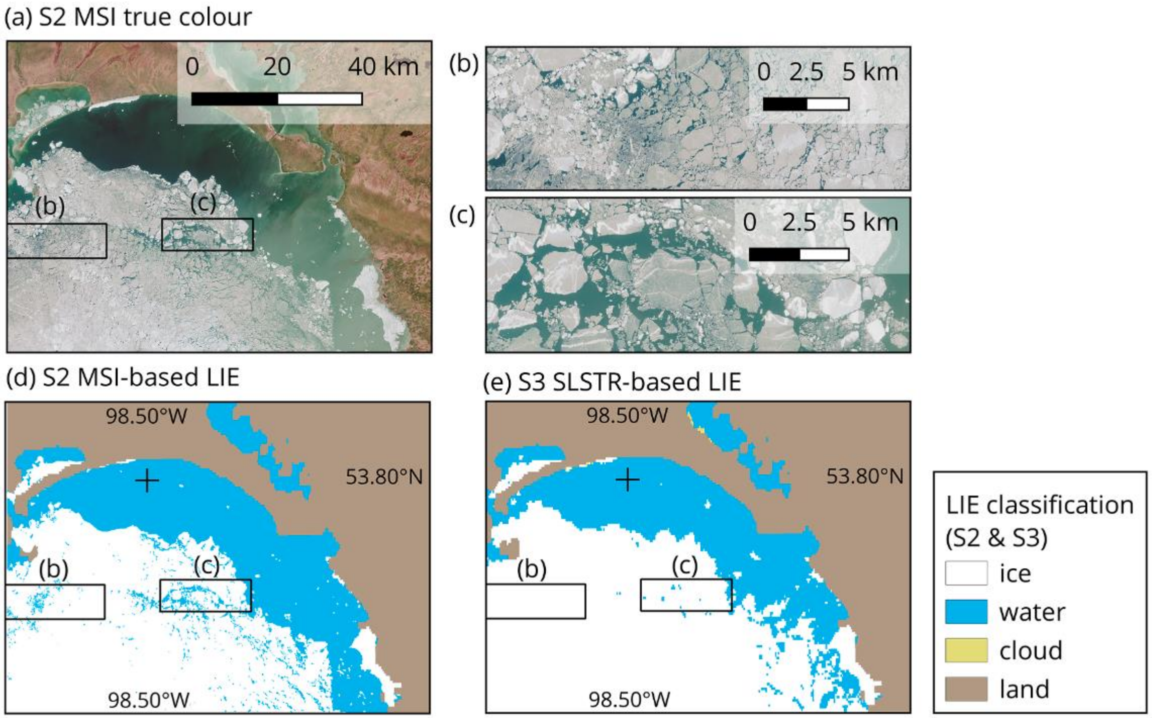
Empirical algorithms

- Exploit spectral characteristics of snow, ice, & water in the visible and NIR
- Simple regression and polynomial models
- Support Vector Machines
- Gaussian Mixture Models
- Fully Conv. Neural Nets.

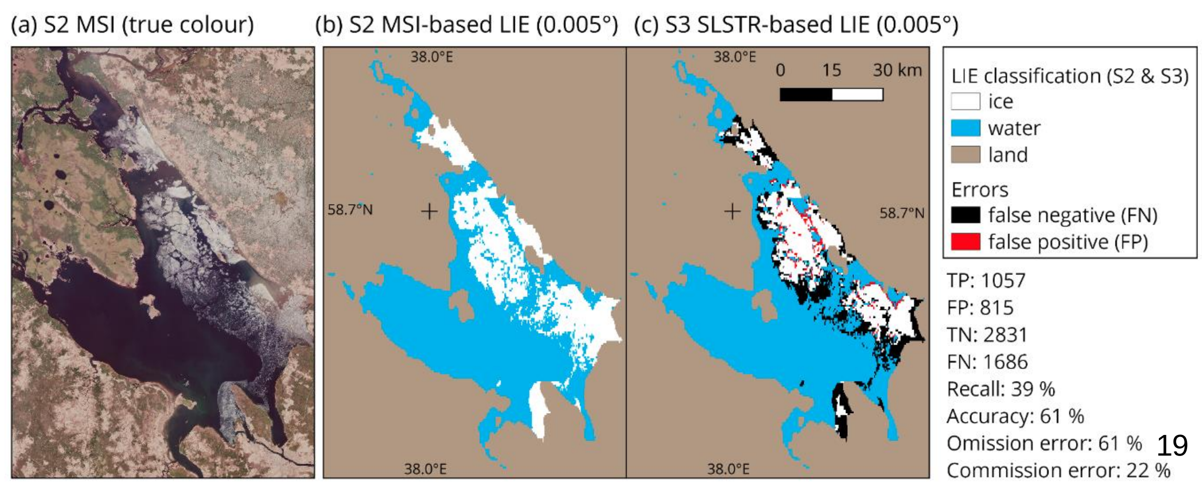
Major difficulties

- Clouds: limited visibility & similar spectral characteristics
- Low light conditions: at high latitudes during polar night
- Thin ice at melting stage (black ice) is transparent and appears with the same color of the underlying water

Sea ice



(Heinilä et al., 2021)



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Sea surface temperature (SST)

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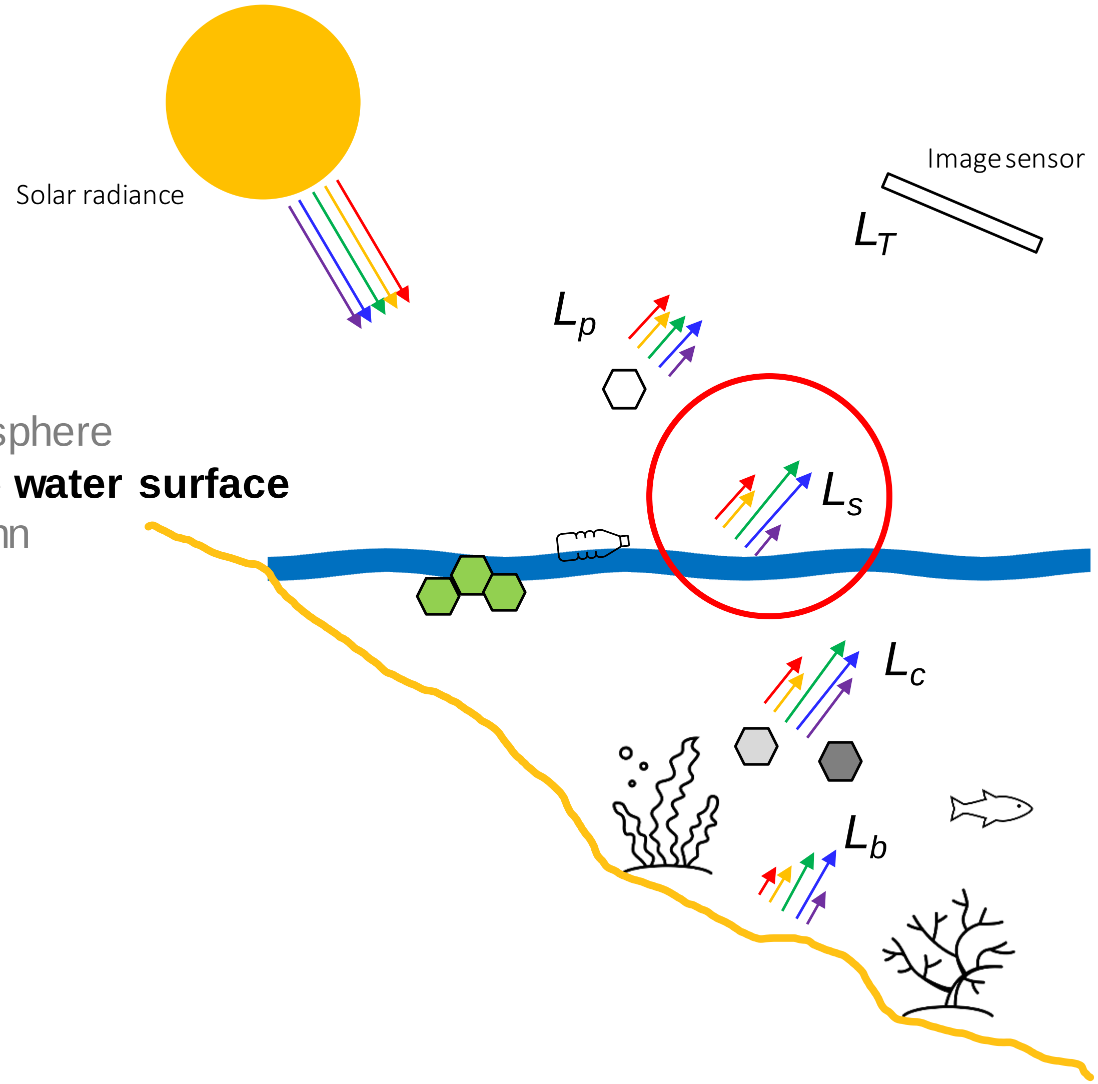
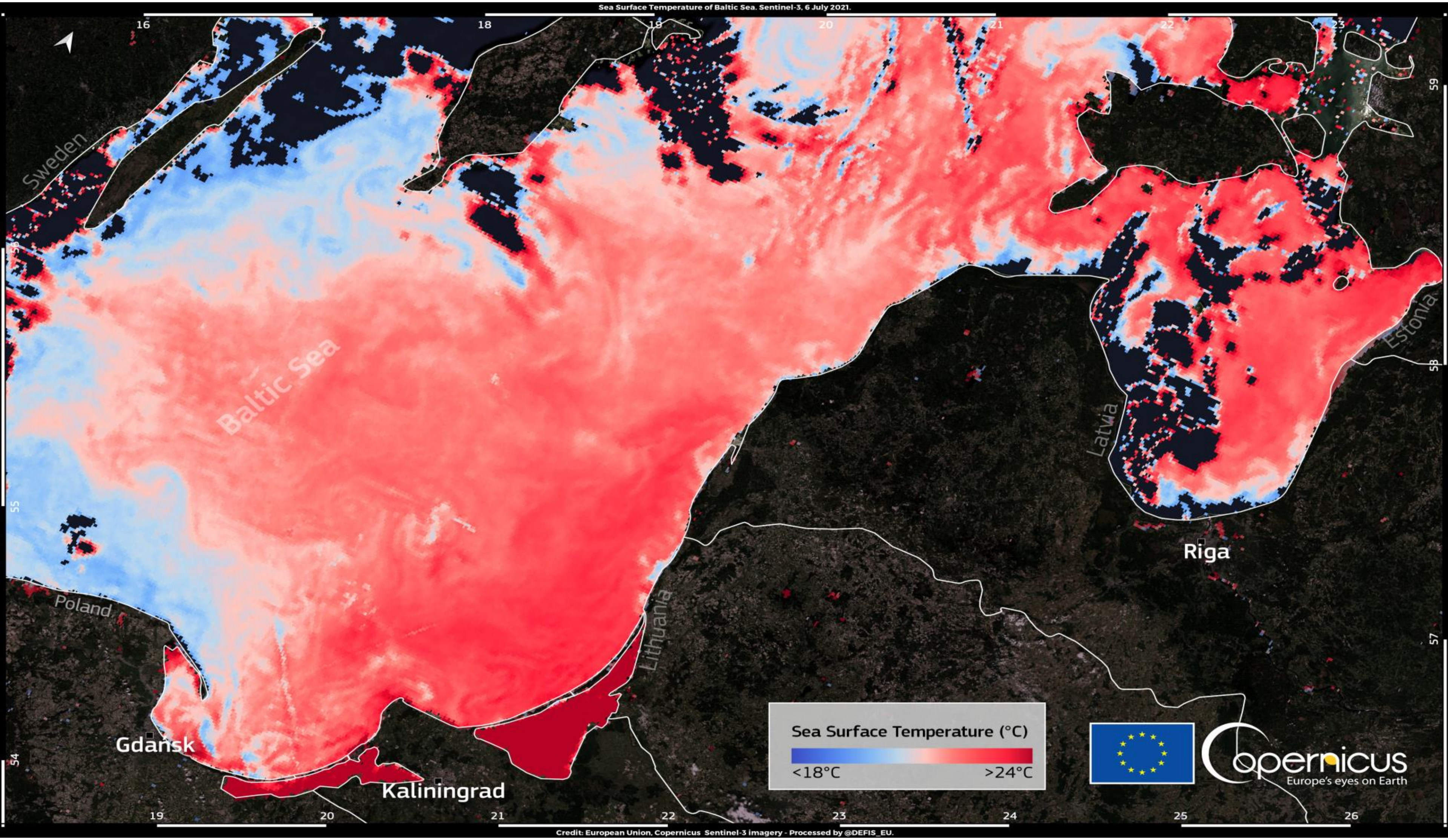


Sea Surface Temperature (SST)



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Sea Surface Temperature (SST)

How?

Highly accurate calibration of the three IR channels @ 3.74, 10.85 & 12 µm (S7-S8-S9) absorption & observation of the same on-ground pixel by means of two atmospheric path views for correction of aerosol effects.

Split-window algorithm

(SWA) that utilizes knowledge of land surface emissivity

$$T_s = a_{f,i,pw} + b_{f,i}(T_{11} - T_{12})^{\frac{1}{\cos(\theta/m)}} + (b_{f,i} + c_{f,i})T_{12}$$ *(Remedios et al., 2012)*

Sentinel-3

Absolute accuracy >0.3 K
Spatial resolution 1 km

Facts

SST varies between -1.8°C
and +30°C

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Marine Debris

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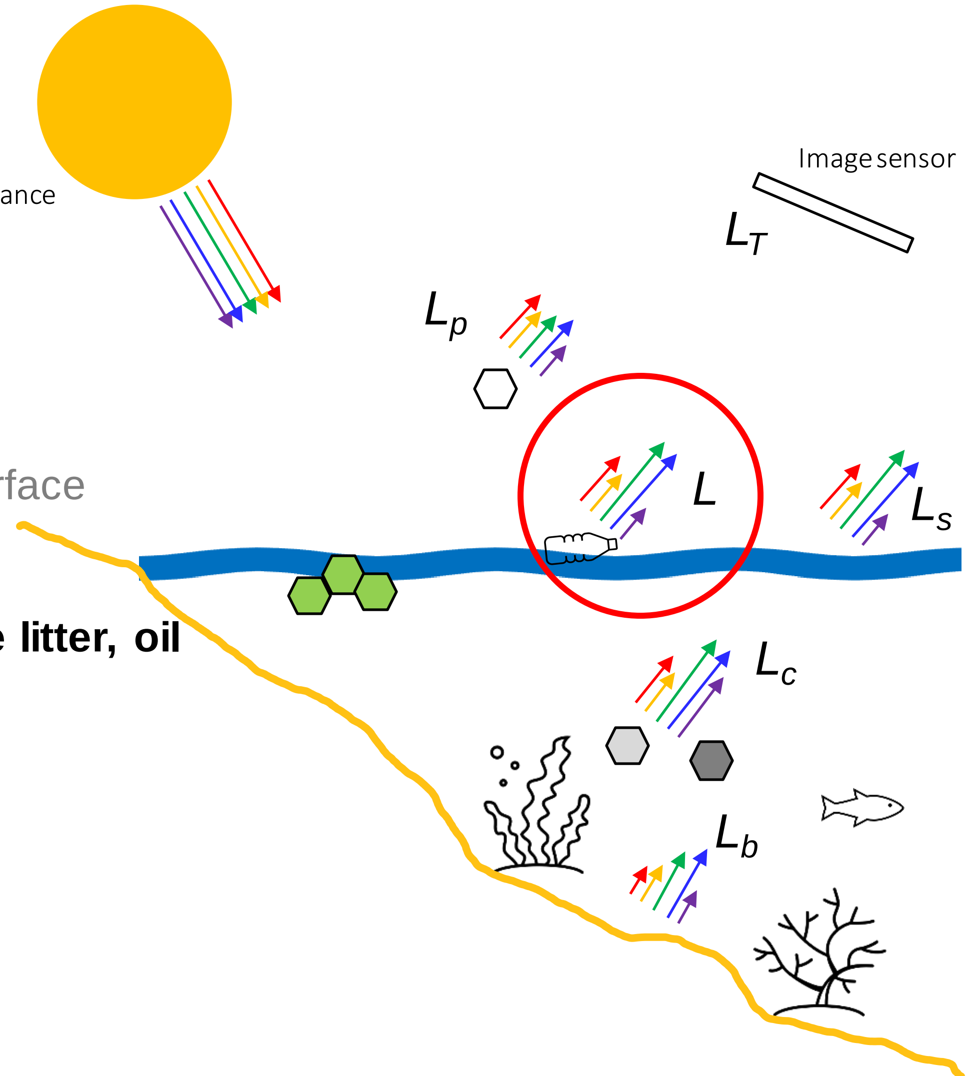
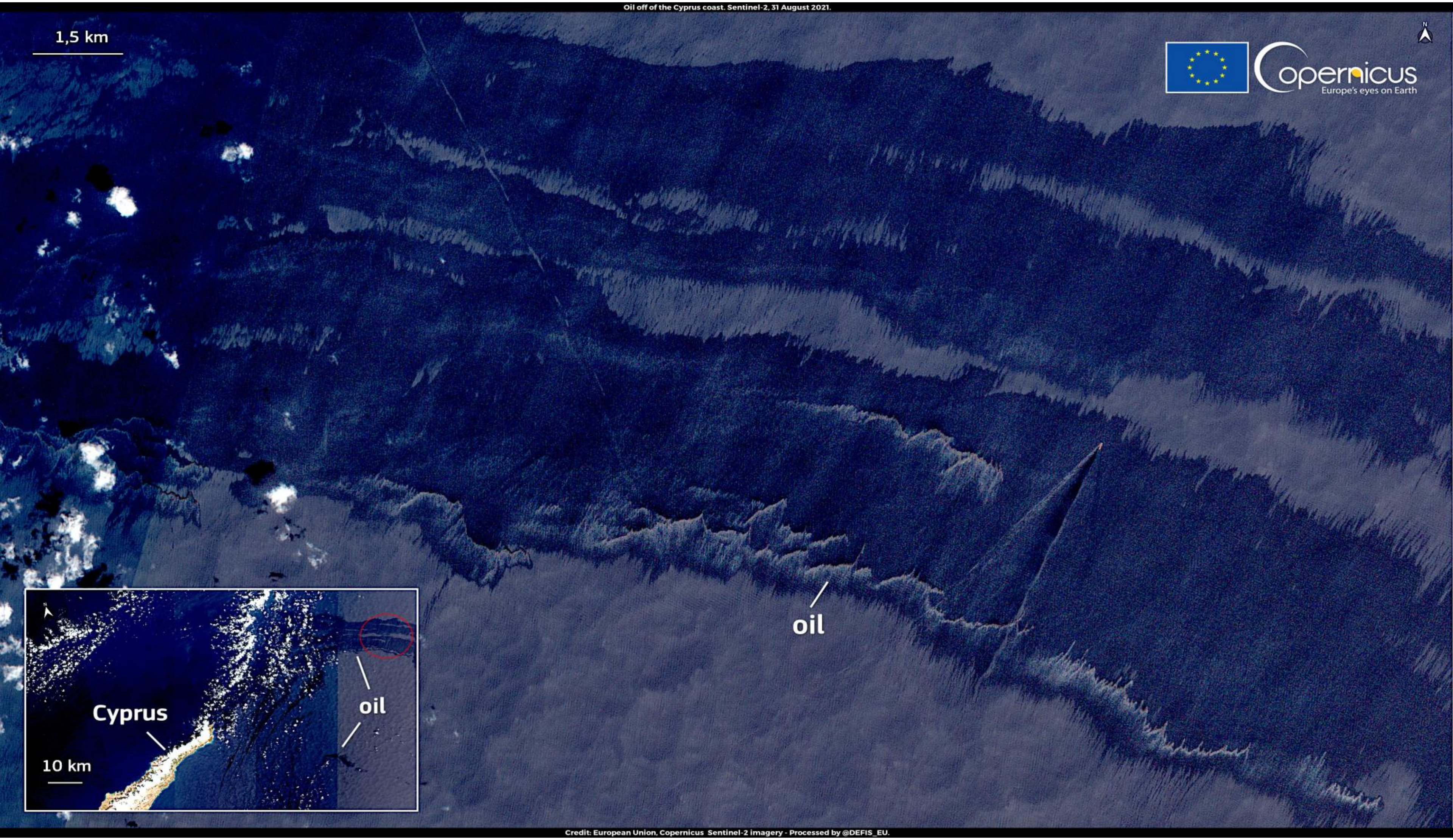
L is the radiance reflected from the marine litter, oil spills etc.



Pollution/oil spill detection

Oil off of the Cyprus coast. Sentinel-2, 31 August 2021.



Credit: European Union, Copernicus Sentinel-2 imagery - Processed by @DEFIS_EU.

Marine Debris

(Kikaki et al., 2022)

Marine Debris

How?

Empirical models

Statistically relate measurements marine debris (i.e. plastic) and reflectance through regression, polynomial expressions or **ML methods**

Some ML baselines

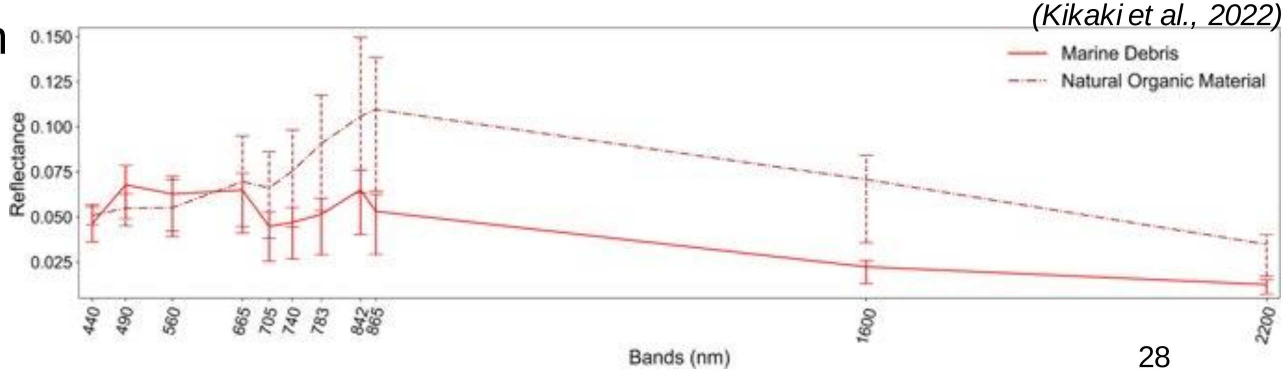
Weakly supervised semantic segmentation and multi-label classification:

- RF_{SS} (spectral signatures)
- RF_{SS+SI} (+ calculated spectral indices)
- $RF_{SS+SI+GLCM}$ (+ extracted Gray-Level Co-occurrence Matrix (GLCM) textural feat.)
- U-Net (11 Rayleigh reflectance S2 bands)

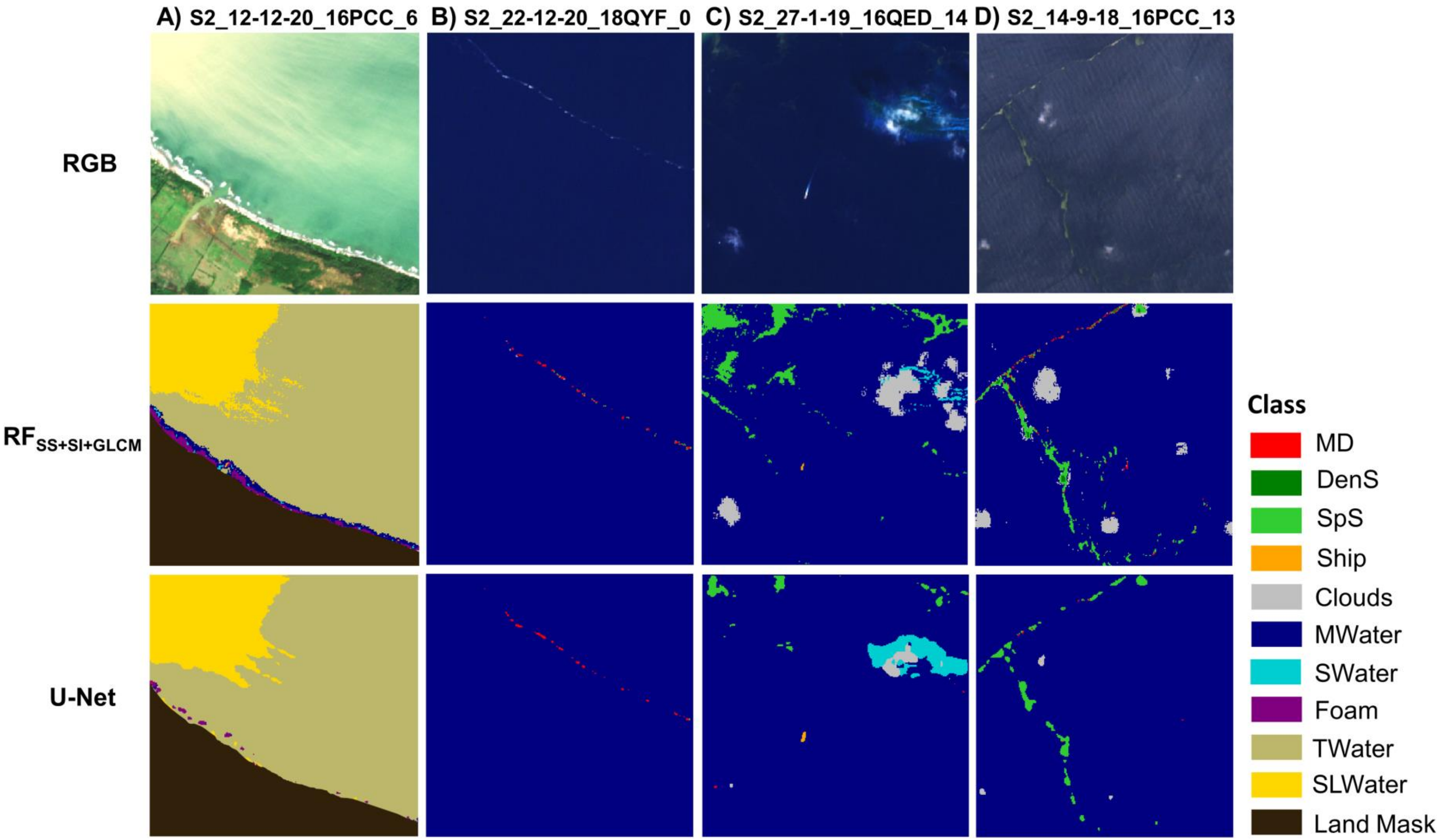
Multi-label classification

- ResNet

(Kikaki et al., 2022)



Marine Debris



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RSiM

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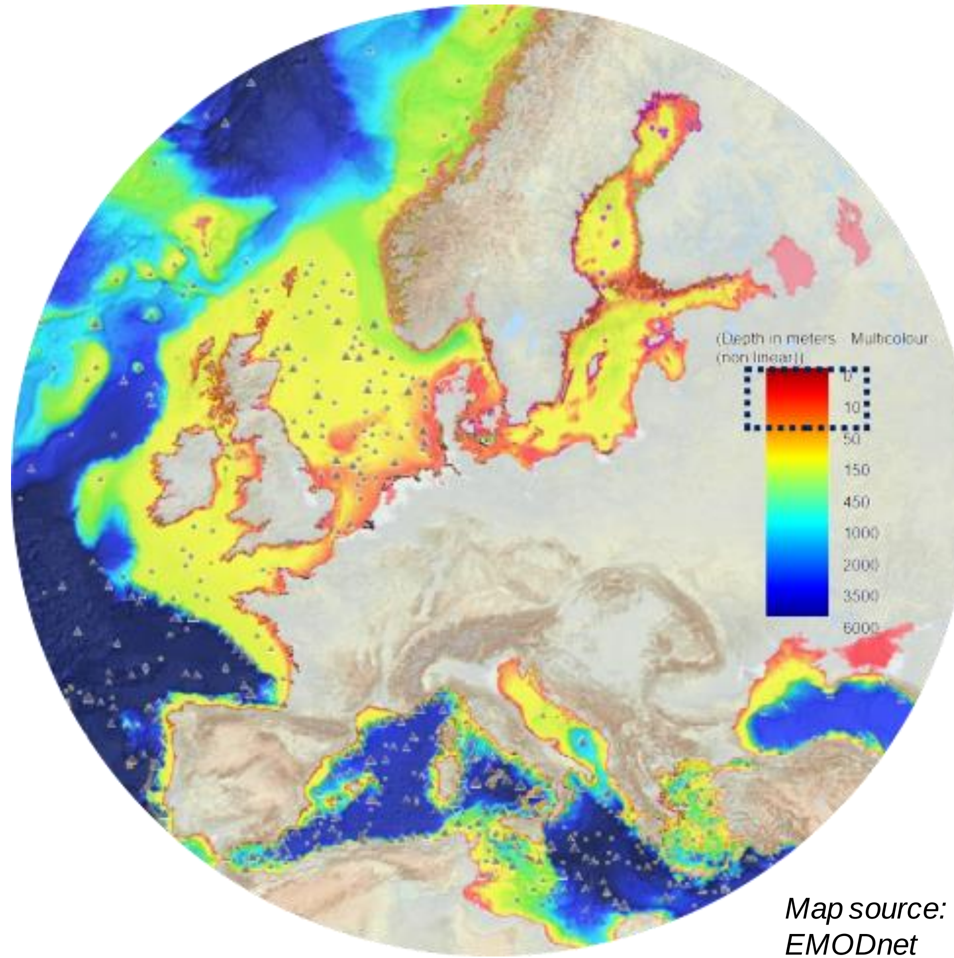
- Shallow seabed cover maps

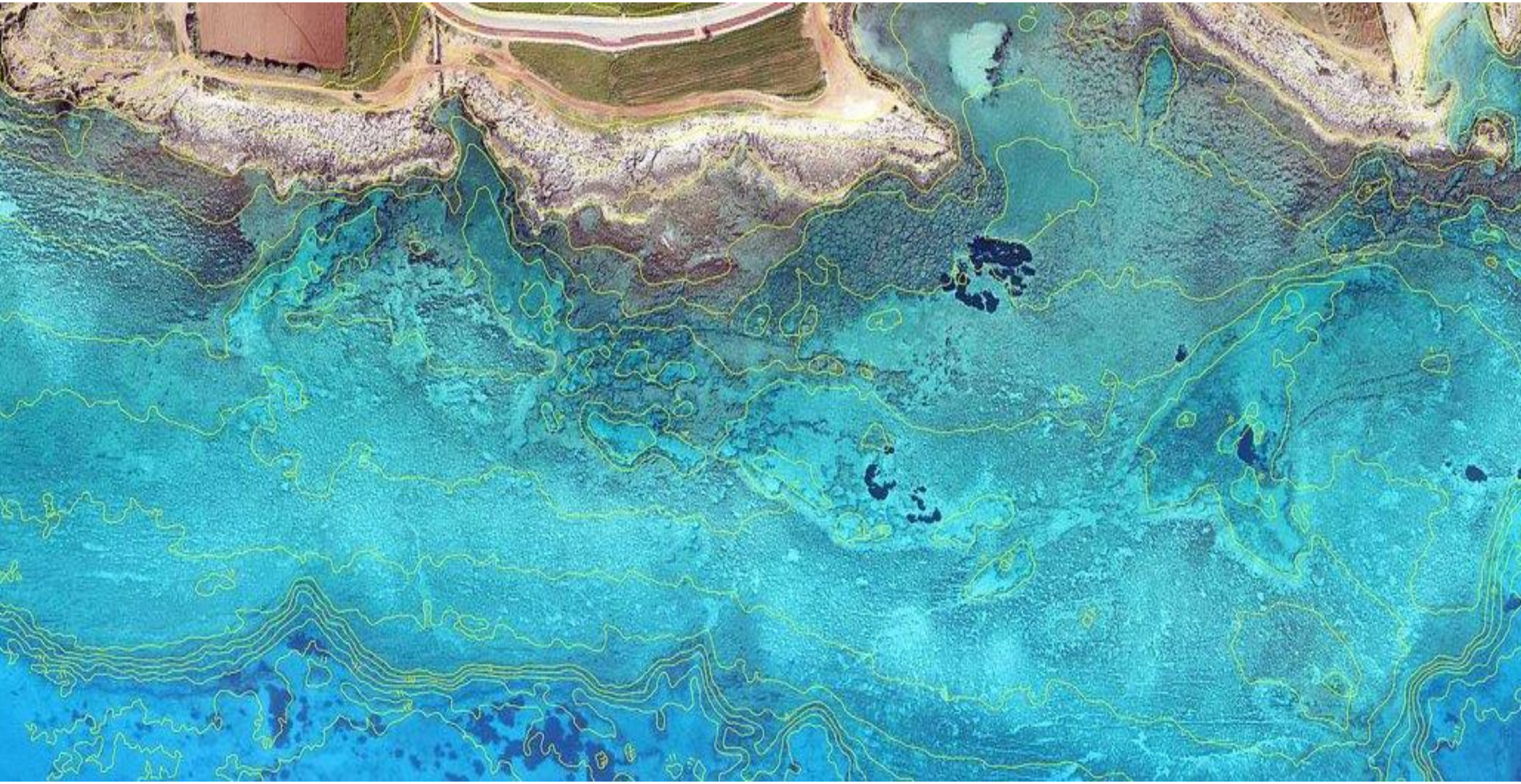
Shallow Water Bathymetry

2.5% of the EU seabed is “shallow” (<20-25m depth) excluding lakes



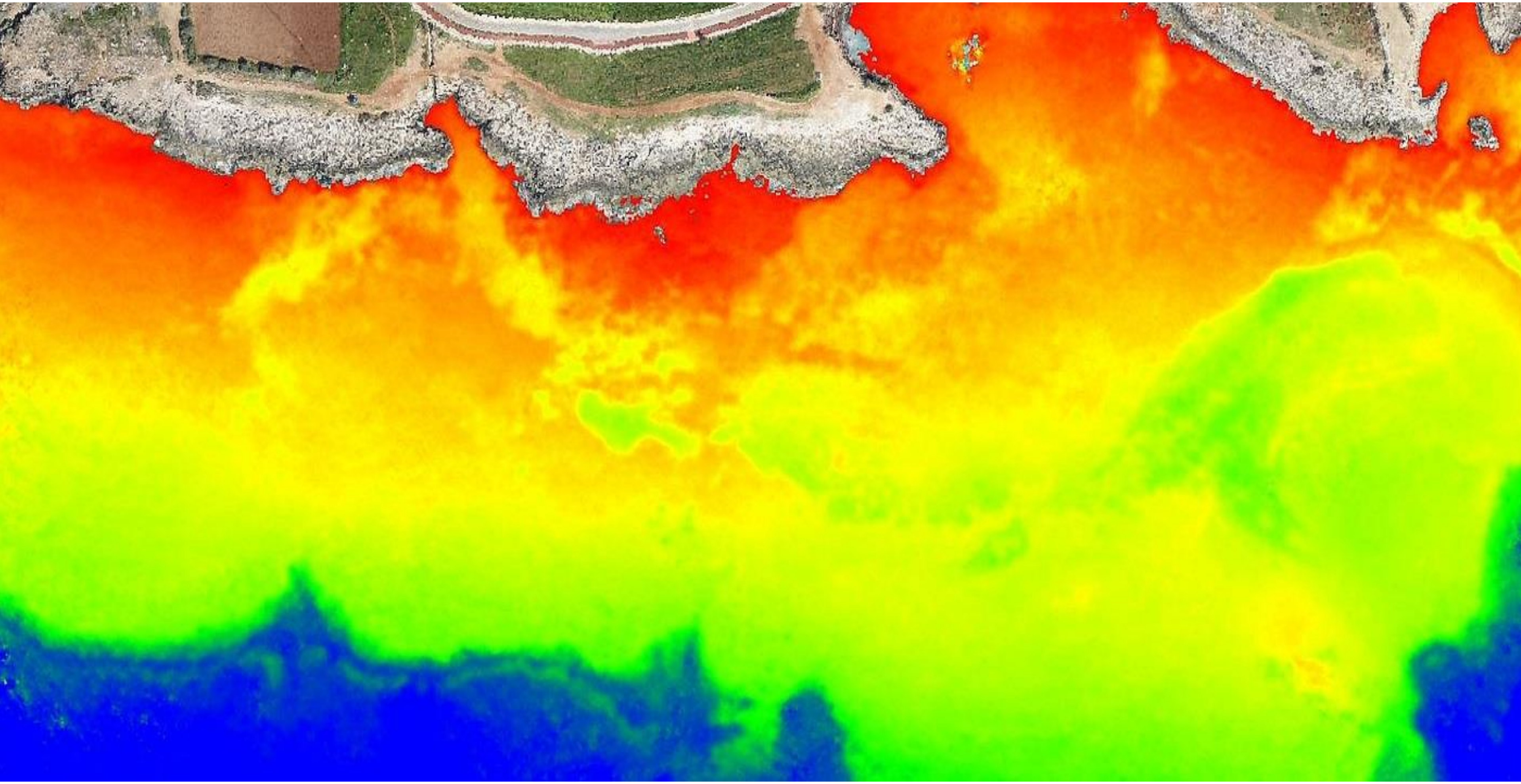
Map source: EMODnet

Shallow water Bathymetry



Data and Processing: Ph. Vision Lab. CUT

Shallow water Bathymetry



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- **Shallow water bathymetry**
  - **Spectral-based**
  - Stereo-based
- Shallow seabed cover maps

Basics of spectral-based bathymetry

$$L_T(\lambda)=L_p(\lambda)+L_s(\lambda)+L_c(\lambda)+L_b(\lambda)$$

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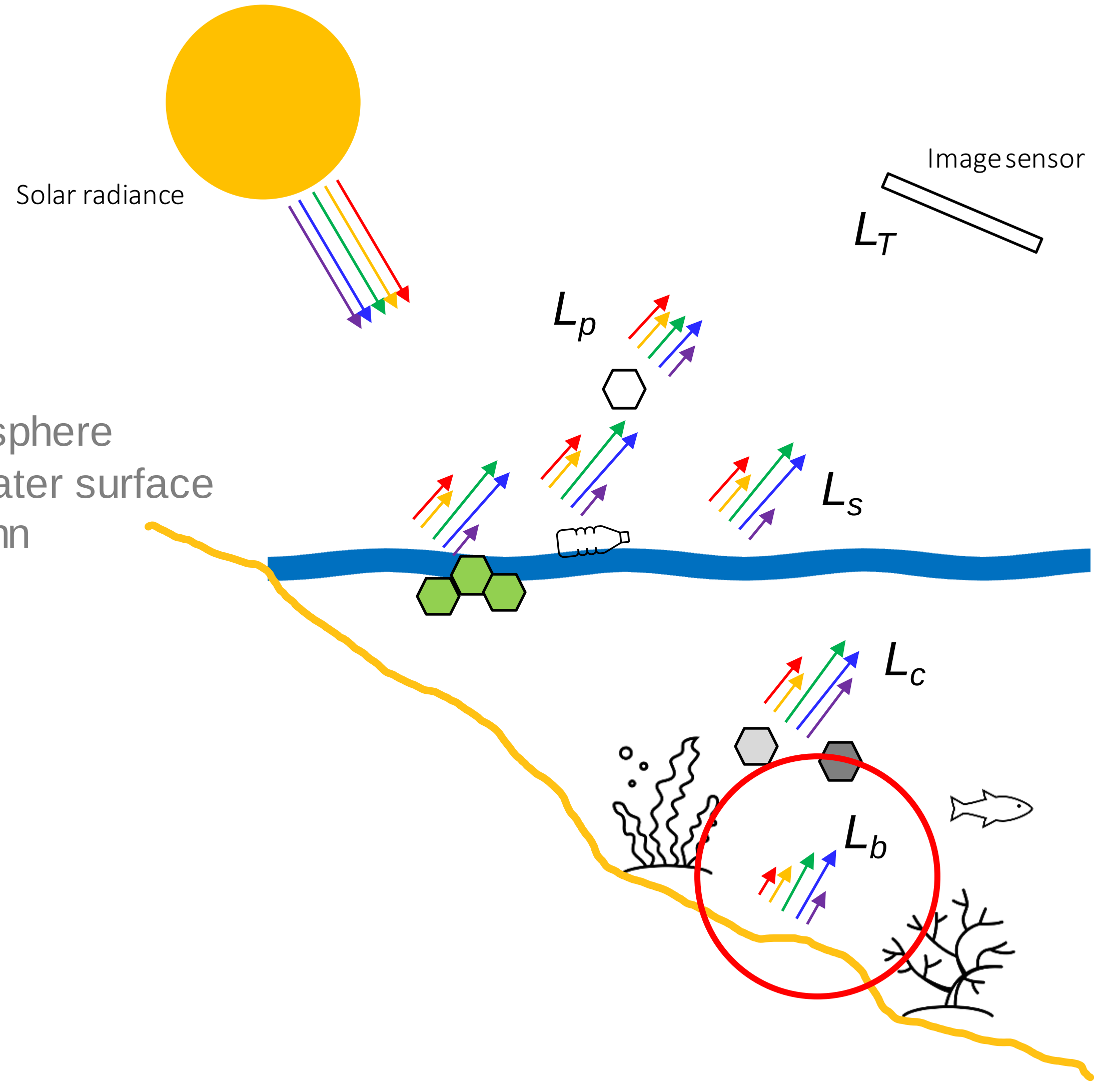

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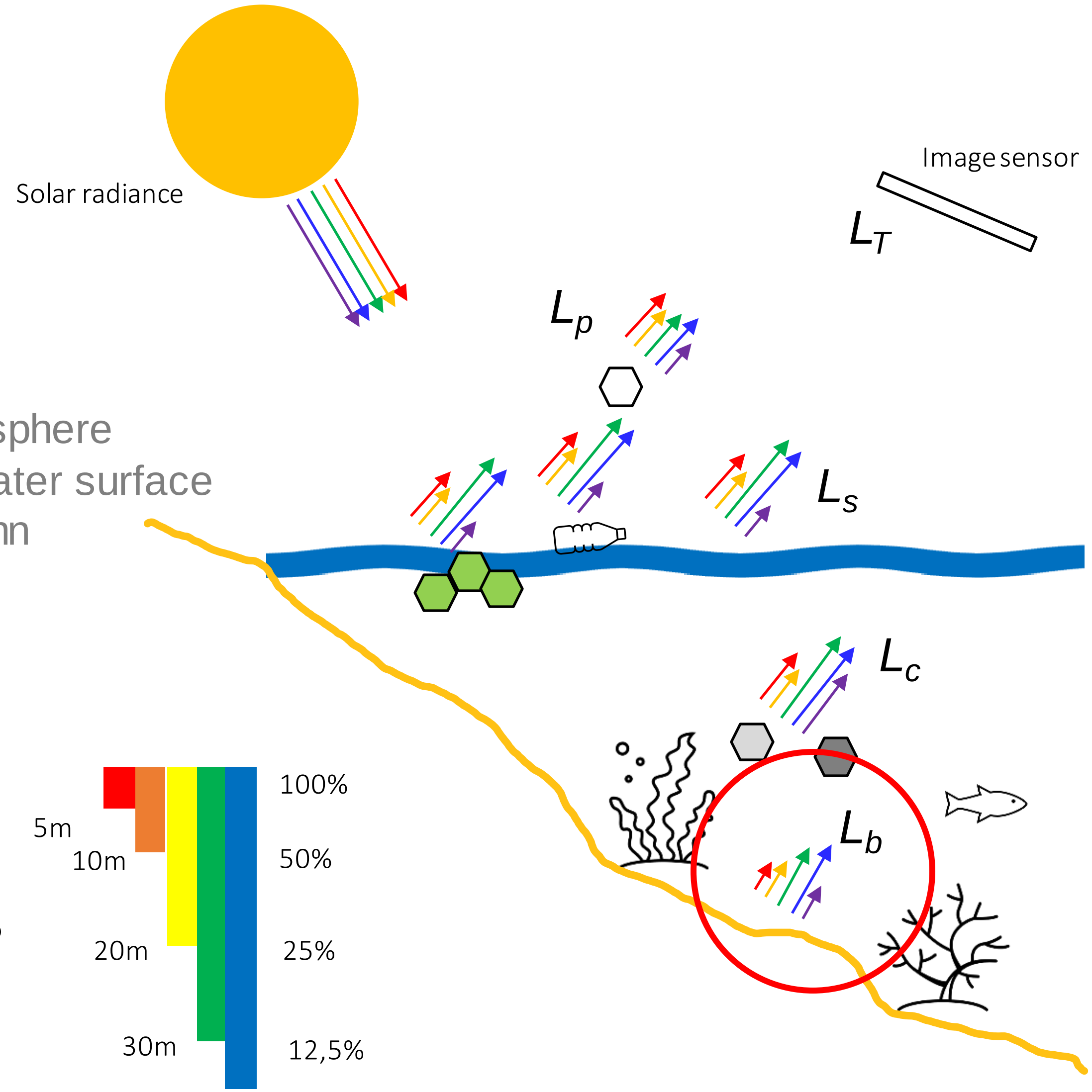
Easy way
Correlate color loss and depth

What about different seabed classes ?



Spectral-based Bathymetry

How?

Statistical models: Statistically relate meas. depth and reflectance – need for ground truth data

- From simple linear regression to ML (RFs, SVMs) and DL (FCNs, GANs)

Physics-based radiative transfer models (bio + physio-optical):

- Inversion of a radiative transfer models (RTM) – no need for ground truth data
- Analytical
- Semi-empirical (band ratio, band difference, PCA, ANN, regression)
- Semi-analytical (direct linear inversion, spectral deconvolution)

Hybrid methods

Statistical models

Common approaches

- The standard linear algorithm (Lyzenga, 1978) assumes a log-linear relationship between reflectance (R(λi)) and water depth (z):.

$$z = b \log R(\lambda_i) + c$$

- Stumpf et al., 2003 bathymetric algorithm

The method approximates “physics” of light in the water:

pSDB “pseudo depth”

$$Z = m_1 \frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} - m_0$$

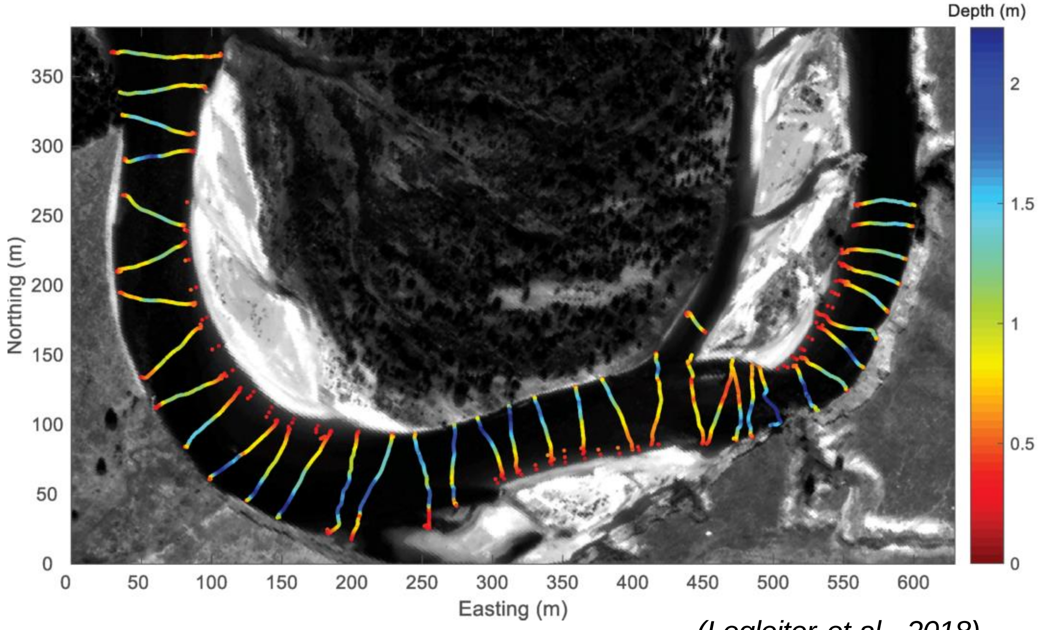
where m_1 is a tunable constant to scale the ratio to depth, n is a fixed constant for all areas, and m_0 is the offset for a depth of 0m

- Sample-specific multiple band ratio techniques *(Niroumand-Jadidi et al., 2020)*
- Physics-based radiative transfer model (RTM) inversion techniques
- **Shallow and Deep ML techiques (RFs, SVMs, FCNs)**

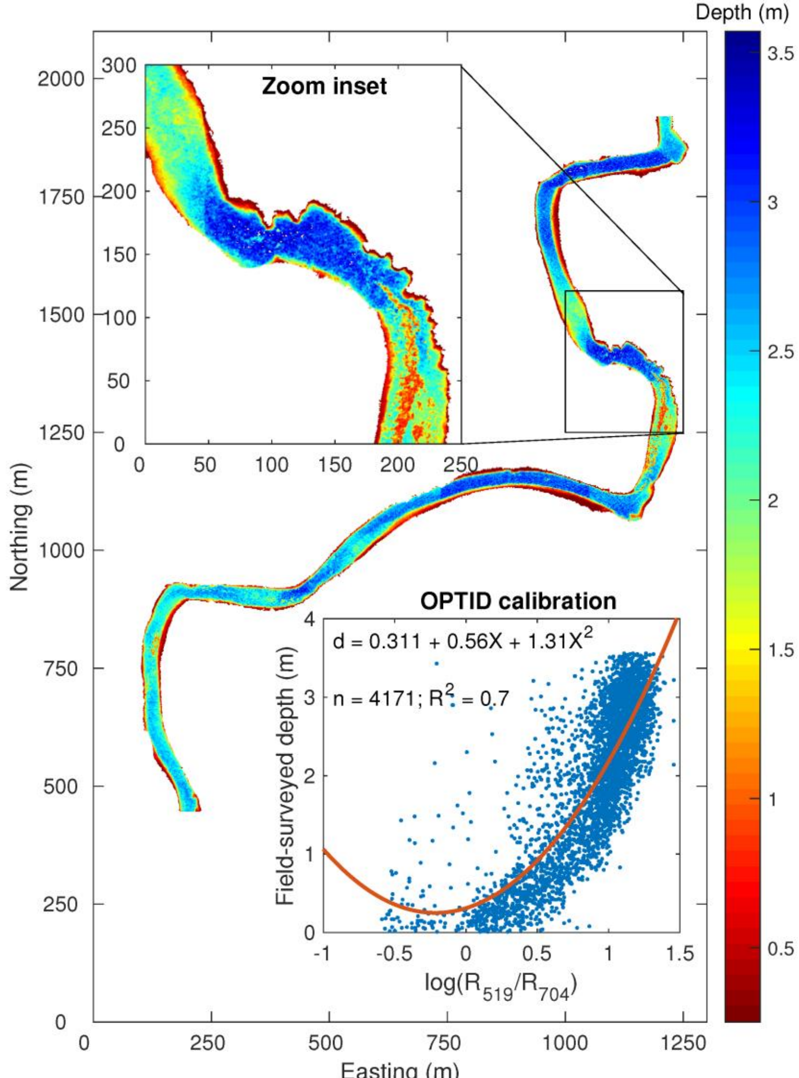
Statistical models

Examples
Airborne HS images

Polynomial regression
Ground truth bathymetric data used: Acoustic Doppler Current Profiler (ADCP)



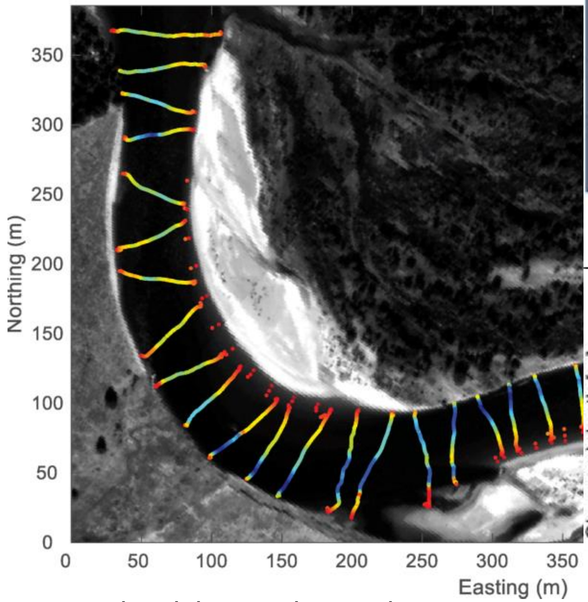
(Legleiter et al., 2018)



Statistical models

Examples

K-NN clustering + Polynomial regression



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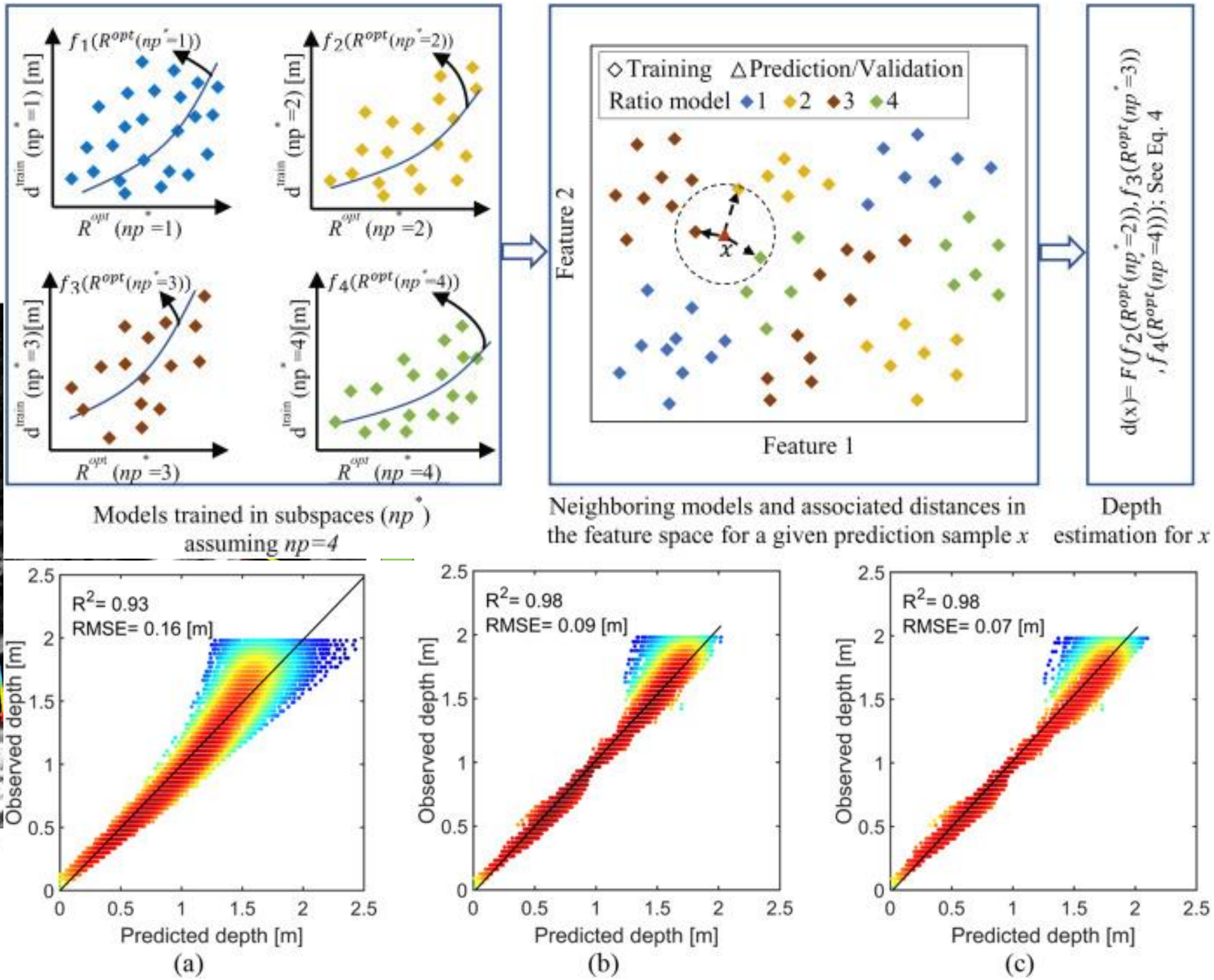
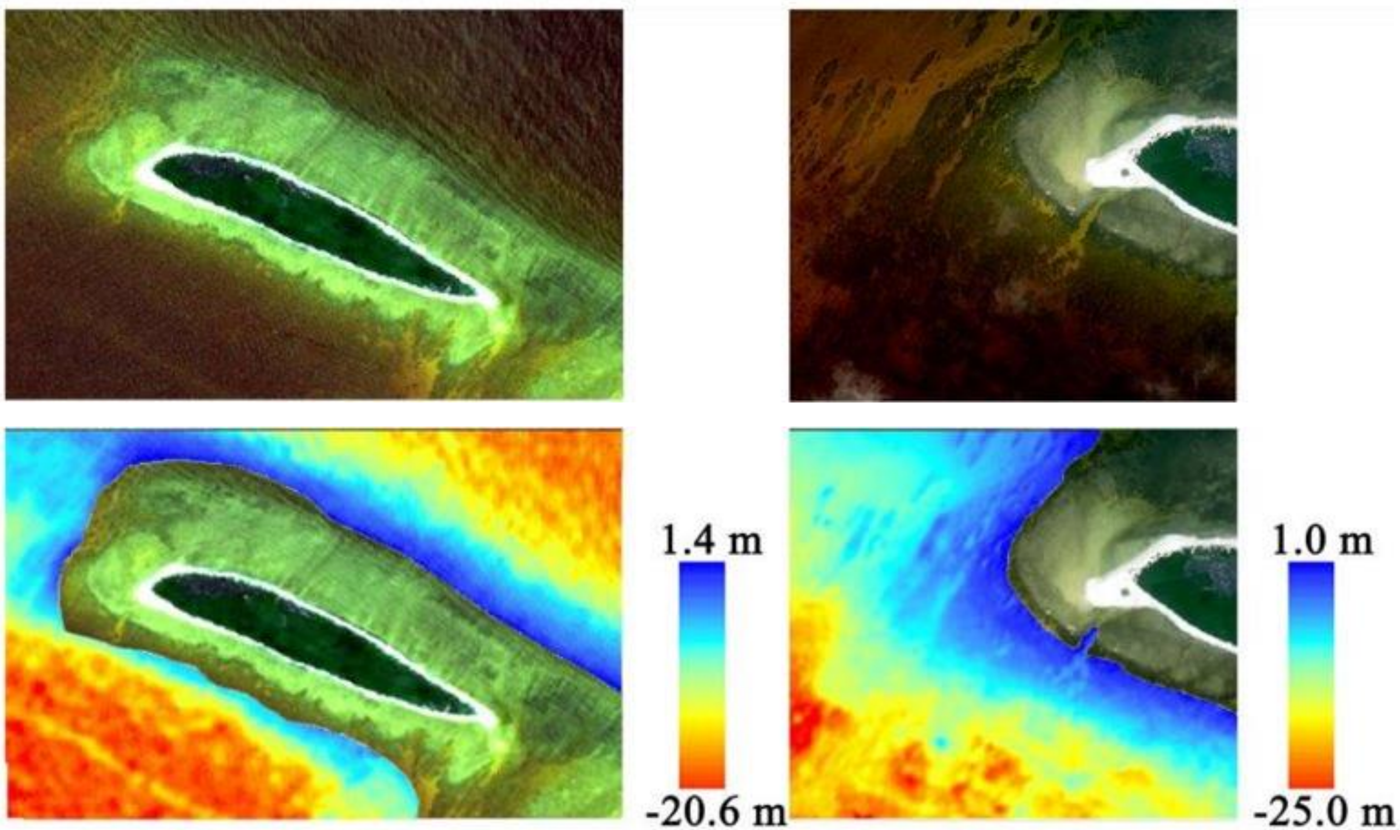


(Niroumand-Jadidi et al., 2020)

Statistical models

Examples
Worldview-2 (WV2) images

CNNs
Ground truth bathymetric data used: Airborne LiDAR



(Ai et al., 2020)

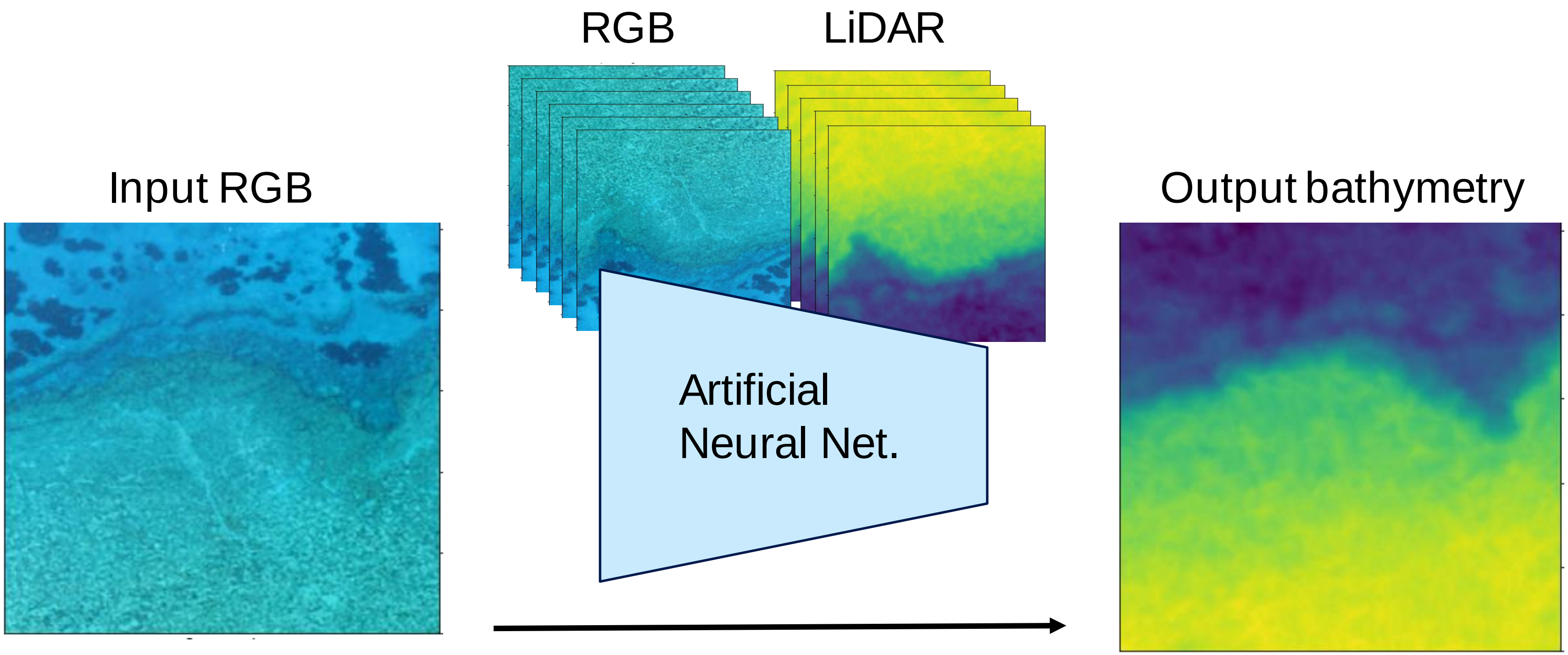
Statistical models

Examples

UAV RGB images

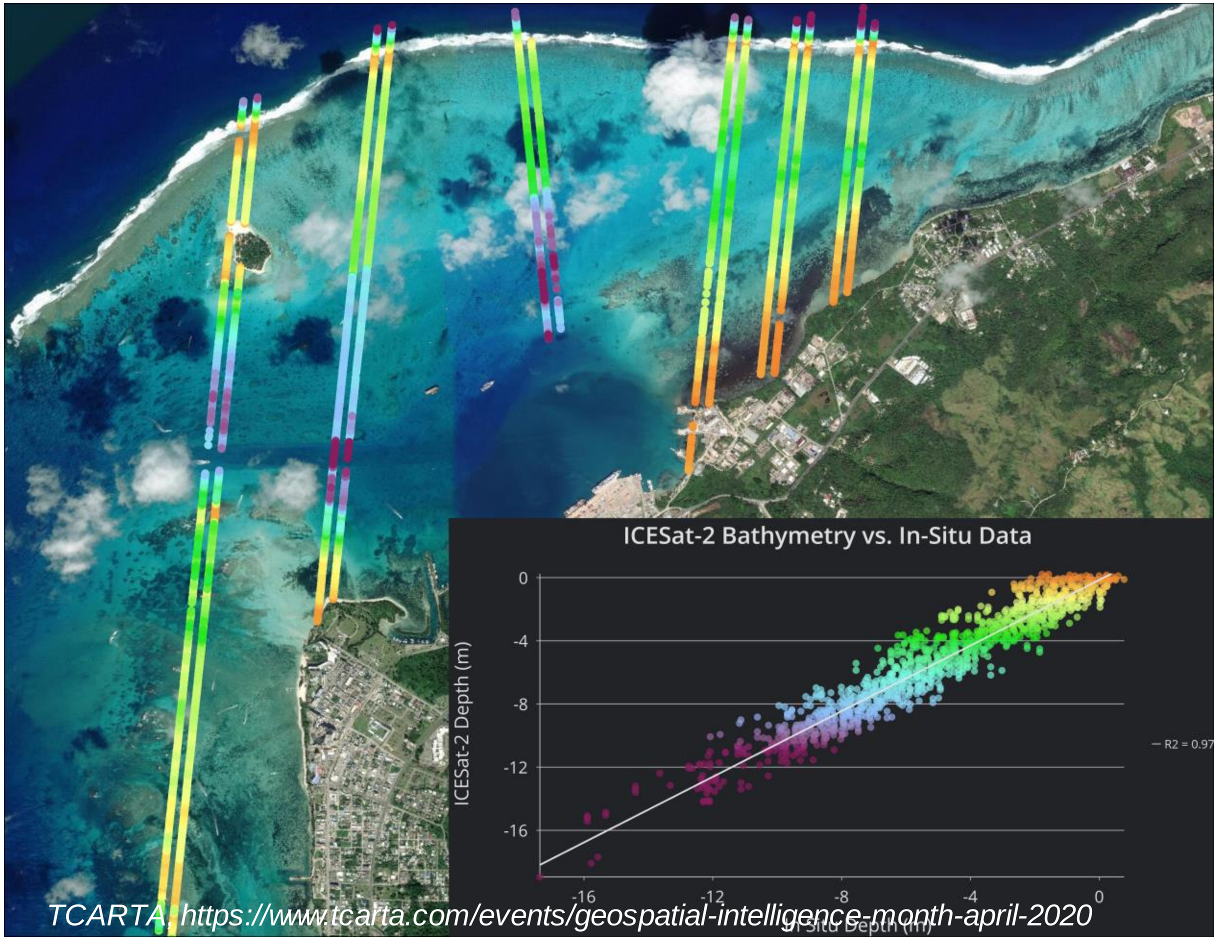
CNNs

Ground truth bathymetric data used: Airborne LiDAR



Ground truth data

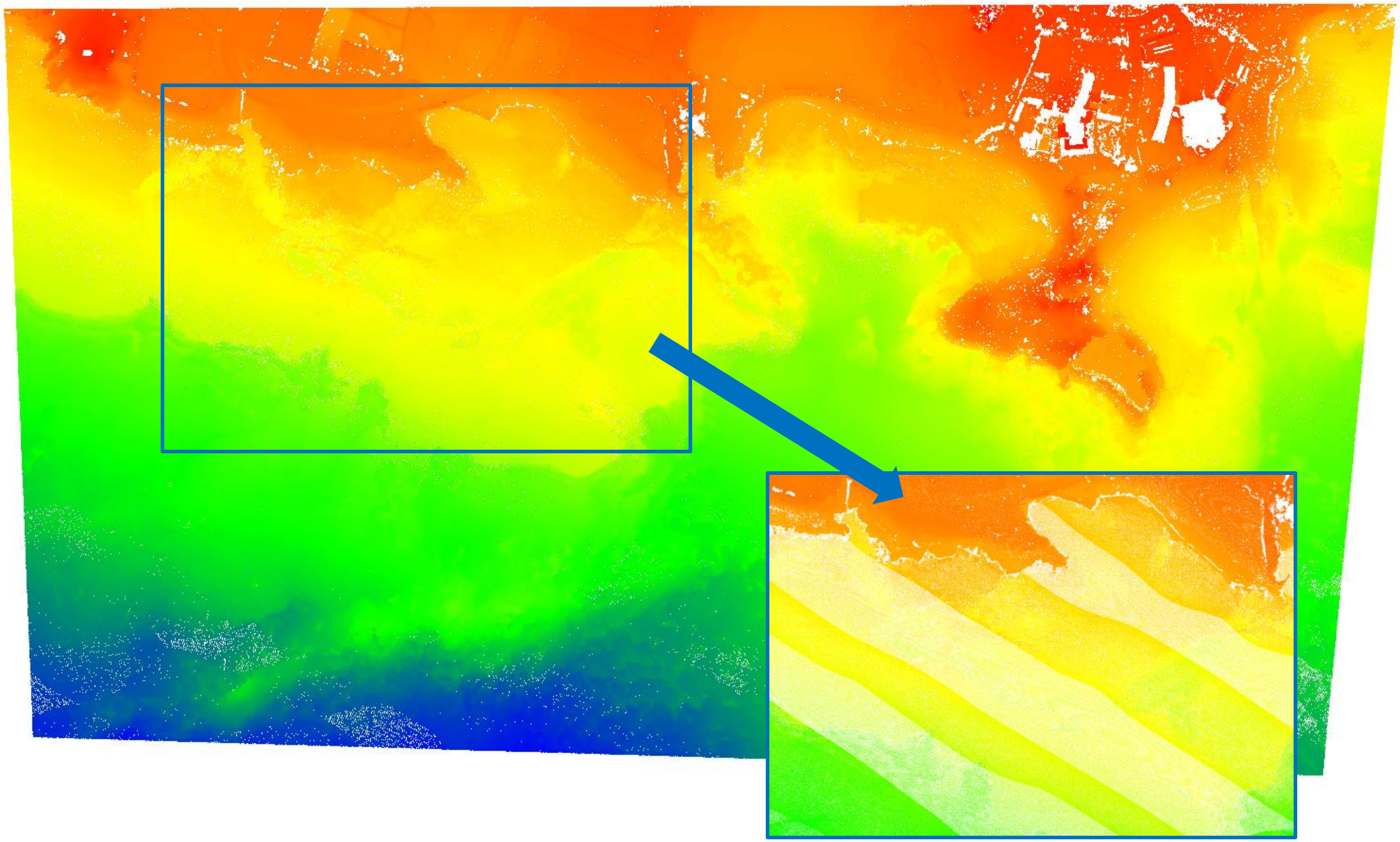
ICE-Sat2 satellite or similar



TCARTA, https://www.tcarta.com/events/geospatial-intelligence-month-april-2020

Ground truth data

Airborne LiDAR or shipborne Echosounder

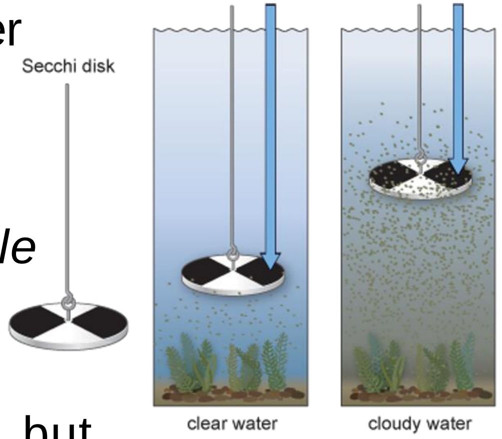


RSiM

Spectral-based methods

Pros, Issues and Limitations

- <u>No sophisticated geometry processing necessary</u>
- Can handle certain differences in substrate type and water clarity
- <u>Covers large areas (satellites)</u>
- Max depth ~ 1 **Secchi** → *the max depth a disk 30cm is visible*



- Requires visibility of bottom features (similar to SfM-MVS, but not texture is required here)
- Work better on homogenous seabed
- **Requires ground-truth for calibrating coefficients**
- **Heavily affected by sun glint, high aerosol, turbidity etc.**
- **Lack of generalization potential** due to the daily/seasonal etc. variability of spectral values

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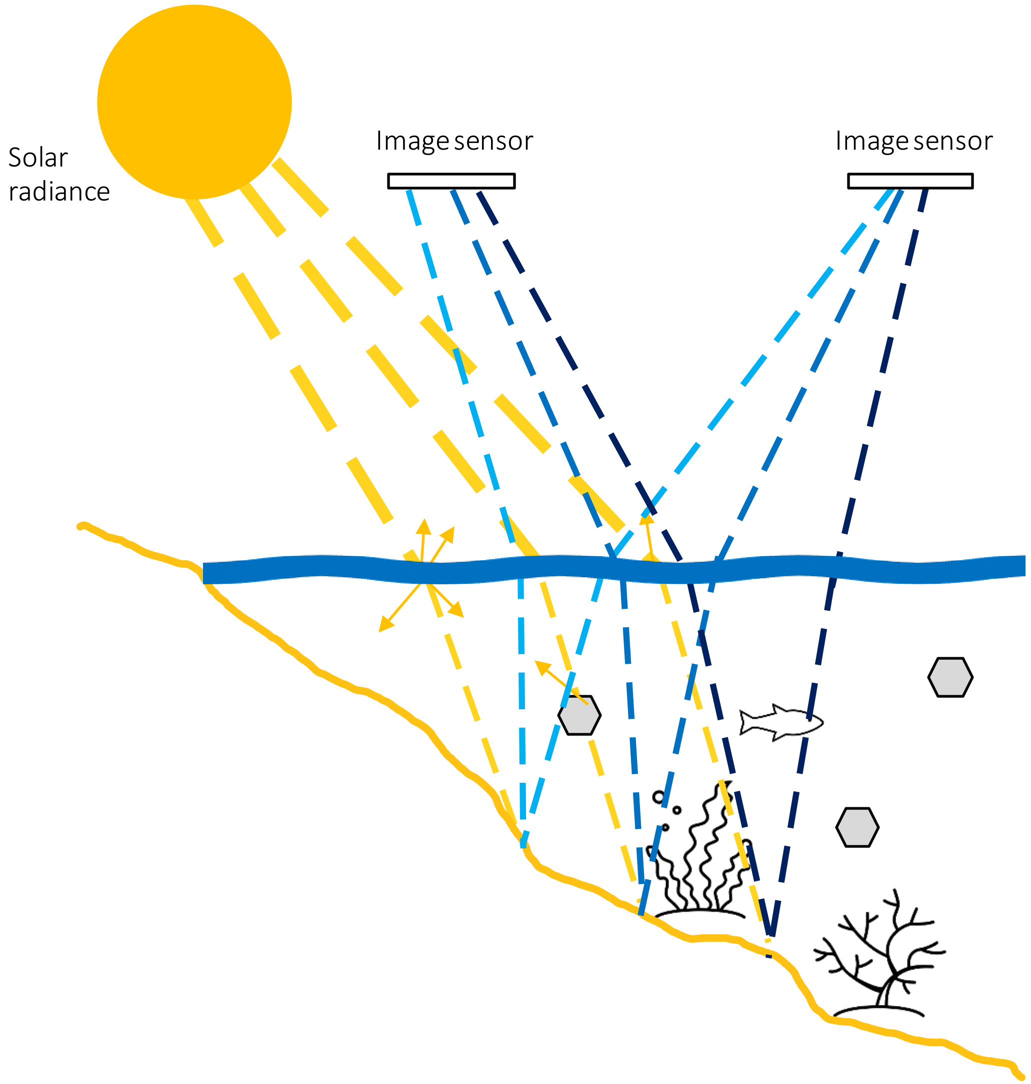
RSiM

Basics of stereo-based models



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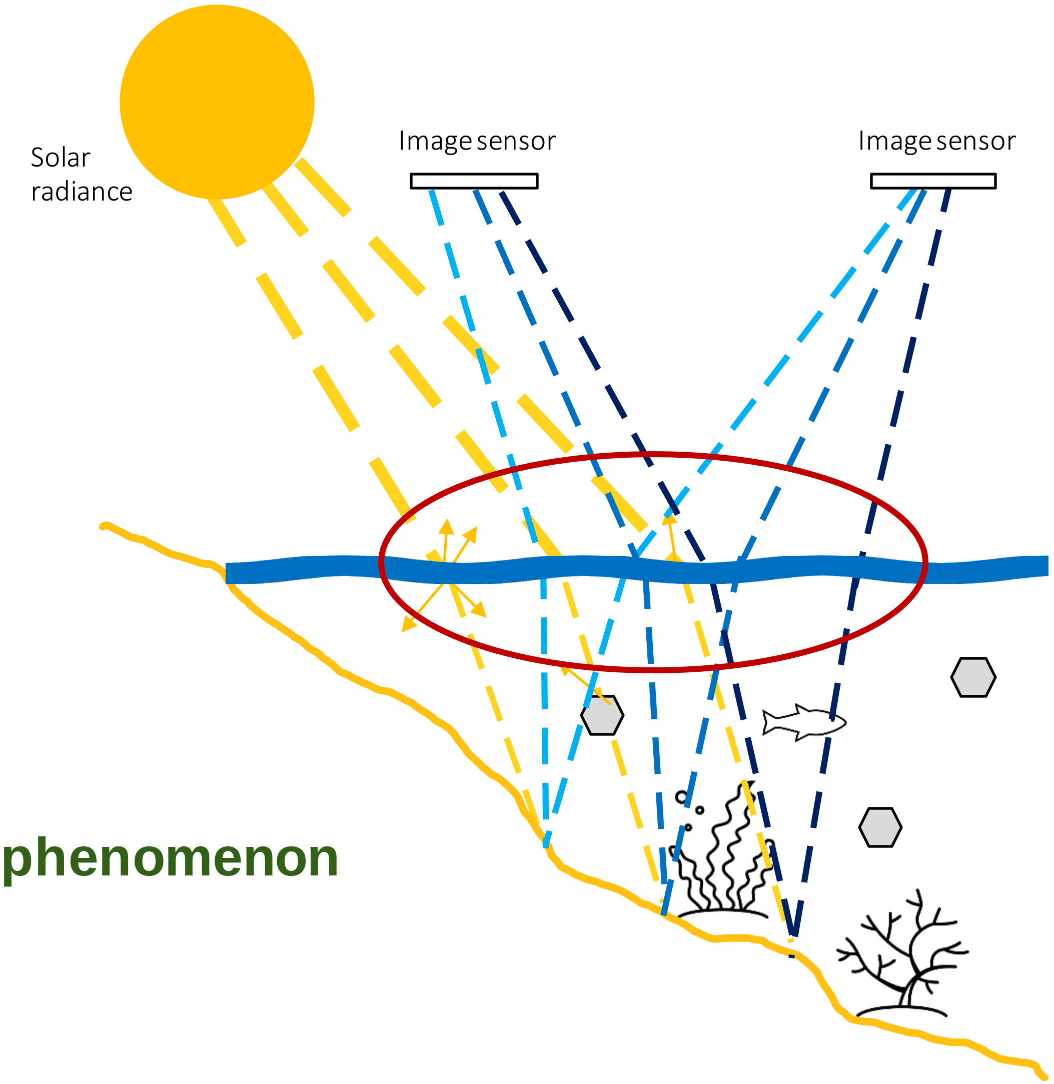


Refraction phenomenon

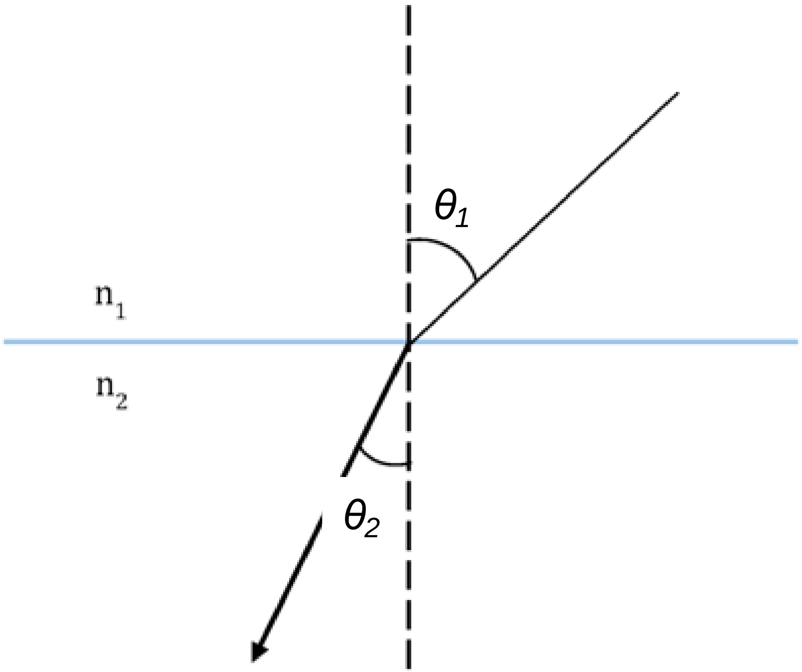
RSiM

Refraction phenomenon

Snell's law

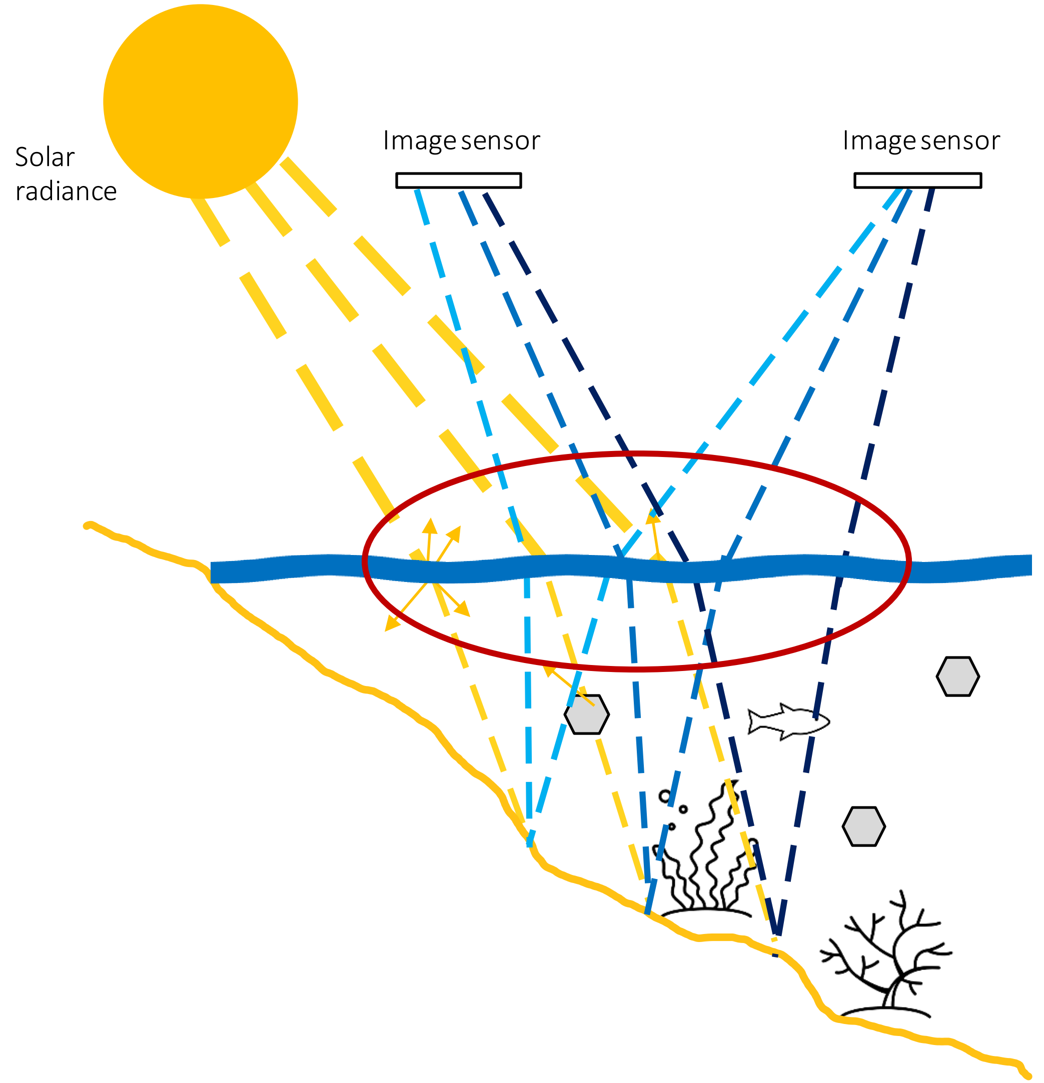
The ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \frac{n_1}{n_2}$$



The law is based on **Fermat's principle**, also known as the principle of least time
Fermat's principle states that the path taken by a ray between two given points is the path that can be traversed in the least time.

Refraction phenomenon



Refraction effect is totally different for each image and each image point!

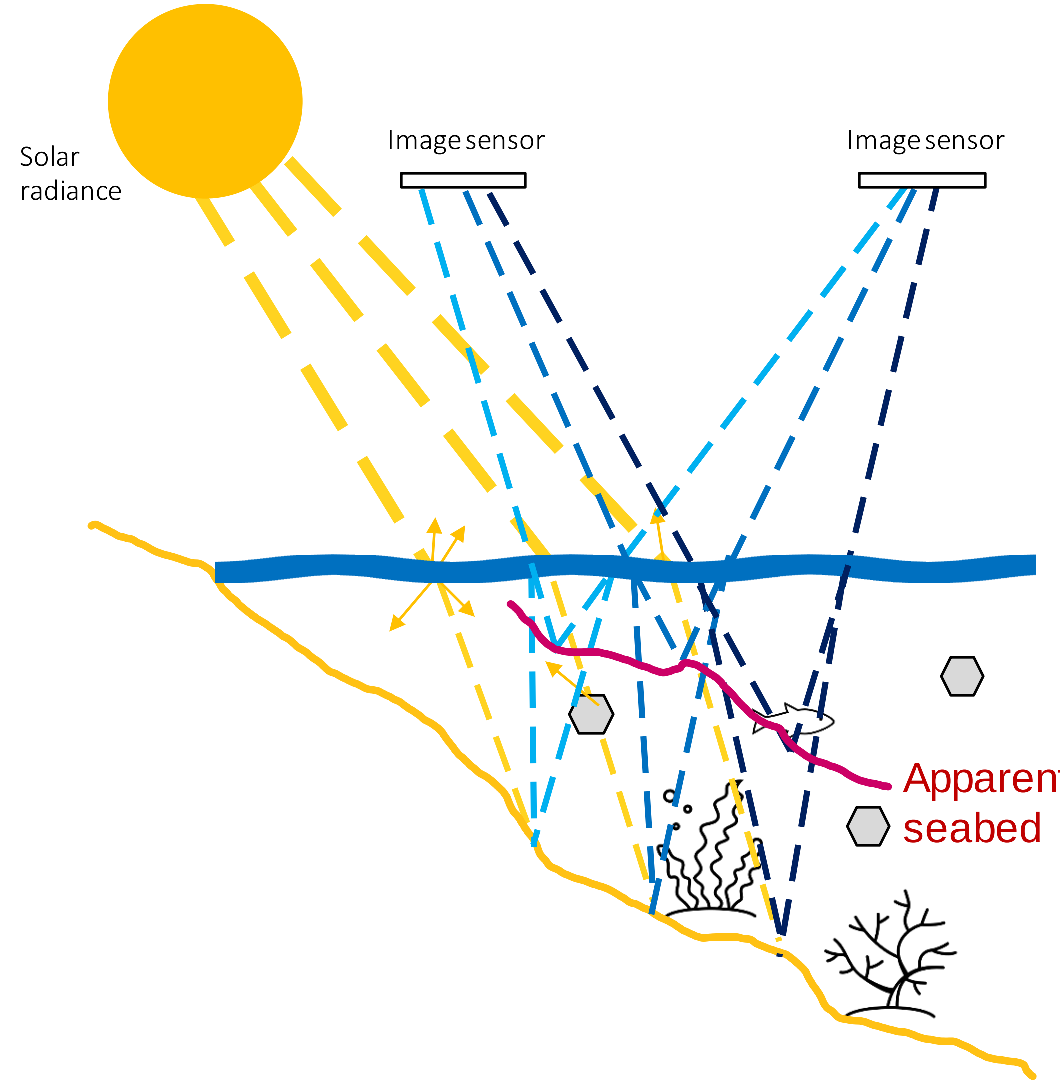
It depends on

- Depth
- Angle
- Camera position

Refraction phenomenon

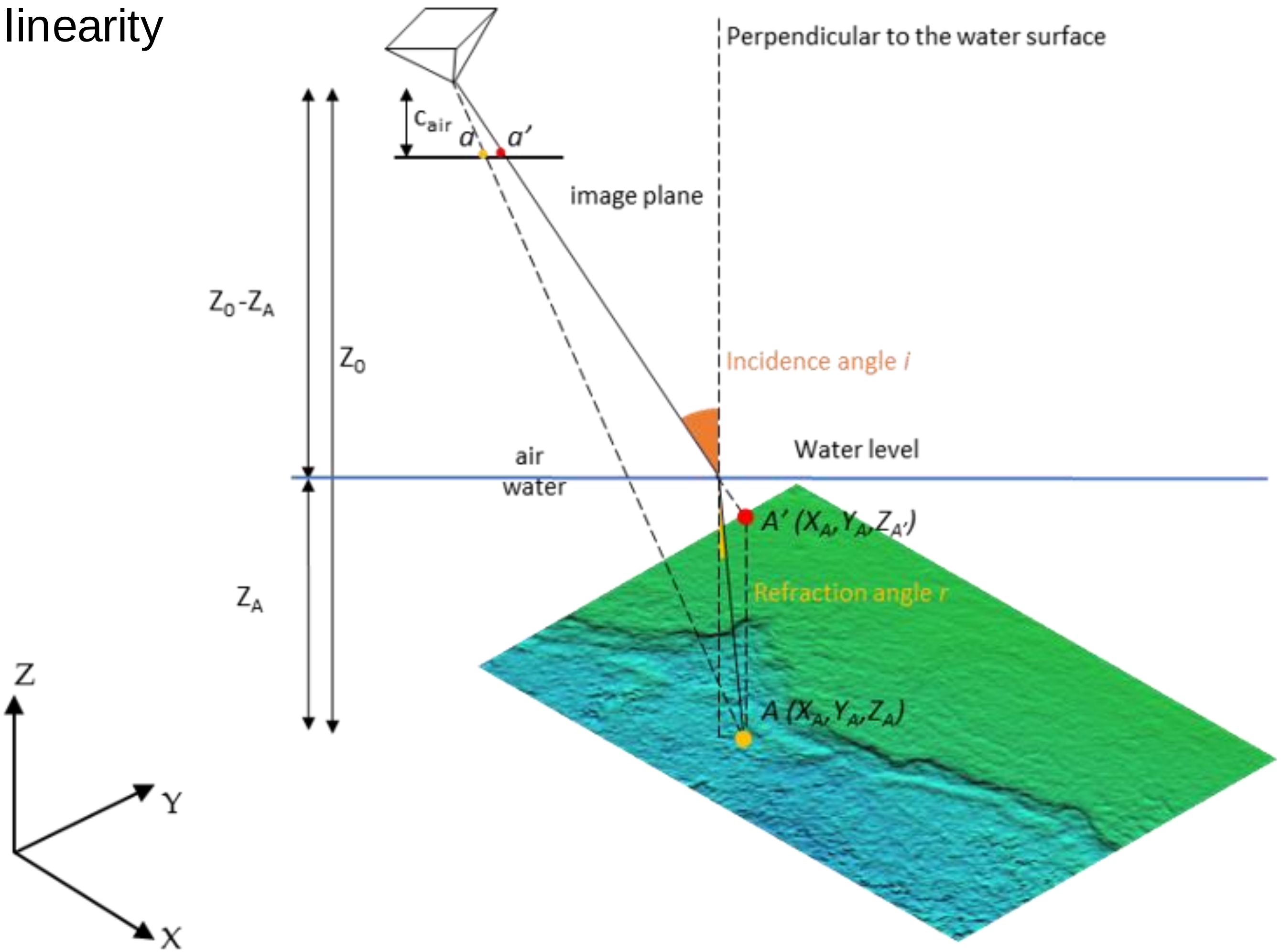
RMSE of about 30-40% of the real depth value!

Example:
A point at 13.5m depth would appear at 10m depth



Single View Geometry

- Violation of the Collinearity Equation
- Apparent depths



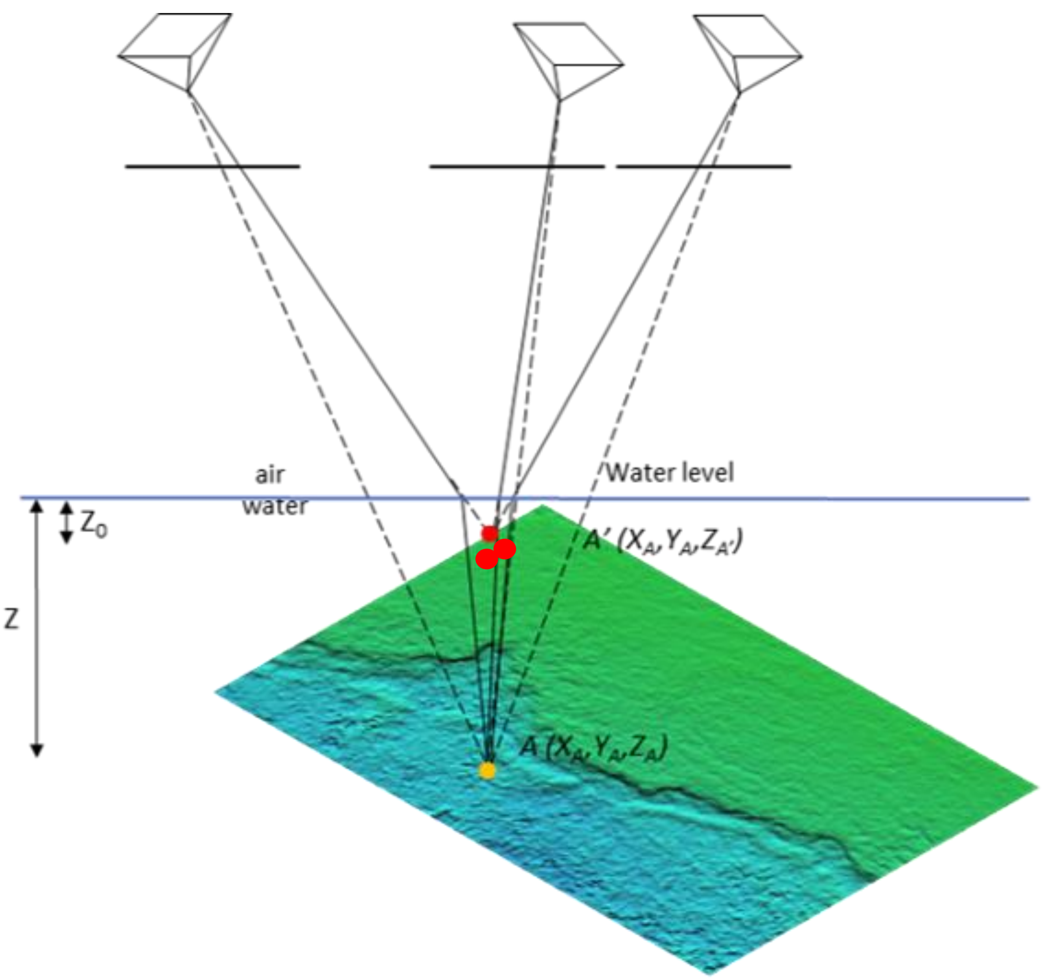
RSiM

Multiple-View Geometry

- Violation of the Collinearity Equation – different for each point -> for each image

- Apparent depths

- Increased noise in the 3D point clouds



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Refraction correction basics

Since SfM-MVS software is delivering 3D point clouds even when refraction is ignored, can we skip it?

– **NO**, it's physics!

To deliver accurate SfM-MVS results, orthoimages, Digital Elevation Models etc., the correction of refraction effects is necessary!

Stereo-based bathymetry

How?

Structure from Motion – Multi-View Stereo + Refraction correction

Refraction correction

Analytical correction

Modification of the collinearity equation. (1950…)

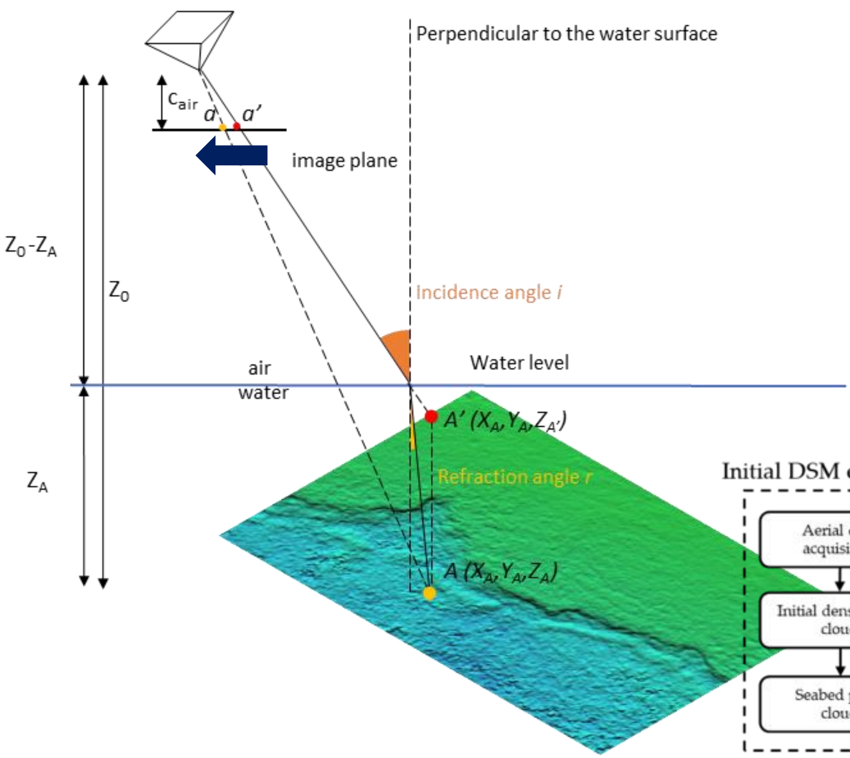
Image-space correction

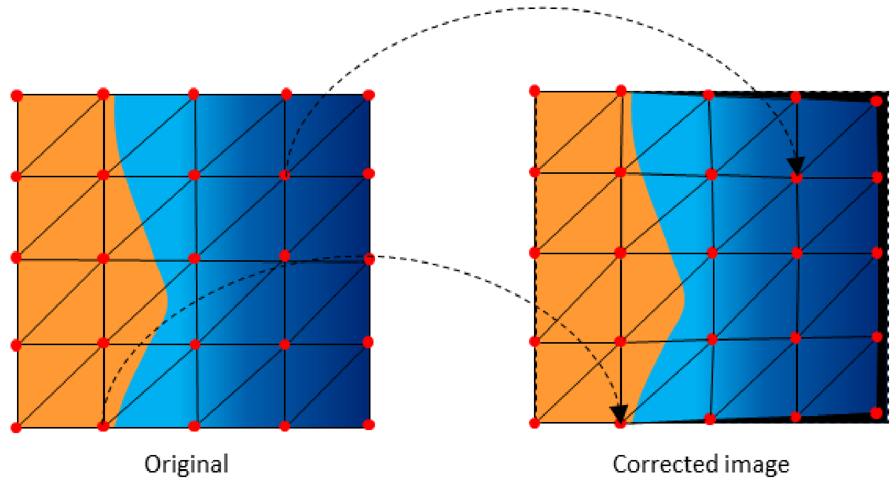
Re-projection of the original photo to correct the water refraction. (2018…)

Machine learning-based

Depends on machine learning models that learn the underestimation of depths and predict the correct depth knowing only the apparent one. (2019…)

Image Space Correction





Agrafiotis et al., 2019

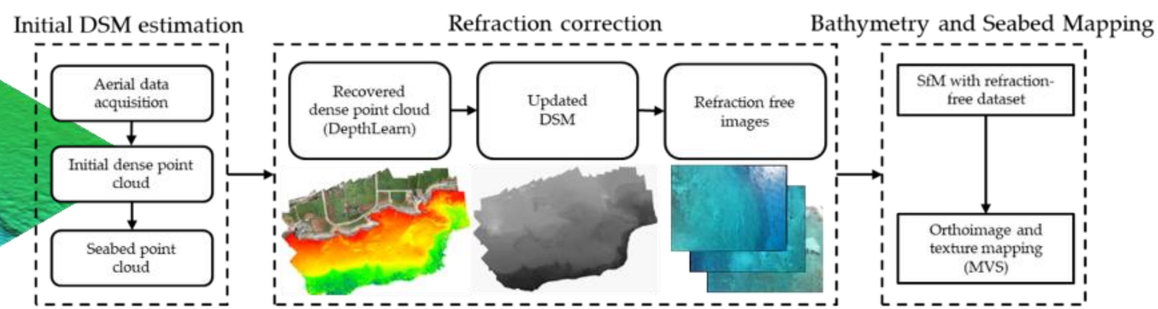


Image Space Correction

Uncorrected image

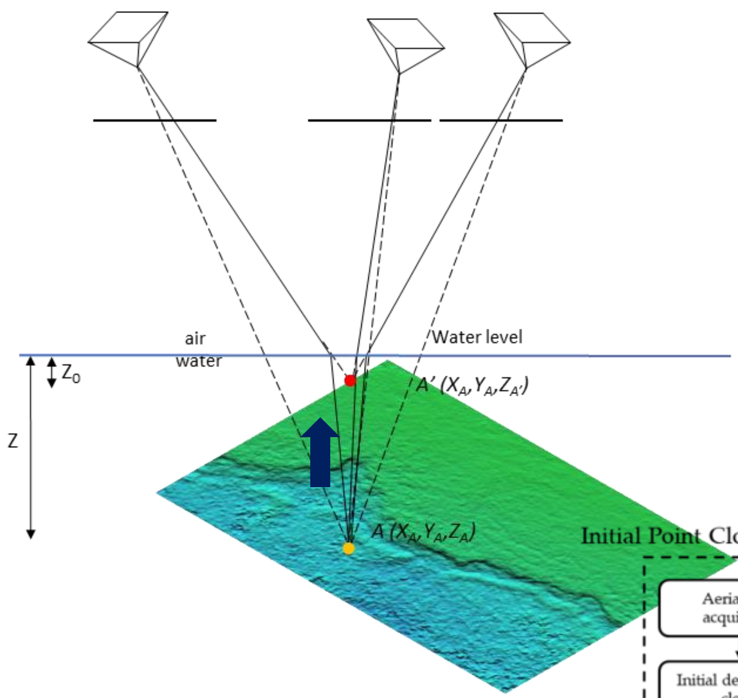
RSiM

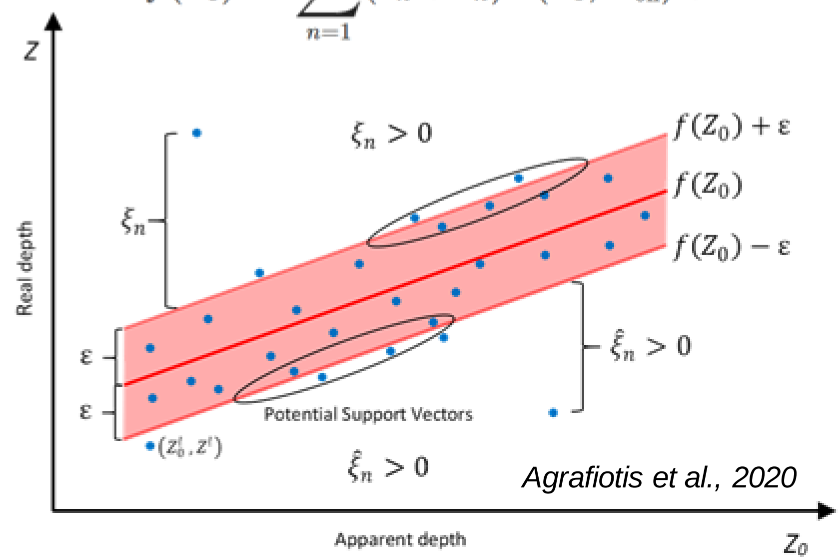
Image Space Correction

Corrected image

3D Space Correction

$$f(Z_0) = \sum_{n=1}^{N} (a_n + \hat{a}_n)\, k(Z_0,\, Z_{0n}) + b$$





Agrafiotis et al., 2020

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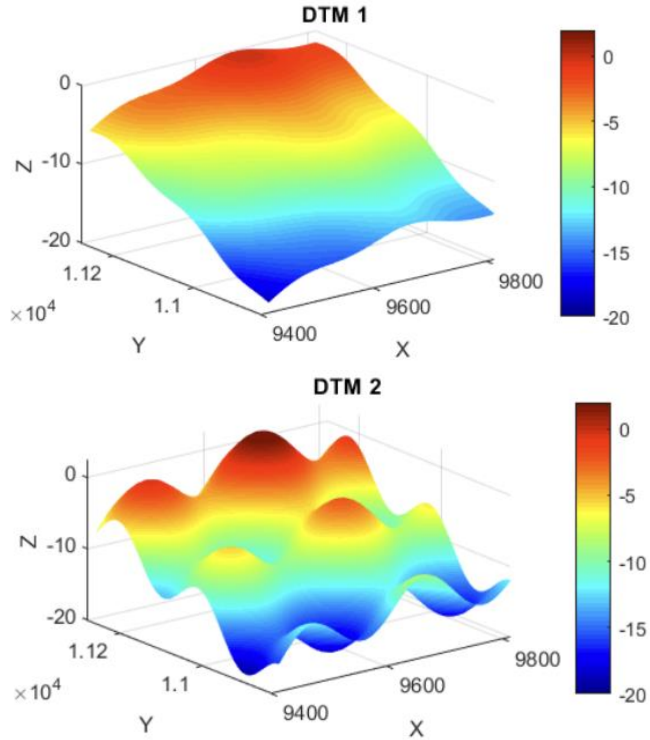
Need for synthetic data

Train ML models

- Avoid errors and limitations in image matching caused by the visibility restrictions (turbidity, caustics, sun glint)

- Avoid errors introduced by the wavy surface

The only unknown is the refraction effect

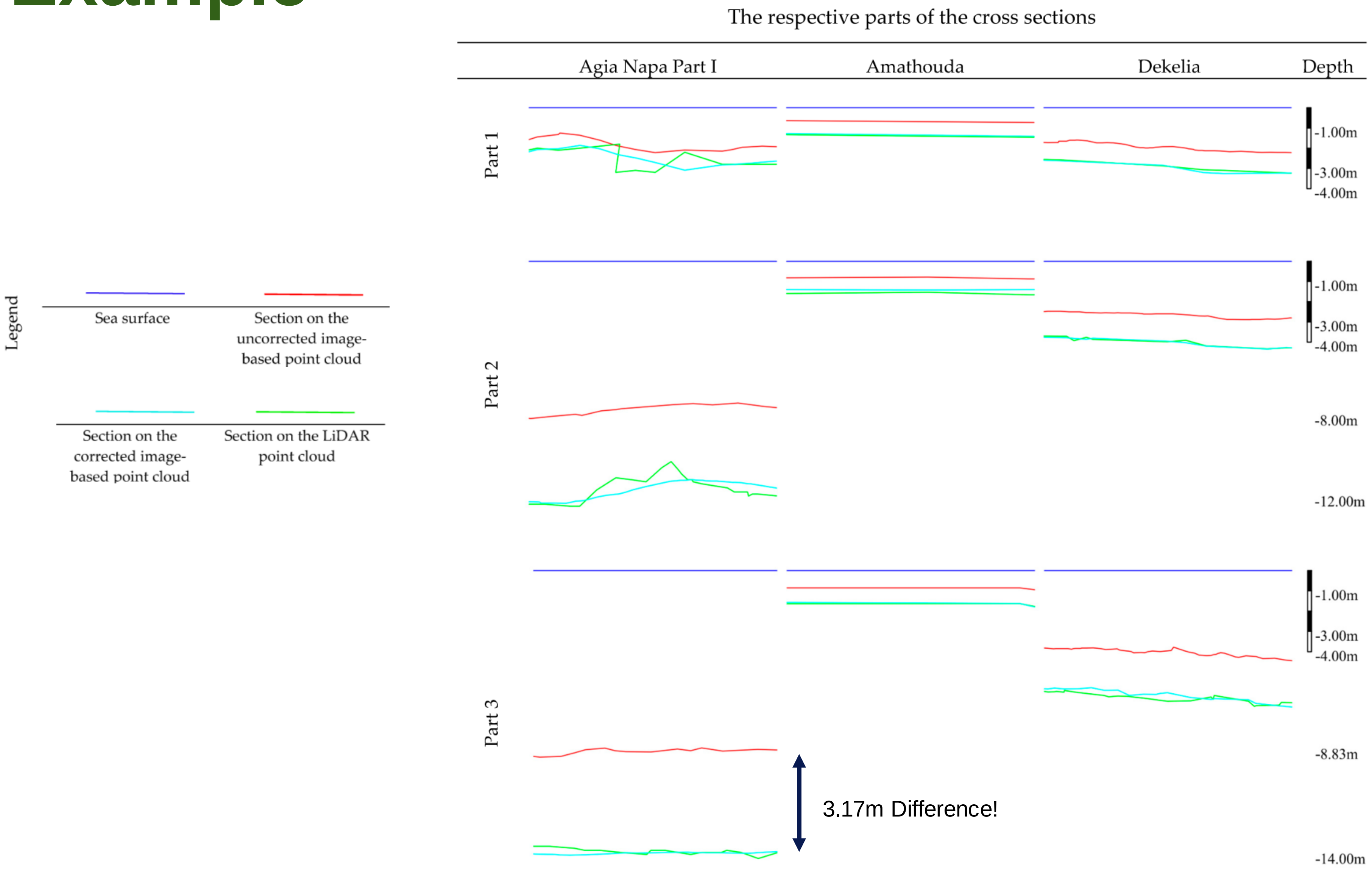


Agrafiotis et al., 2021

Results

65% RMSE reduction compared to the state of the art (LiDAR ground truth data used)
94% RMSE reduction in depth determination between corrected and uncorrected data (LiDAR ground truth data used)

Example



Agrafiotis et al., 2019

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Stereo-based methods

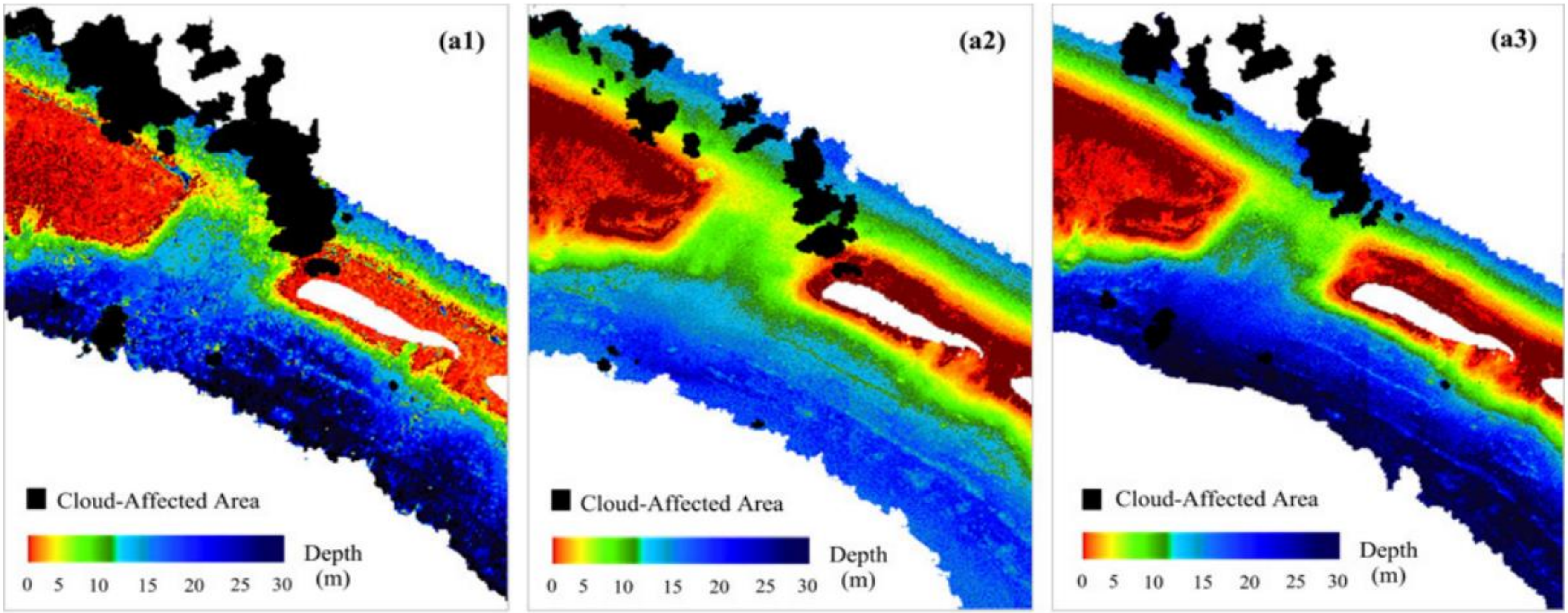
Pros, Issues and Limitations

- Measured depth through triangulation & Delivers color information
- Delivers high 3D point density in shallow water areas
- Max depth ~ 1 Secchi
- Combined DEMs of emerged and submerged areas
- More accurate compared to spectral-based methods, WHEN refraction is corrected

- **Refraction correction is necessary**
- Passive method
- Geometric
- **Requires texture** to perform SfM-MVS

Stereo VS Spectral-based

Stereo-based | **Spectral-based (left image)** | **Spectral-based (right image)**



Cao et al., 2021

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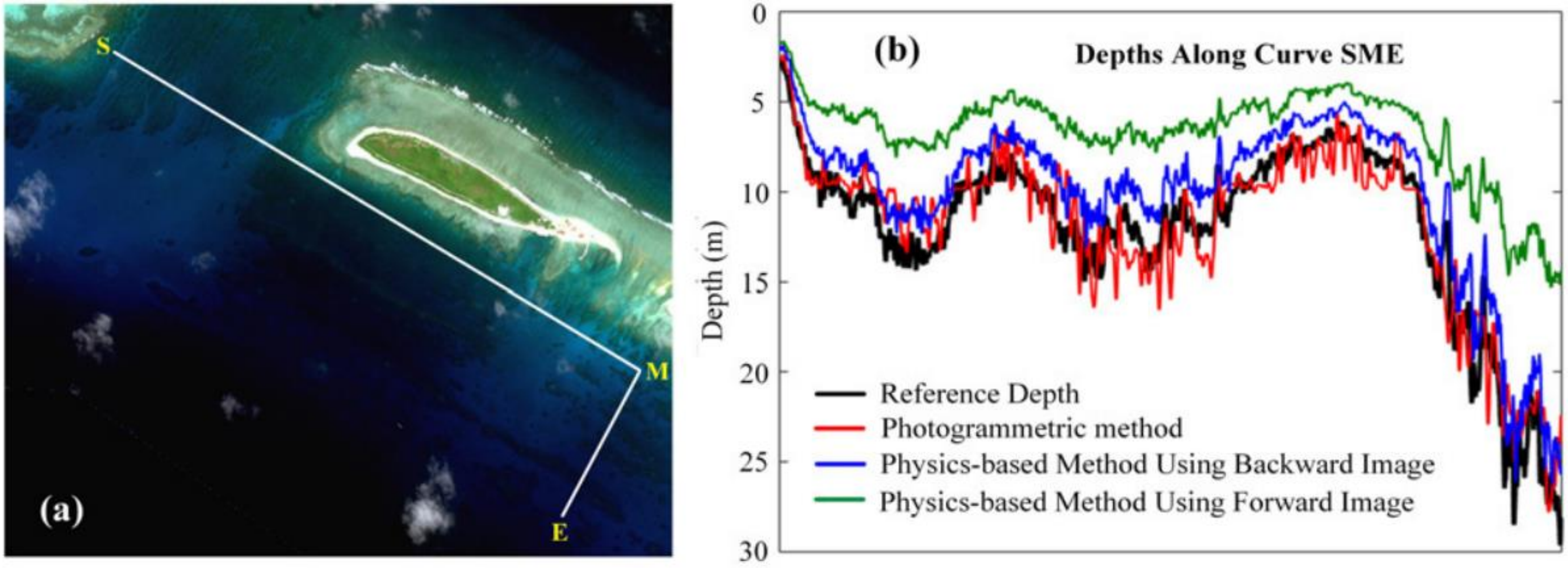
Stereo VS Spectral-based

Cross sections of the derived bathymetries

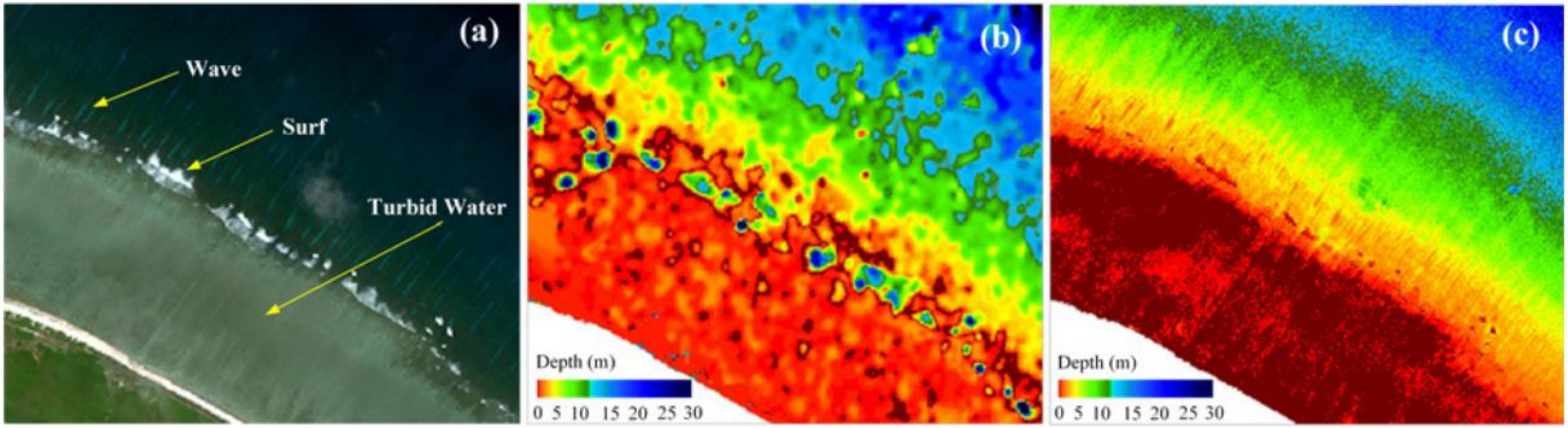


Cao et al., 2021

Stereo VS Spectral-based

Wave breaking and turbidity effects

Stereo-based Spectral-based

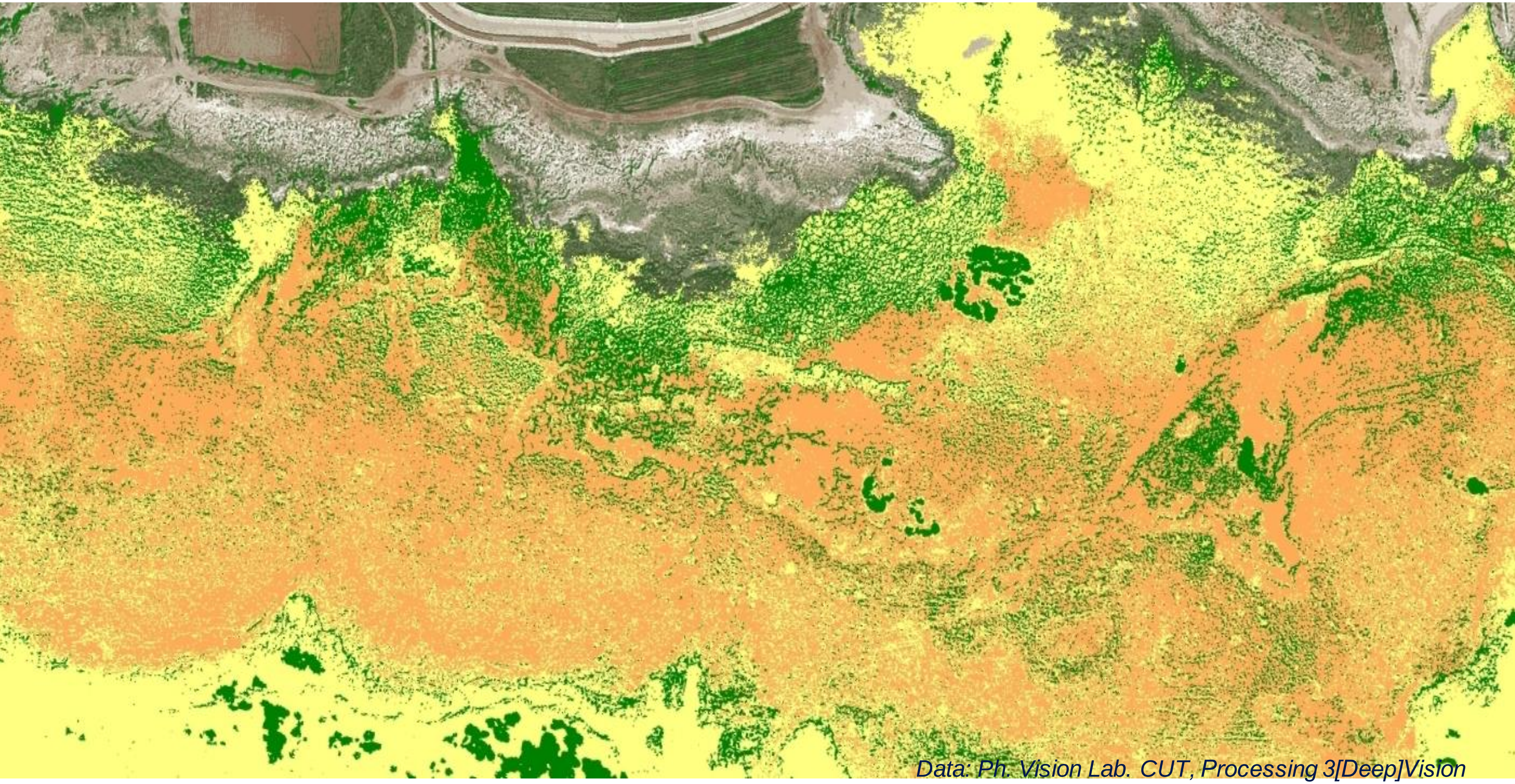


Cao et al., 2021

What info can we get using RGB and MS Remote Sensing Ocean data?

- Biogeochemical indices (chlorophyll, nitrates)
- Sea ice coverage and state
- Sea surface temperature
- Renewable energy monitoring
- Marine debris detection/ tracking
- Pollution/ oil spill detection/ tracking
- Shallow water bathymetry
- **Shallow seabed cover maps**

Shallow seabed cover maps



Data: Ph. Vision Lab. CUT, Processing 3[Deep]Vision

RSiM

Shallow seabed cover maps

How?

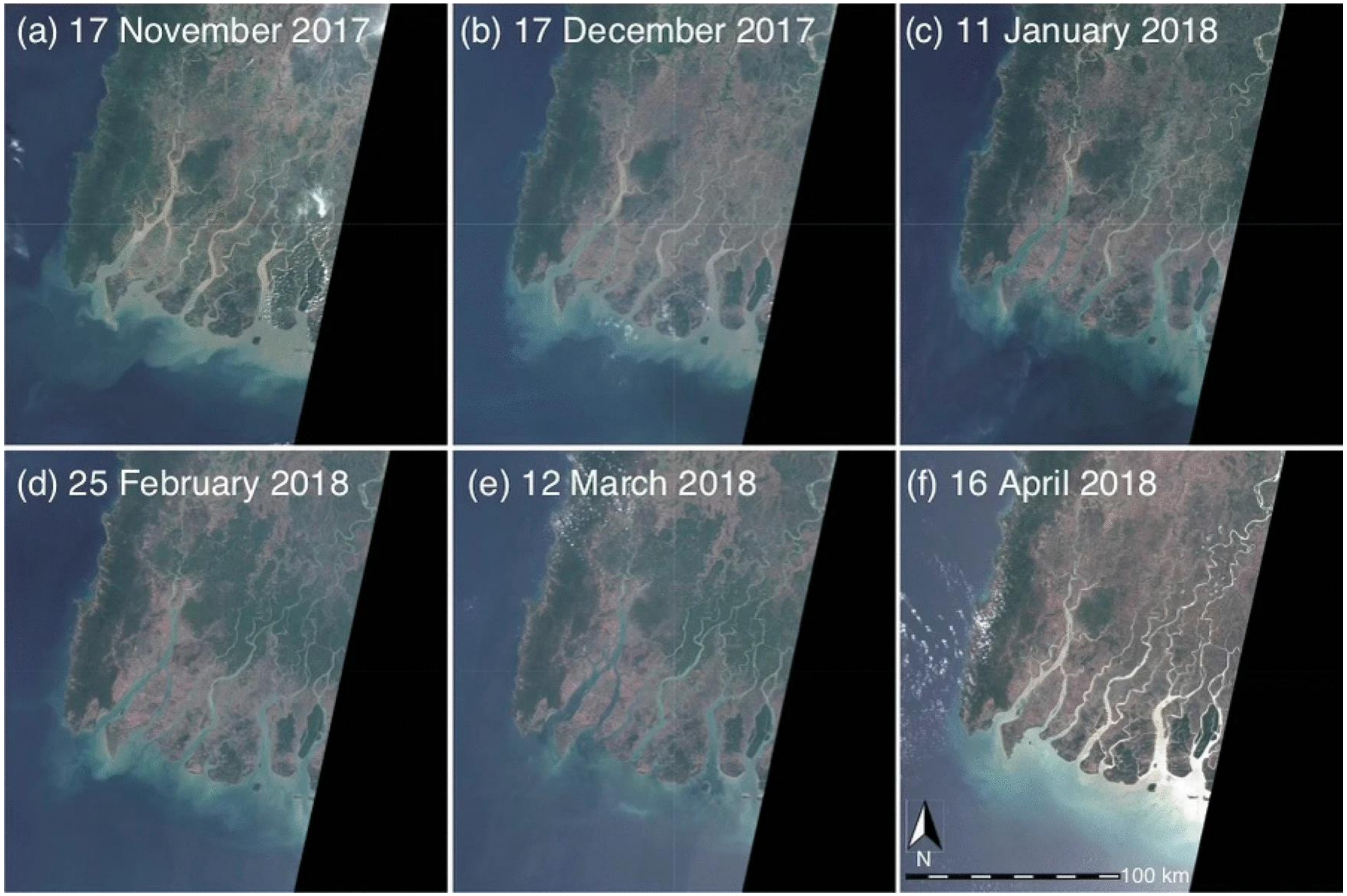
Statistical models: Statistically relate meas. seabed cover and reflectance – need for ground truth data

- From simple linear regression to ML (RFs, SVMs) and DL (FCNs etc.)

Seasonal/Monthly variation

MANY different spectral signatures for same pixels

- Limited generalization of trained models

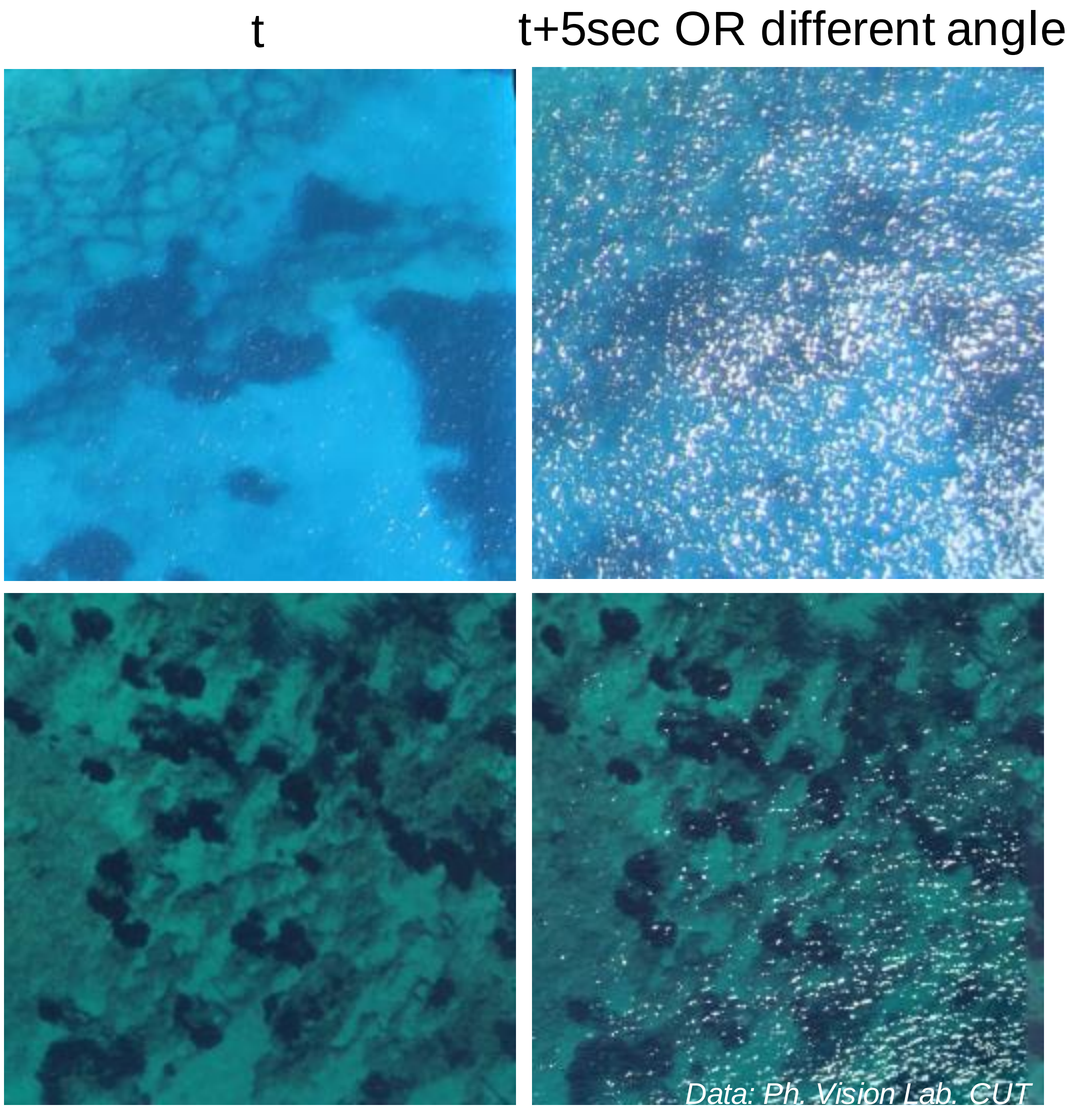


(Sakai et al., 2021)

Instant variation

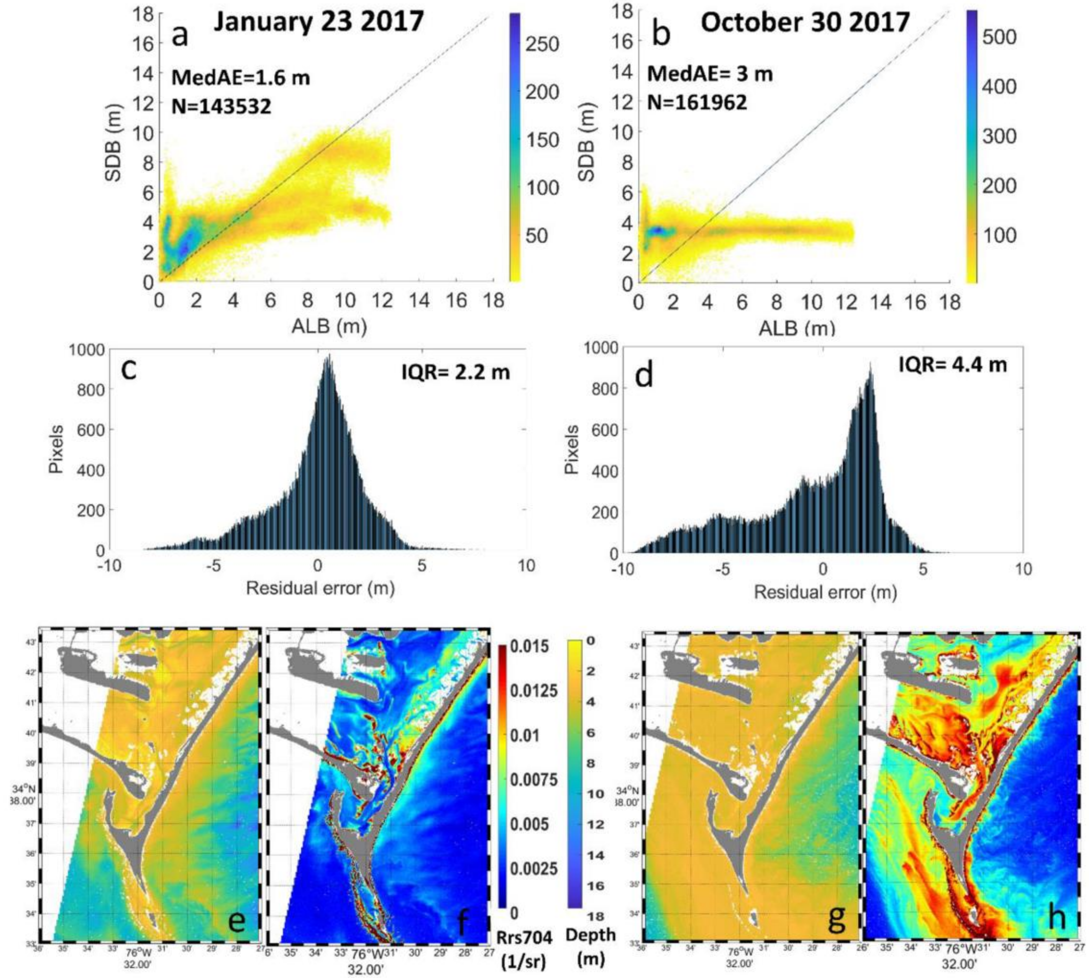
Caused by

- Change in point of view
- Sun glint
- Caustics
- Currents
- Ships and boats
- Clouds



RSiM

Seasonal/Monthly variation



Caballero and Stumpf, 2020

MagicBathy MSCA PF HE Project

MagicBathy

Multimodal multit**A**sk learnin**G** for Mult**I**s**C**ale **BATHY**metric mapping in shallow waters

Funding: HORIZON Europe MSCA Postdoctoral Fellowships - European Fellowships
Host: TU Berlin, RSiM group
Duration: 24 Months
Starting date: 1st of February 2023

Web: https://www.magicbathy.eu/

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