# Satellite Derived Bathymetry (SDB) Using OLI/MSI Based-On Physics-Based Algorithm

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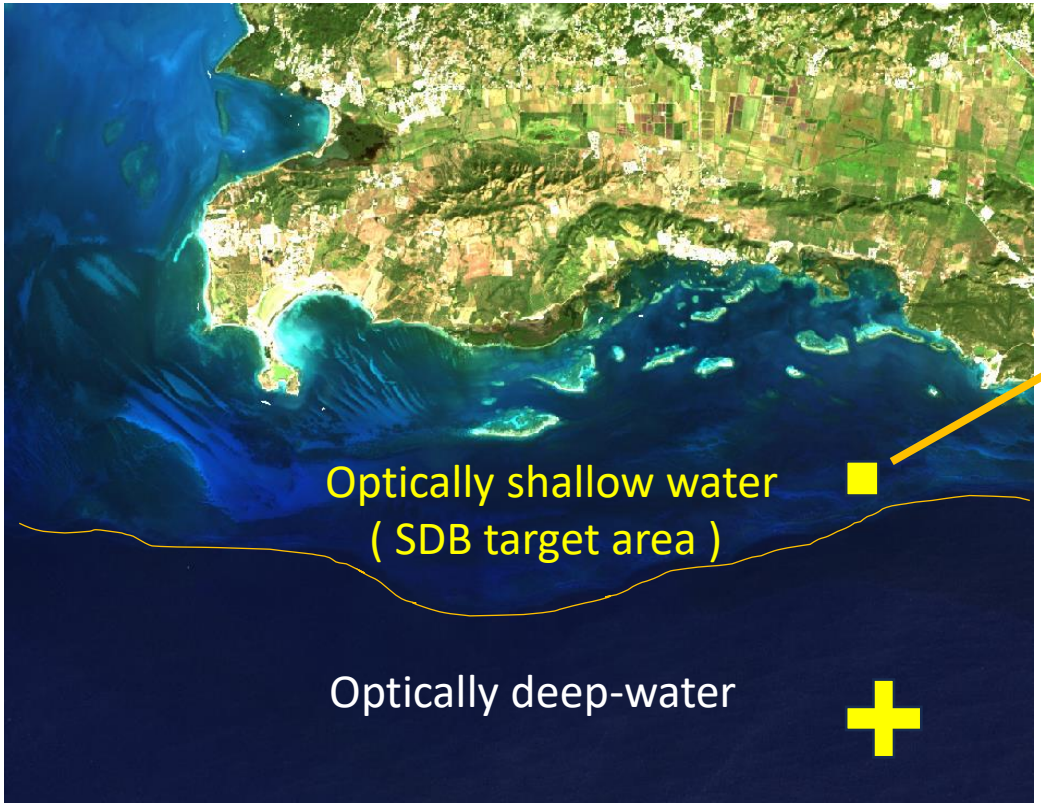
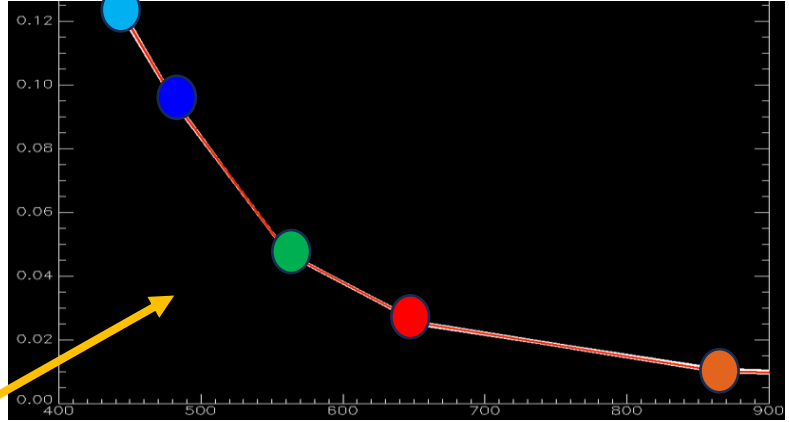
**Work performed under USGS Contract [G15PCXXXXX].**

Jeff Danielson, USGS EROS

**ICESat-2 Bathymetry Workshop**
**Wilmington, NC 2025**


9 + unknowns >> 4 knowns
# of bands

## Unknowns :

1 2 3
1. Atmospheric ( Aerosol, ozone, water vapor, . . . )
2. Water ( Phytoplankton, DOM, particulates, . . . )
4 5 6
3. Depth 7
4. Bottom ( How many bottom types ? )
8 9 . . .

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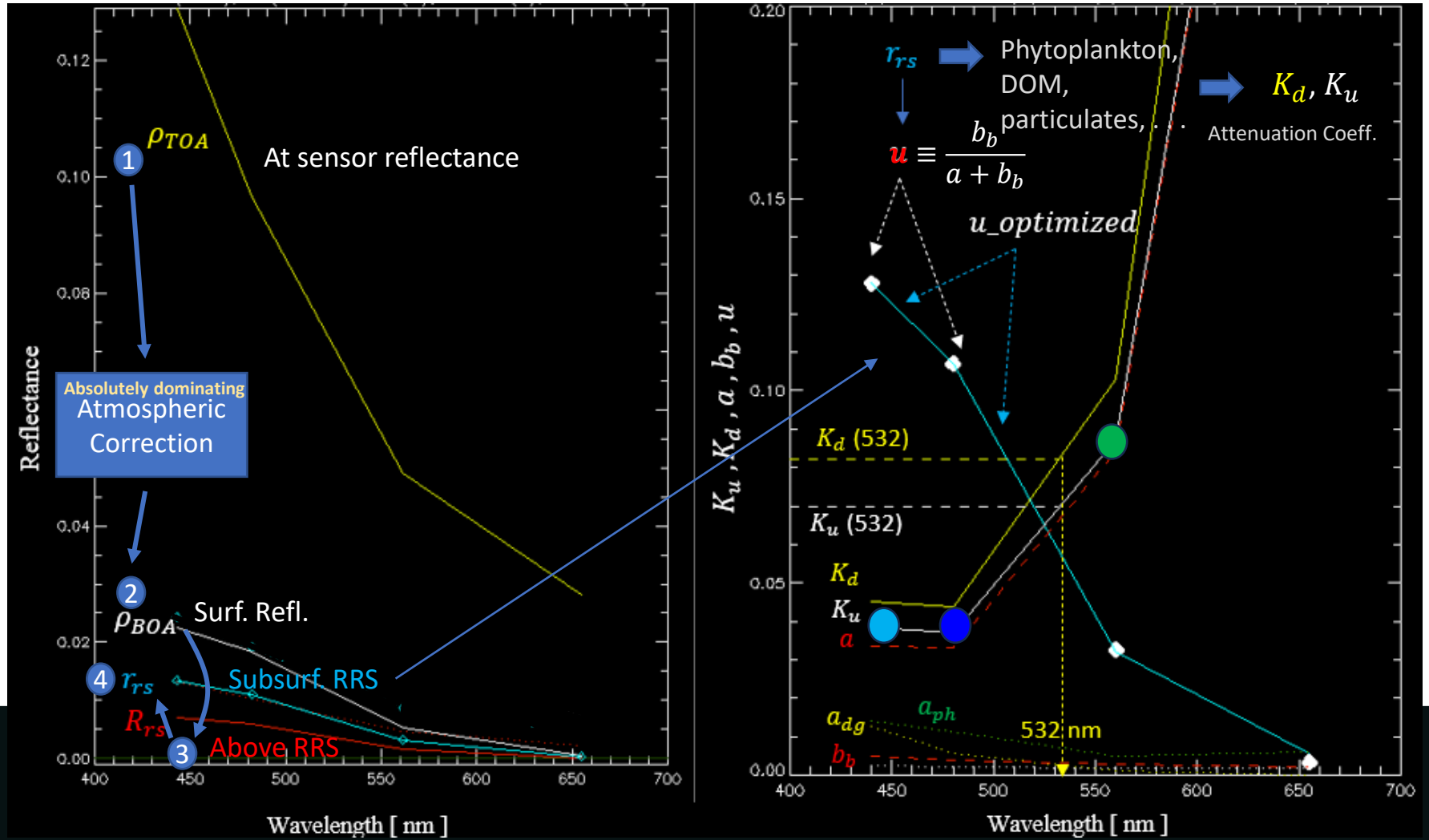
1
$\rho_{TOA}$
At sensor reflectance
Absolutely dominating
Atmospheric
Correction
2
$\rho_{BOA}$
Surf. Refl.
4
$r_{rs}$
Subsurf. RRS
$R_{rs}$
3
Above RRS
Reflectance
Wavelength [ nm ]
$r_{rs}$
Phytoplankton,
DOM,
particulates, . . .
$u \equiv \frac{b_b}{a + b_b}$
$K_d$, $K_u$
Attenuation Coeff.
u_optimized
$K_u, K_d, a, b_b, u$
$K_d$ (532)
$K_u$ (532)
$K_d$
$K_u$
$a$
$a_{dg}$
$a_{ph}$
$b_b$
532 nm
Wavelength [ nm ]

remote sensing

MDPI

*Article*

# Physics-Based Satellite Derived Bathymetry (SDB) using Landsat OLI Image

**Minsu Kim [1,*], Jeff Danielson [2], C**

$$\rho_b = \pi \cdot r_{rs}(z) \cdot \exp[(K_u + K_d) \cdot z] .$$

$$\boldsymbol{\Sigma} = (\boldsymbol{\rho_b} - \overline{\rho_b}) \cdot (\boldsymbol{\rho_b} - \overline{\rho_b})^T .$$

$$\rho_{TOA} = \frac{\pi \cdot L_{TOA} \cdot D_{ES}^2}{\cos SZA \cdot F_0} \cdot$$

$$a_{dg}(\lambda) = a_{dg}(\lambda_0) \cdot \exp[-$$

$$e(\lambda; \boldsymbol{P}) = [u_0(\lambda) - u$$

Atmospheric Optics
Atmospheric R.T.
Atmospheric Correction

Hydro (Ocean) Optics
Ocean R.T.
Bio-optical Inversion

$$\boldsymbol{J}(\Phi_A;\lambda) \equiv \frac{\partial u}{\partial \Phi_A} = \frac{\partial u}{\partial a} \cdot \frac{\partial a}{\partial A} \cdot \frac{\partial A}{\partial \Phi_A} = \exp[-$$

$$\boldsymbol{J}(\Phi_B;\lambda) \equiv \frac{\partial u}{\partial \Phi_B} = \frac{\partial u}{\partial b_b} \cdot \frac{\partial b_b}{\partial B} \cdot \frac{\partial B}{\partial \Phi_B} = \left(\frac{\lambda_0}{\lambda}\right)^n \cdot \frac{a(\lambda)}{(a(\lambda)+b_b(\lambda))^2} \cdot \frac{B_{min} - B_{max}}{2} \cdot \sin\Phi_B ,$$

$$\boldsymbol{J}(\Phi_C;\lambda) \equiv \frac{\partial u}{\partial \Phi_C} = \frac{\partial u}{\partial a} \cdot \frac{\partial a}{\partial C} \cdot \frac{\partial C}{\partial \Phi_C} = 0.06 \cdot 0.65 \cdot C^{-0.35} \cdot a_C^*(\lambda) \cdot \frac{b_b(\lambda)}{(a(\lambda)+b_b(\lambda))^2} \cdot \frac{C_{max} - C_{min}}{2}$$

$$\boldsymbol{J}(\Phi_S;\lambda) \equiv \frac{\partial r_{rs}}{\partial \Phi_G} = \frac{\partial r_{rs}}{\partial C_g} \cdot \frac{\partial C_g}{\partial \Phi_G} = \left(\frac{\rho_{bg}}{\pi}\right) \cdot \exp[-(K_u + K_d) \cdot z] \cdot \frac{G_{min} - G_{max}}{2} \cdot \sin\Phi_G ,$$

$$\frac{\partial r_{rs}}{\partial \Phi_z} = \frac{\partial r_{rs}}{\partial z} \cdot \frac{\partial z}{\partial \Phi_z} = (K_u + K_d) \cdot \left(r_{rs,\infty} - \left(\frac{\rho_b}{\pi}\right)\right) \cdot \exp[-(K_u + K_d) \cdot z] \cdot \frac{z_{min} - z_{max}}{2} \cdot \sin\Phi_z .$$

$$\left(\frac{\rho_{bs} - \rho_{bg}}{\pi}\right) \cdot \exp[-(K_u + K_d) \cdot z] \cdot \frac{S_{min} - S_{max}}{2} \cdot \sin\Phi_S .$$

$$K_d = \frac{a + b_b}{\cos(SZA\_w)} , \qquad SZA_w = sin^{-1}\left(\frac{\sin(SZA)}{n_w}\right)$$

$$K_u = \frac{a + b_b}{\cos(VZA\_w)} , \qquad VZA_w = sin^{-1}\left(\frac{s}{}\right)$$

$$\rho_b/\pi) \cdot \exp[-(K_u + K_d) \cdot z] ,$$

$$\rho_{bg} .$$

**PB-SDB**
( Physics Based SDB )

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# SDB pixel-by-pixel

Atmospheric Correction

Optically Deep

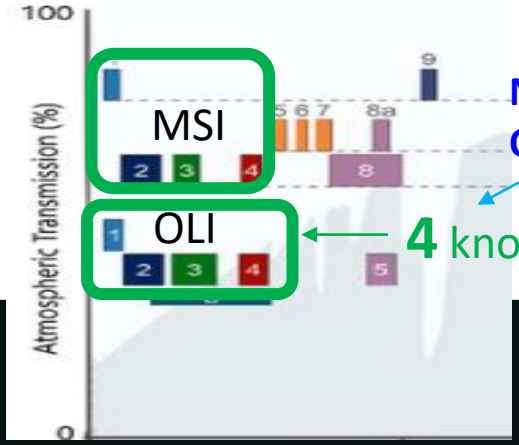
$$\boldsymbol{u(\lambda)} \leftarrow r_{rs} \leftarrow R_{rs} \leftarrow SR \leftarrow TOAR$$

Each Pixel

Ocean Optical Inversion

Depth

$$r_{rs}(z) = r_{rs,\infty} \cdot \{1 - \exp[-(K_u + K_d) \cdot z\} + (\rho_b/\pi) \cdot \exp[-(K_u + K_d) \cdot z]$$




**3** unknowns

**Nonlinear Optimization**

**4** known bands

$C_s \rho_{bs} + C_g \rho_{bg}$

Sand

Grass

Bottom library

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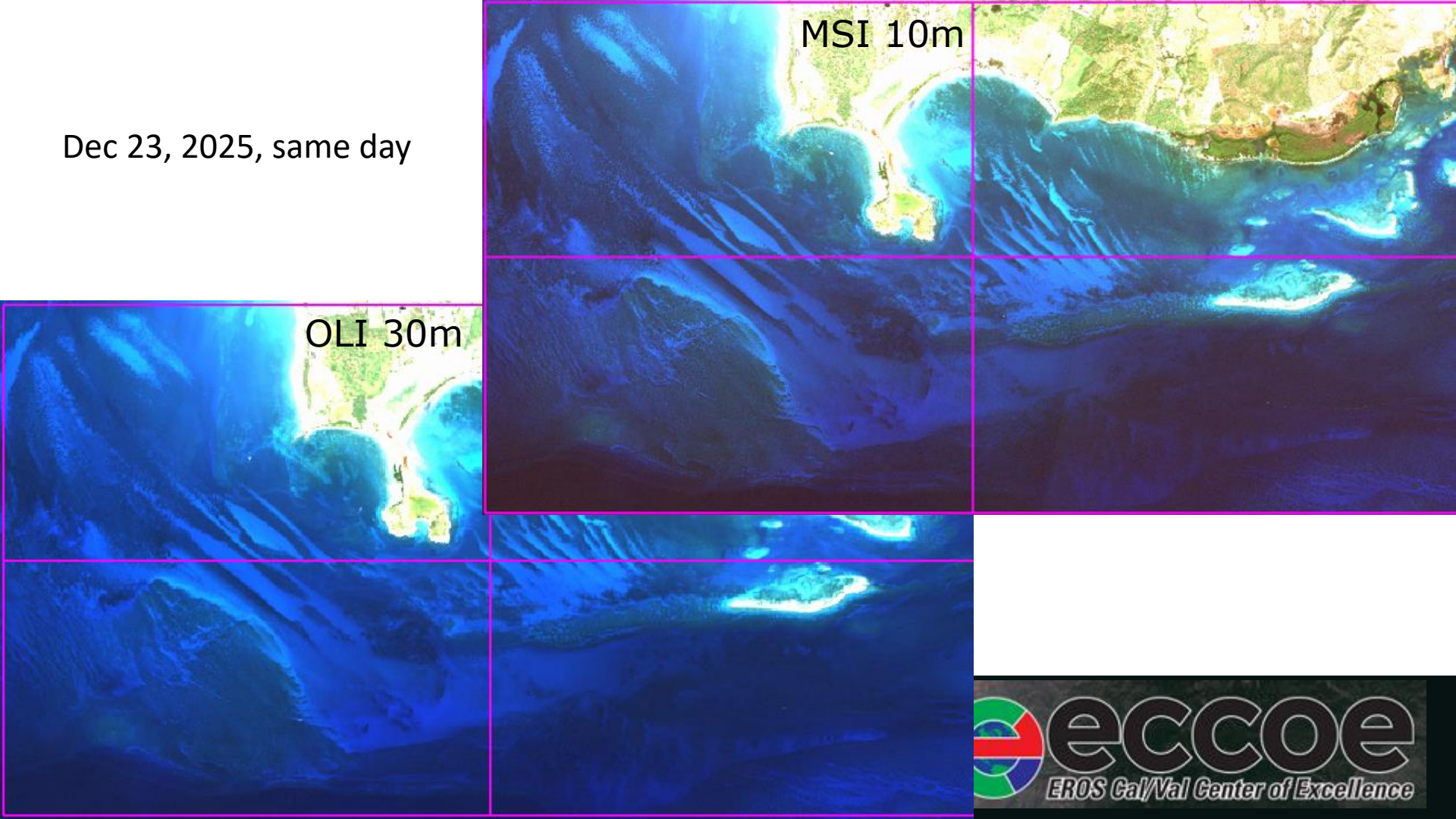
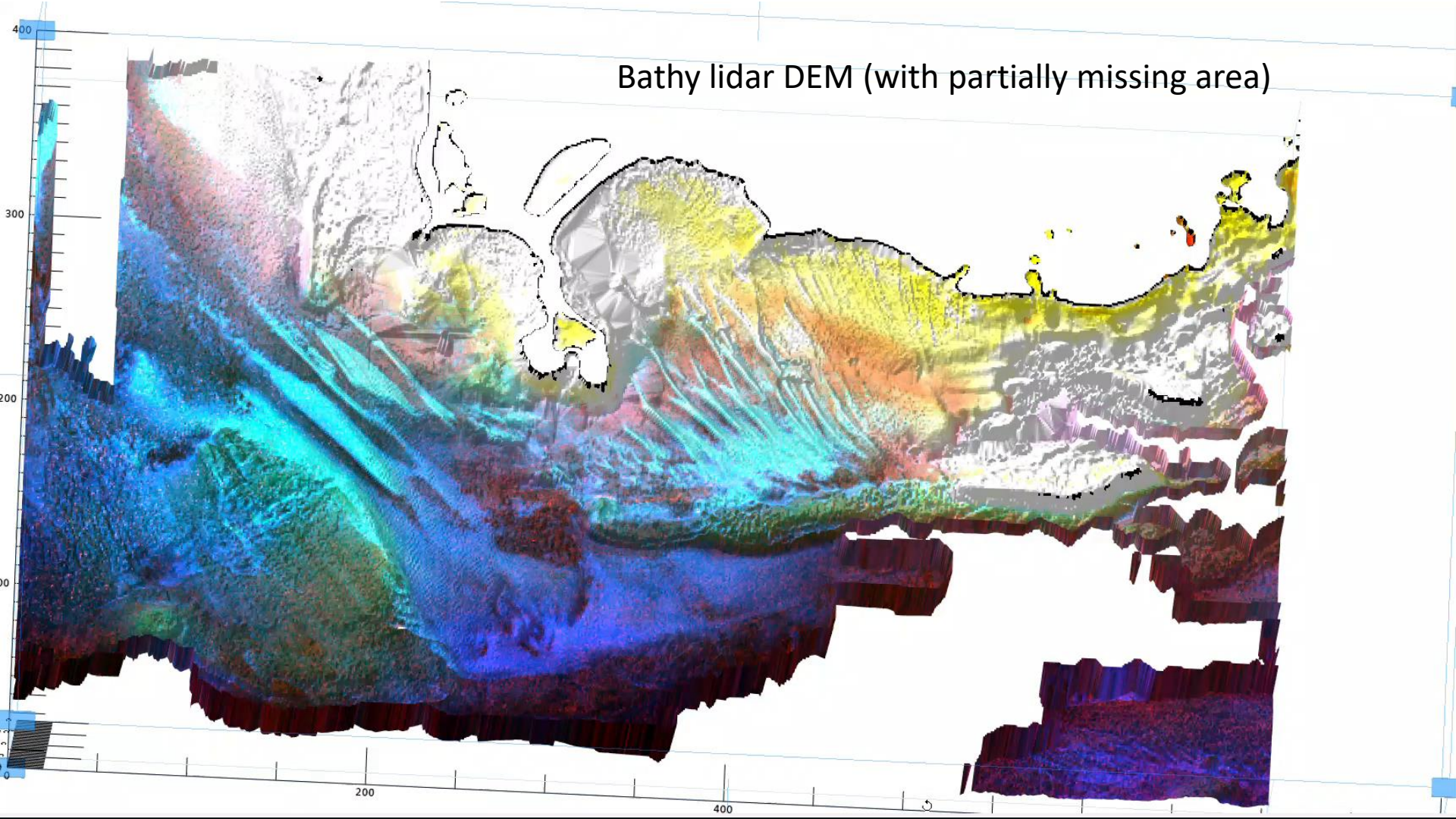
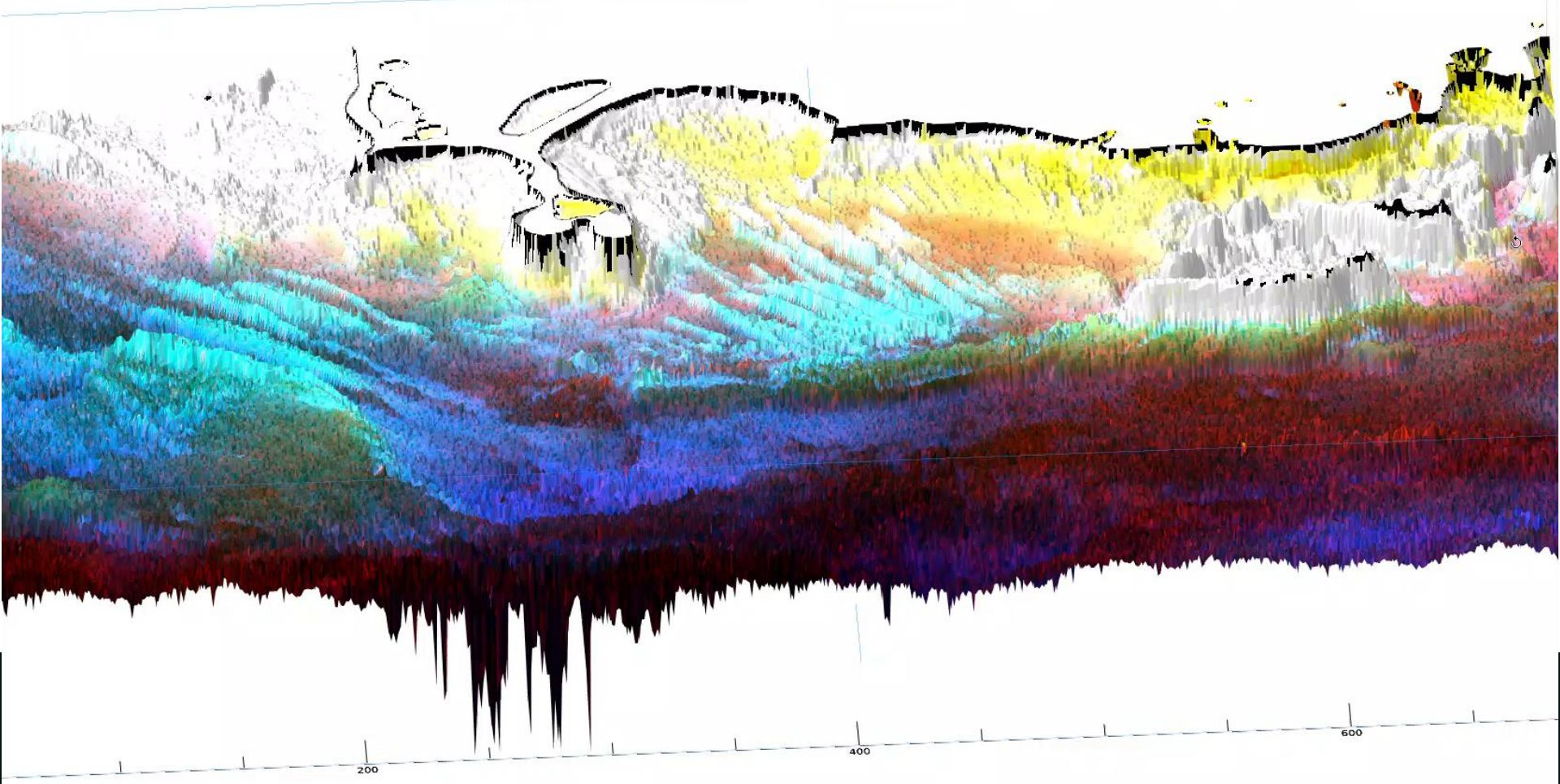
Dec 23, 2025, same day

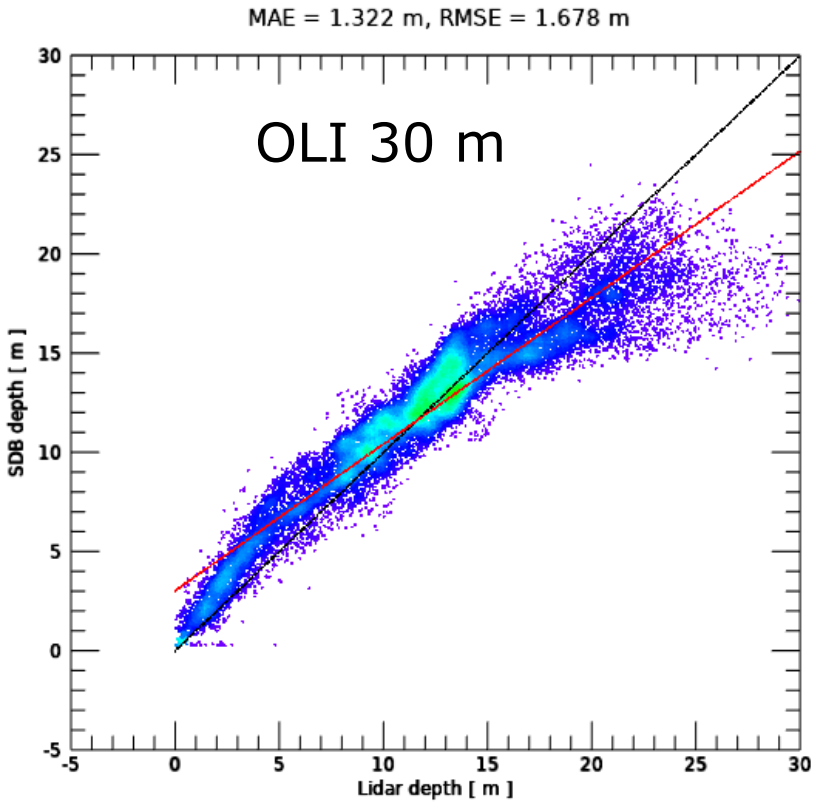


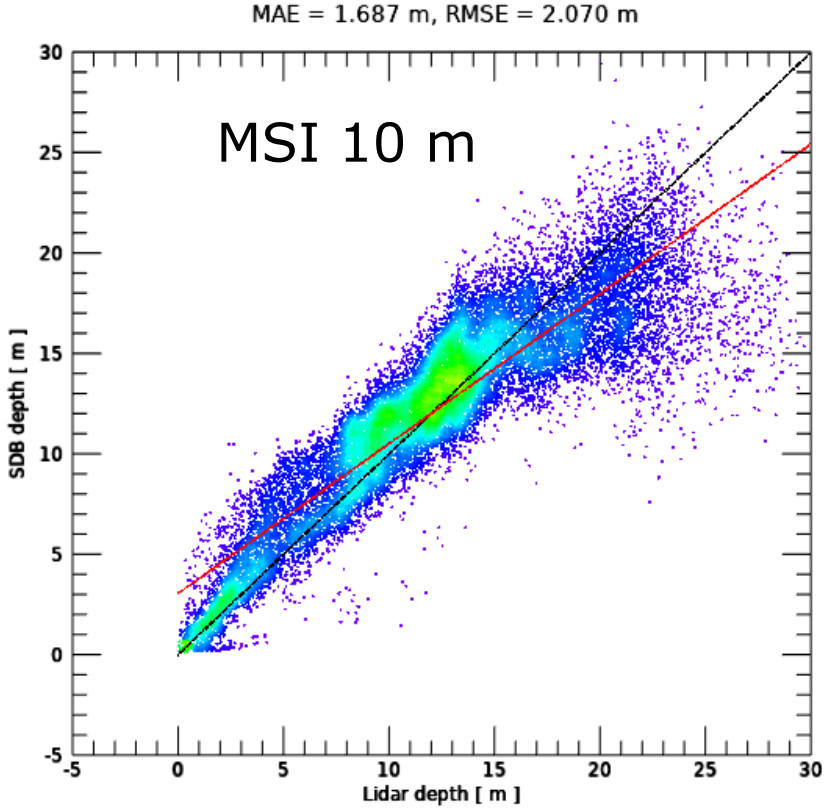

Bathy lidar DEM (with partially missing area)
400
300
200
200
400

# SDB DEM OLI (no missing area)

No MSI result (3M pixels → visualization issue)



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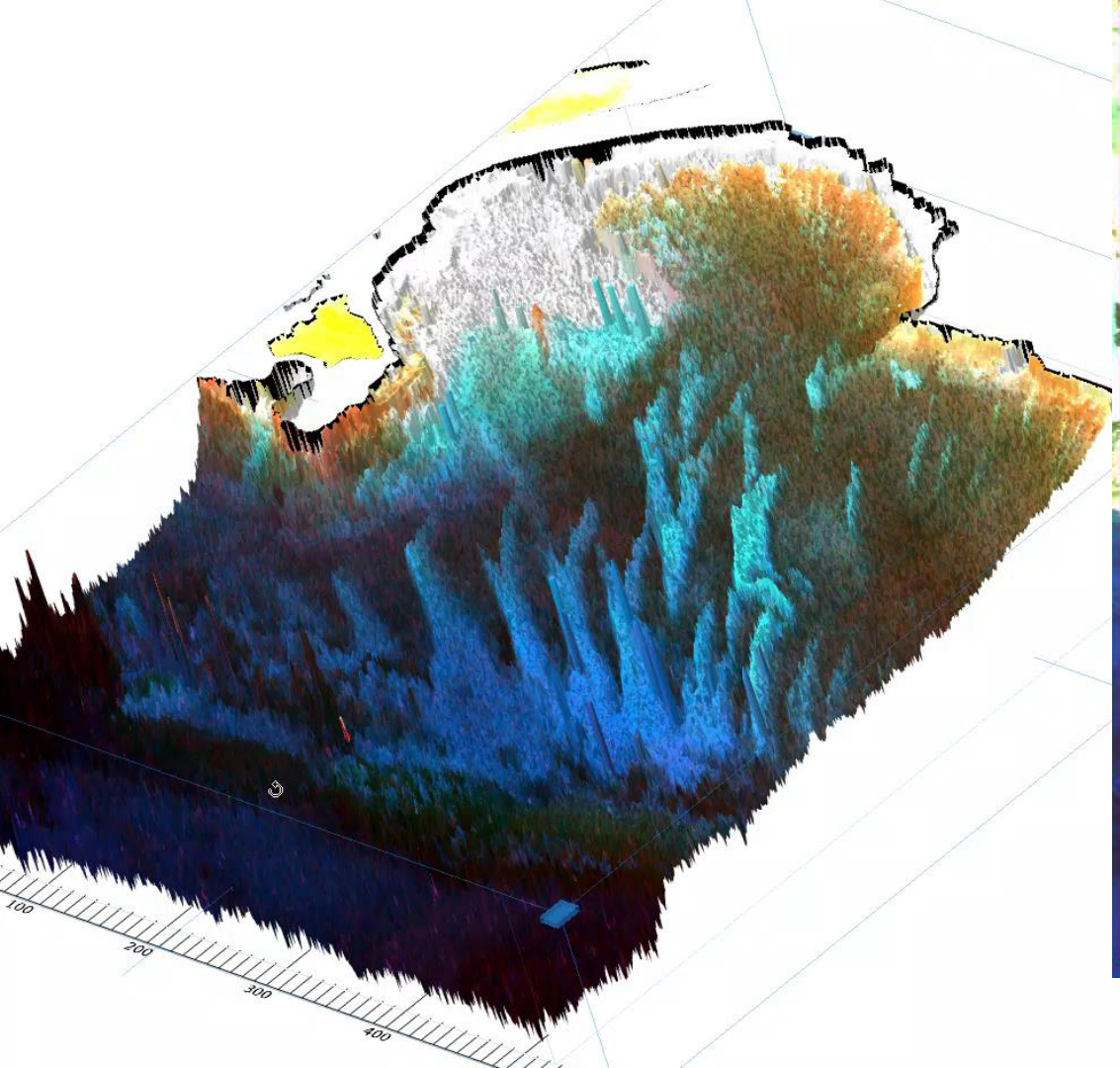
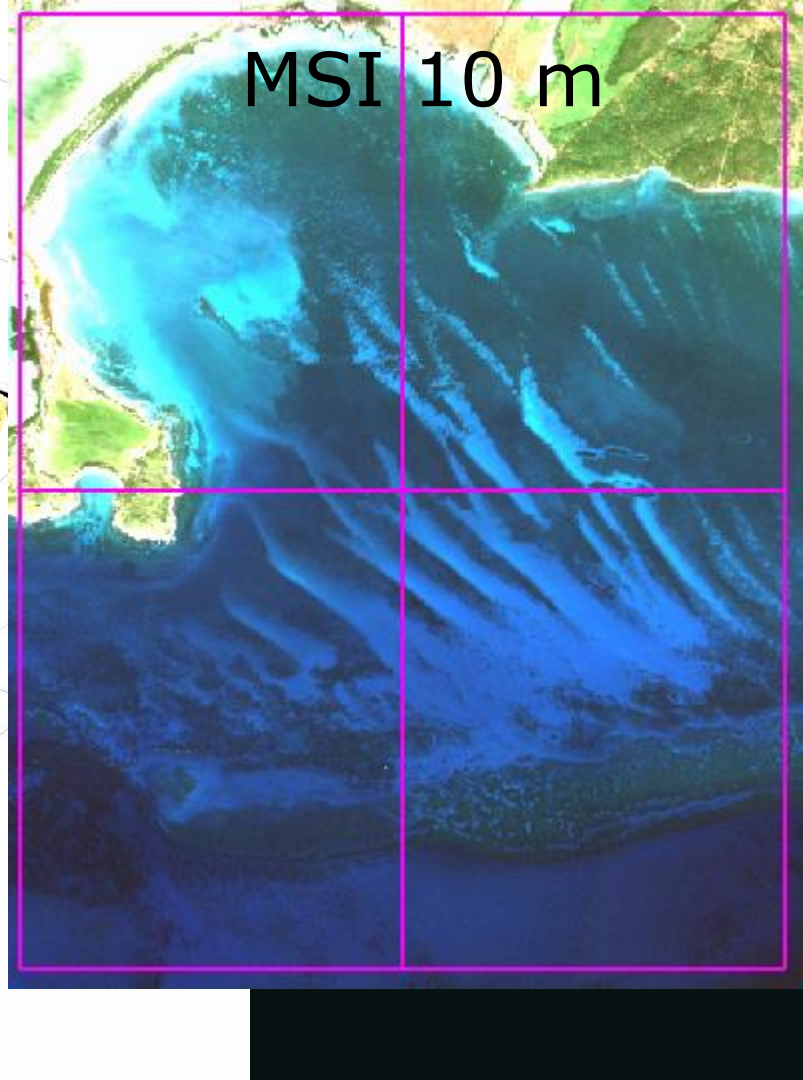
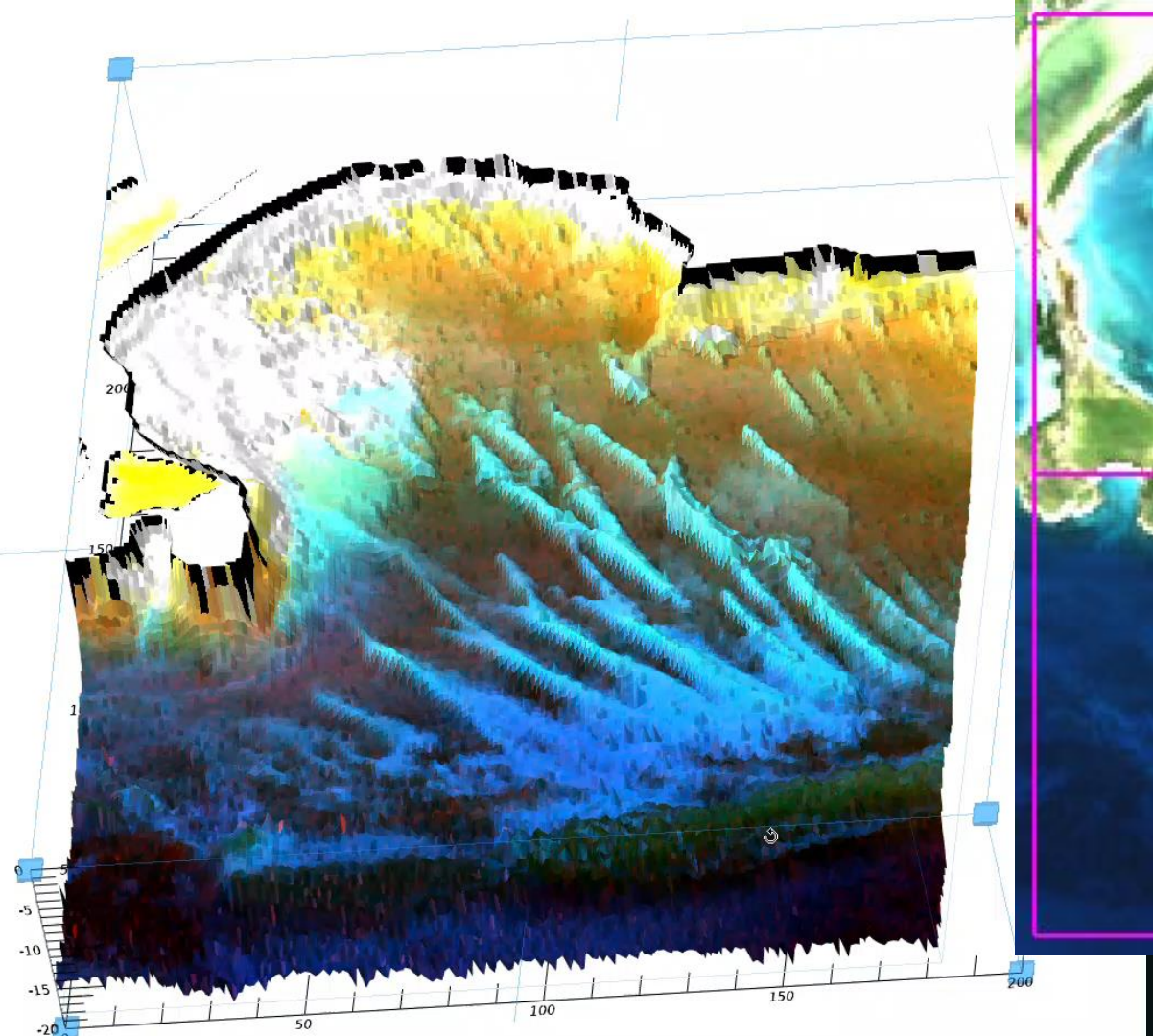
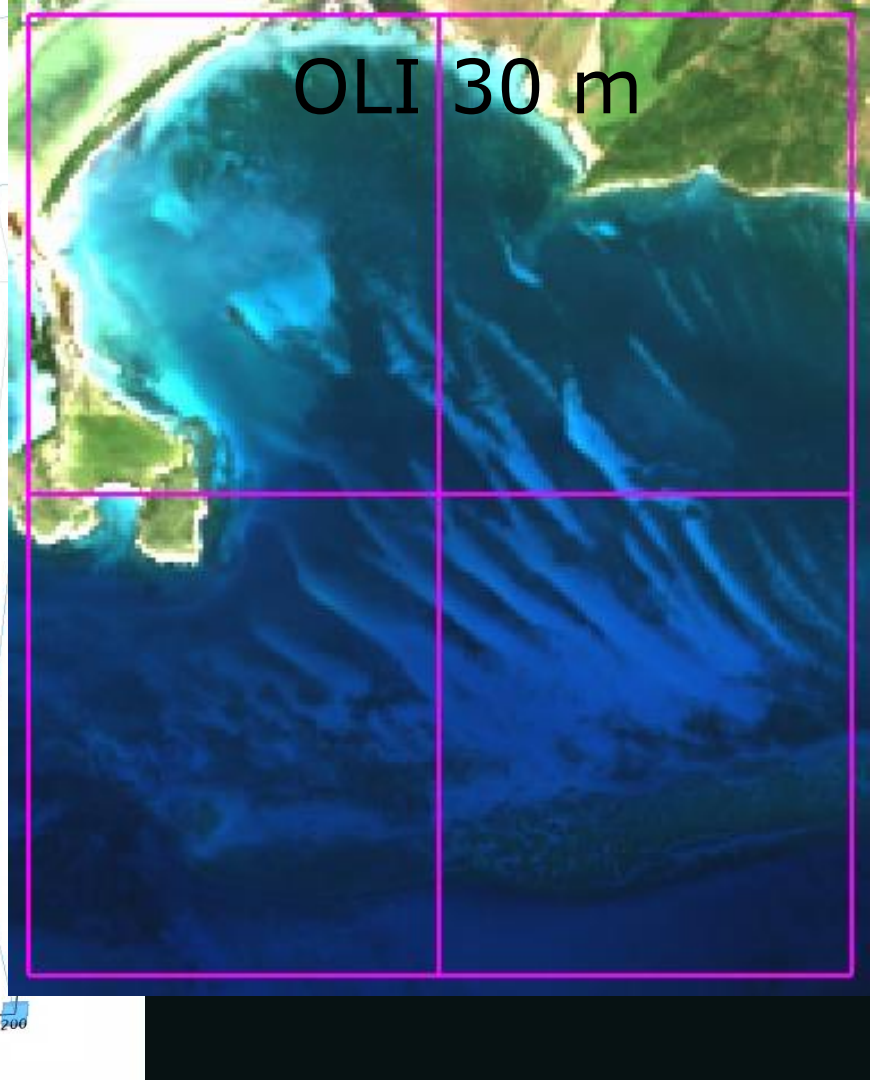
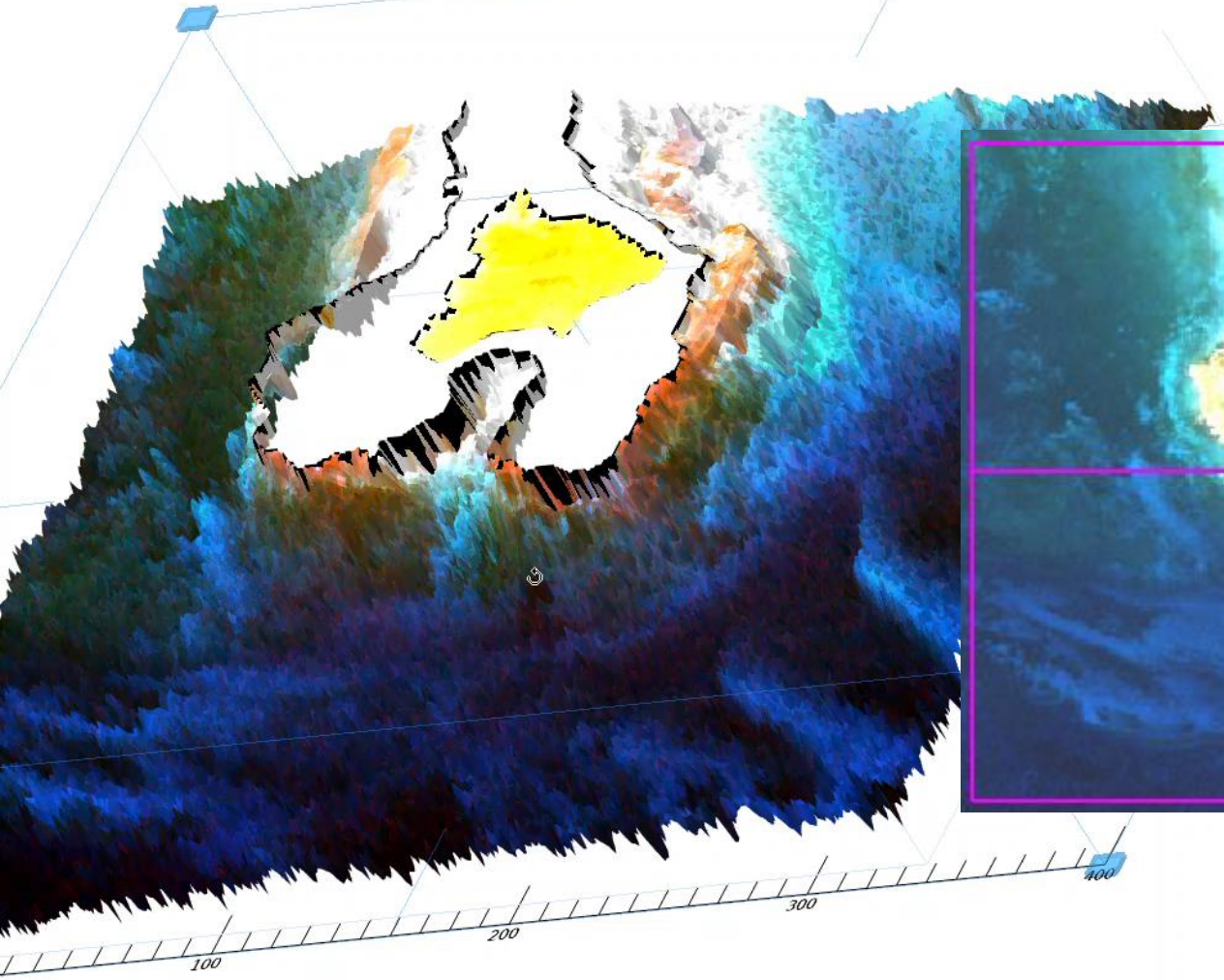

100
200
300
400

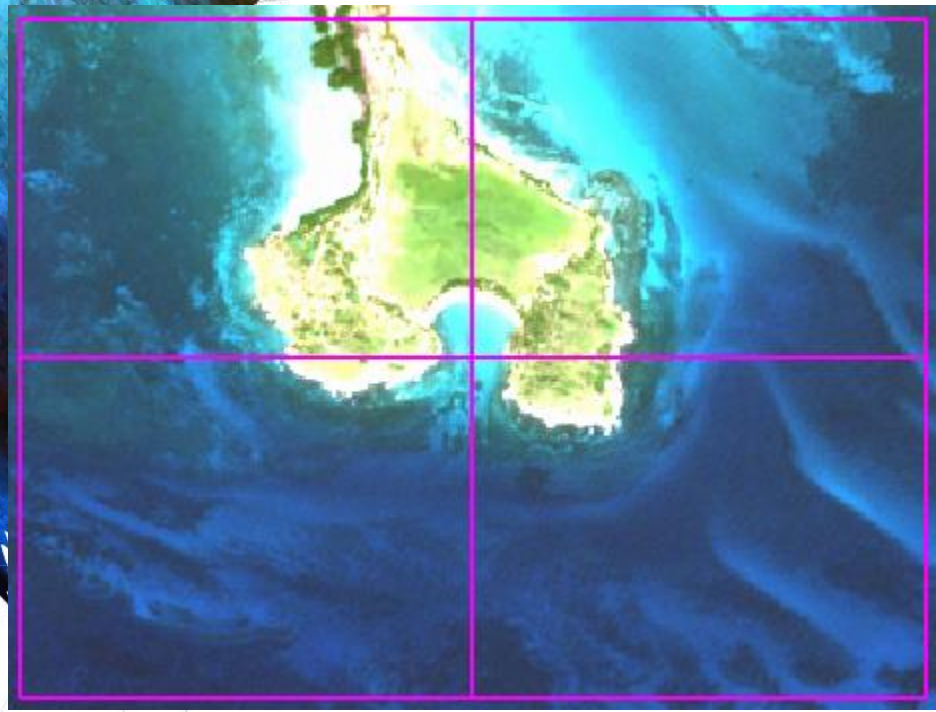

MSI 10 m

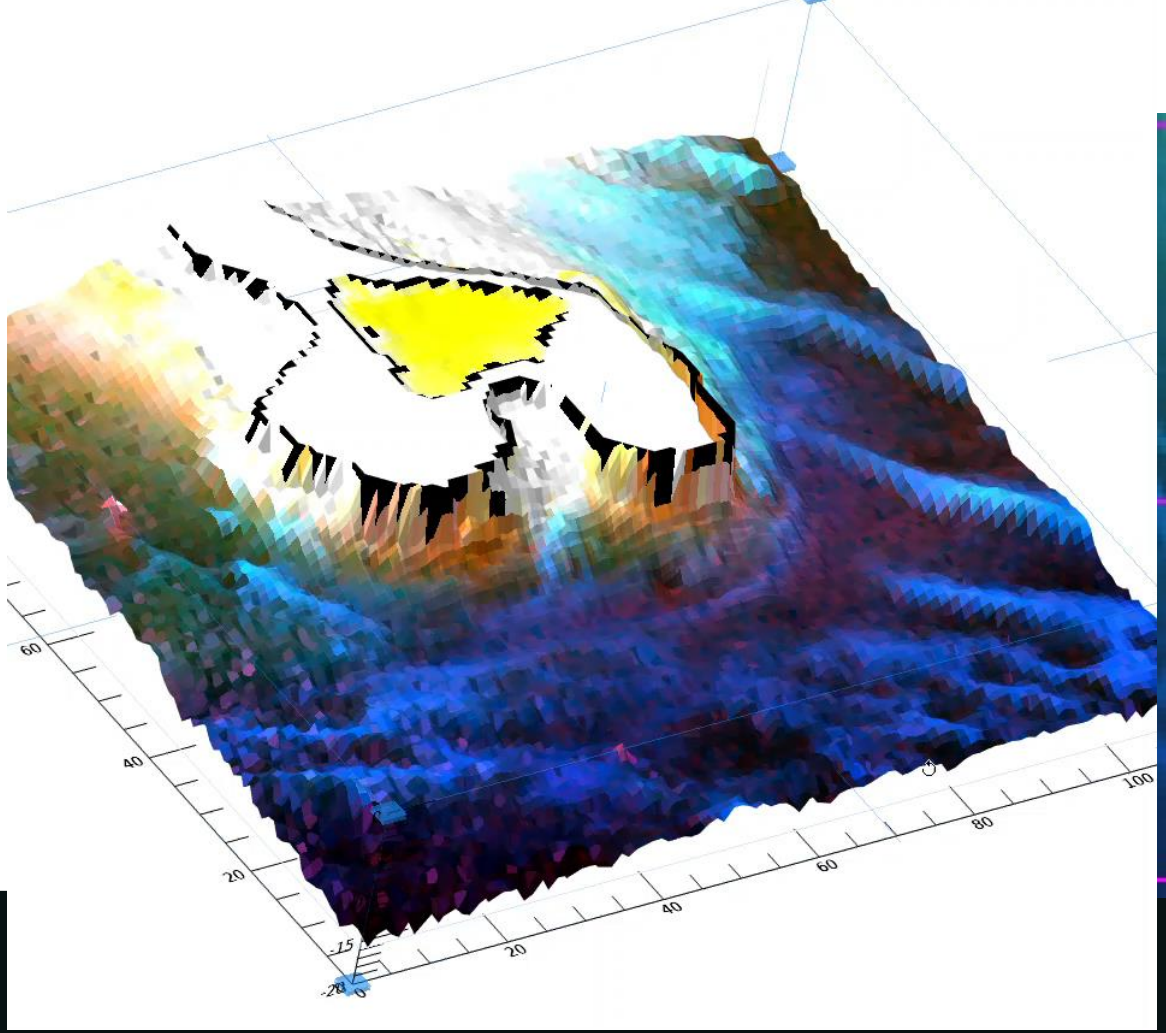

200
150
-5
-10
-15
-20
50
100
150
200


OLI 30 m

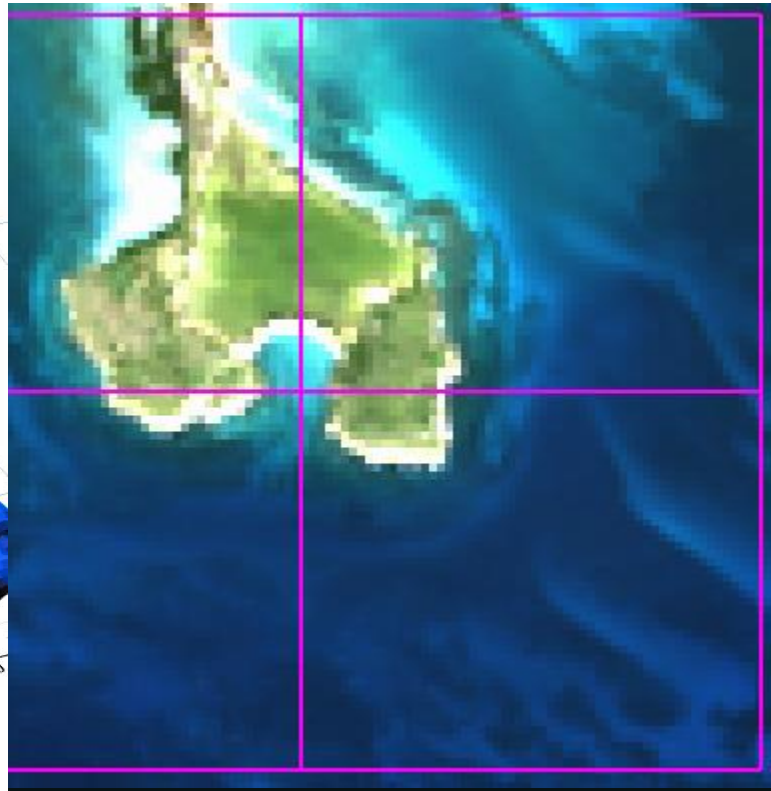
# MSI 10 m



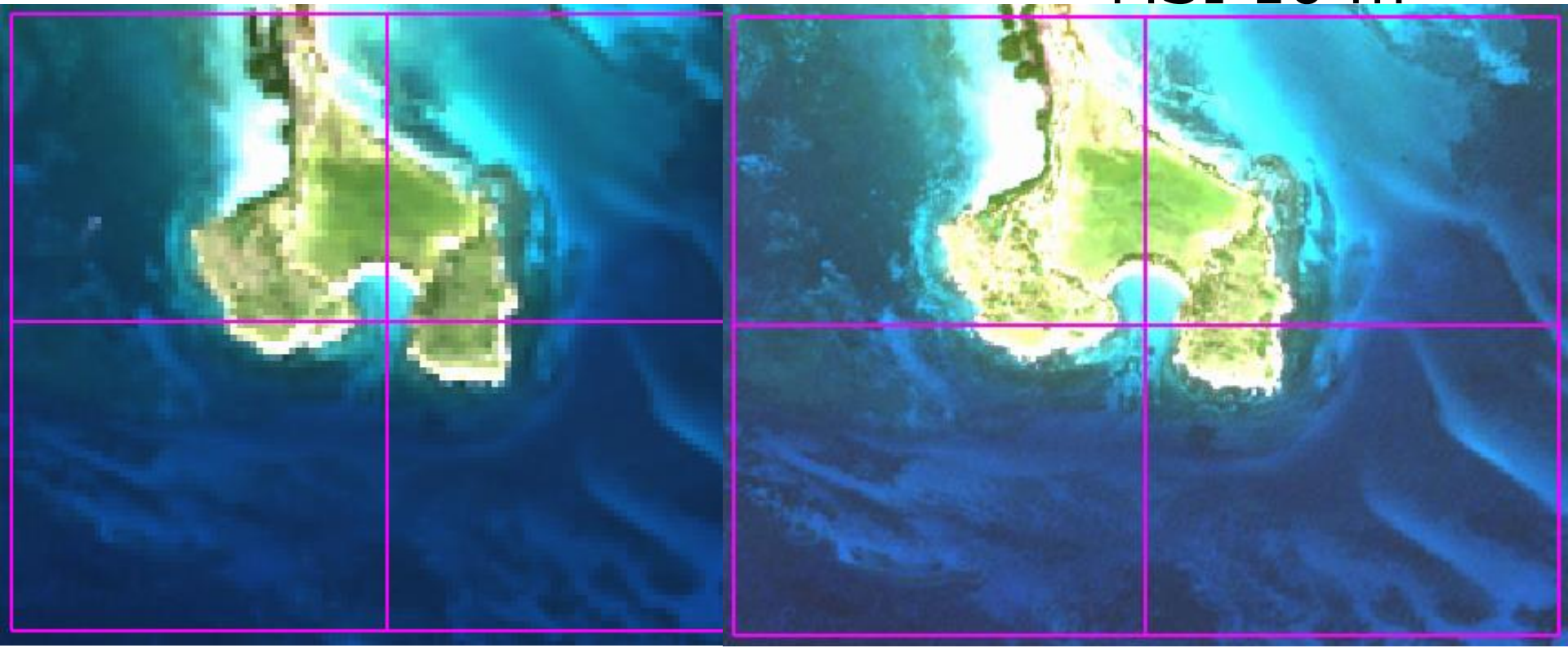



OLI 30 m



OLI 30 m

MSI 10 m



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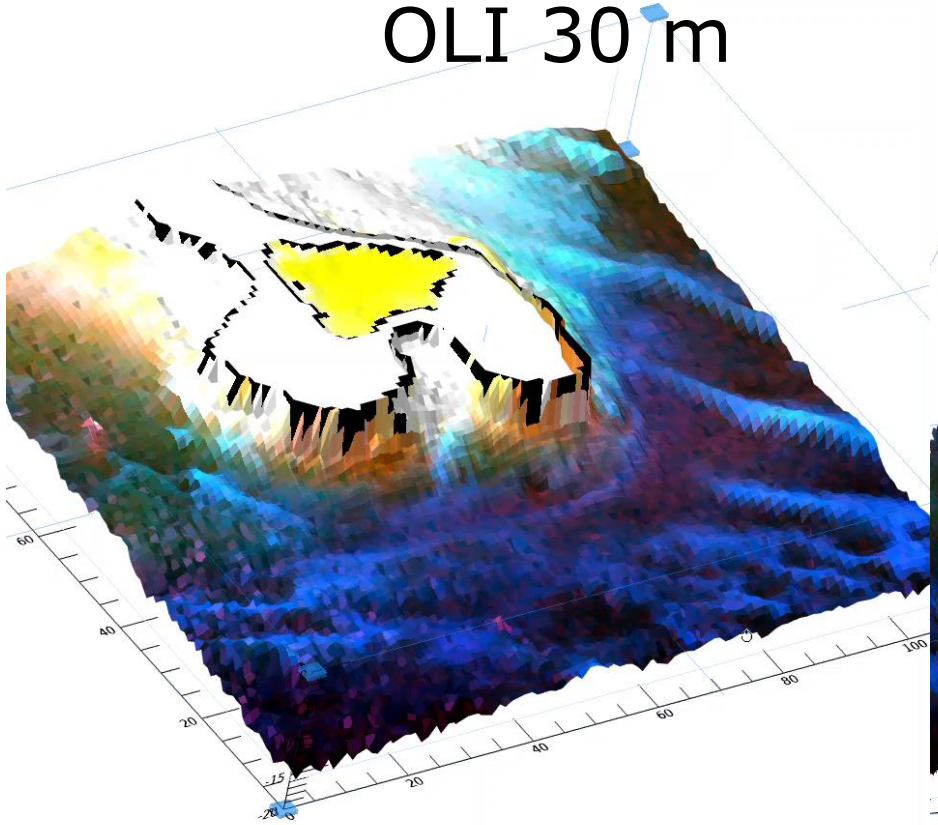
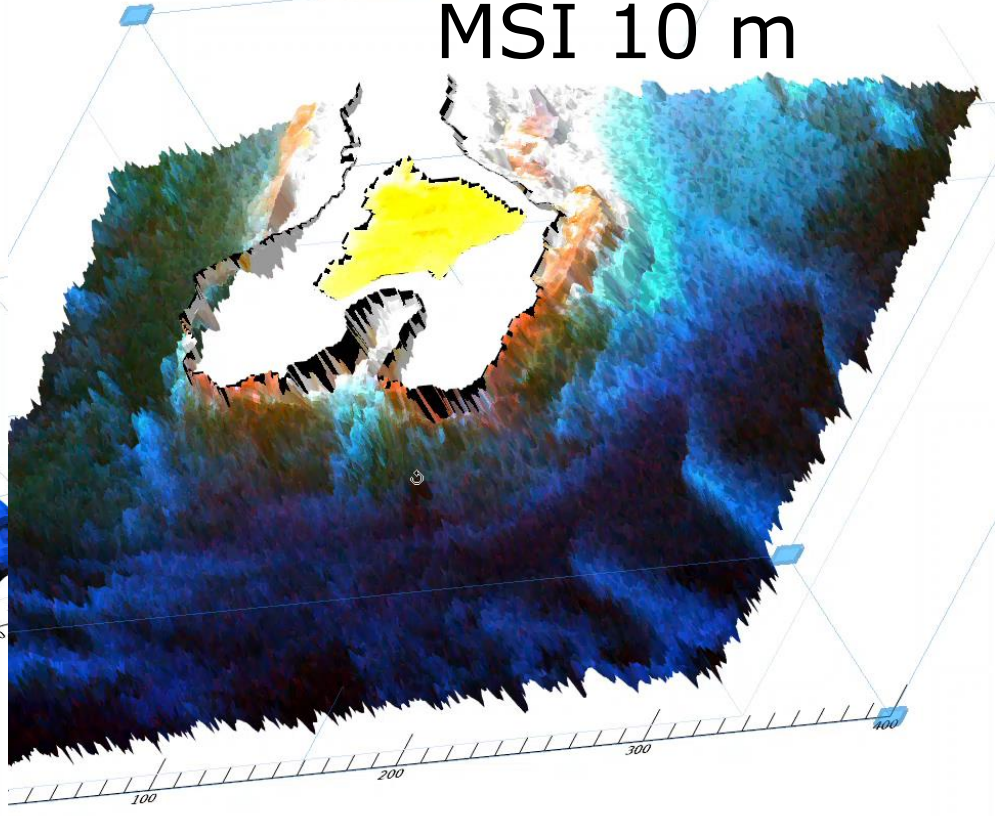
OLI 30 m



MSI 10 m



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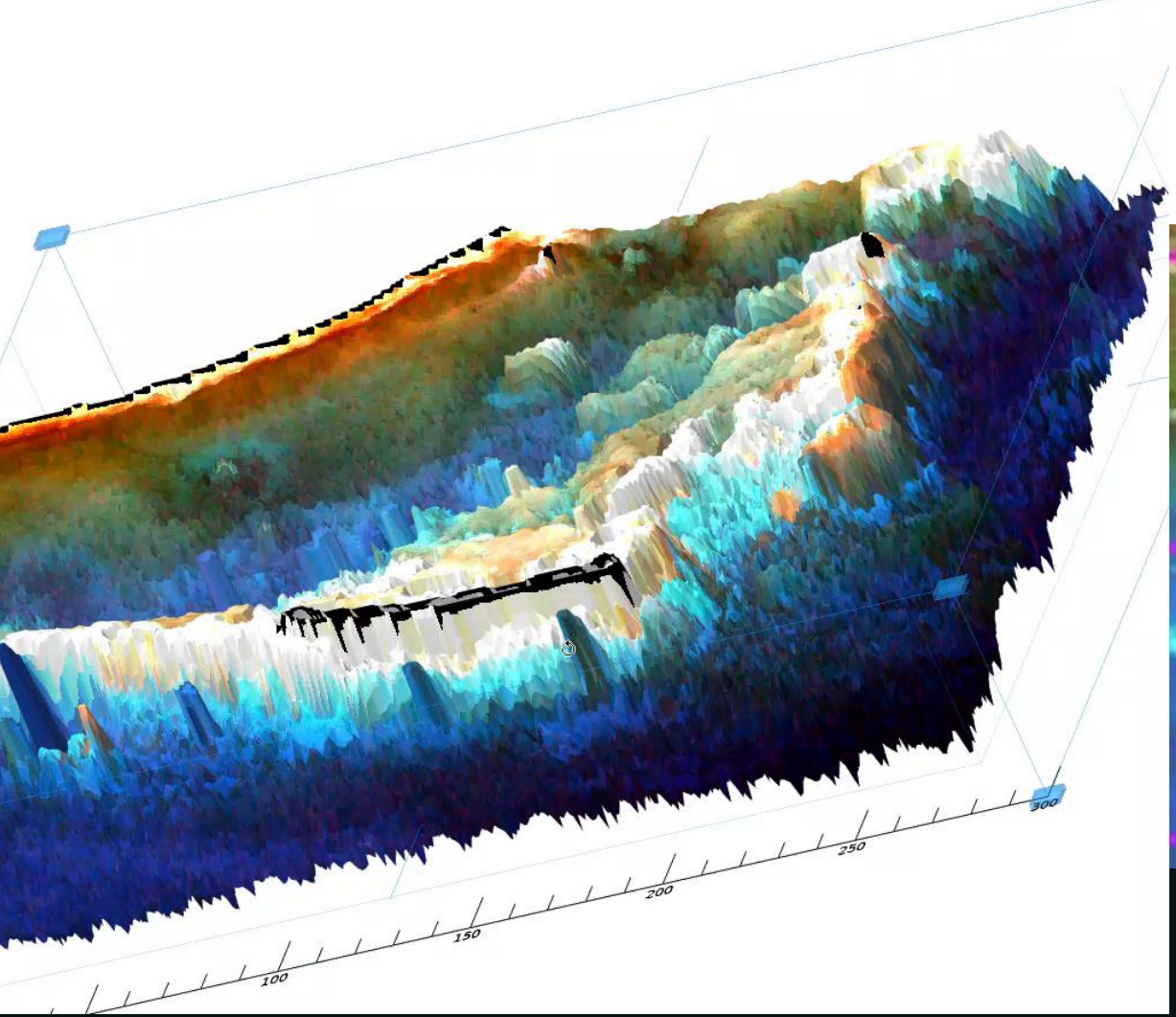
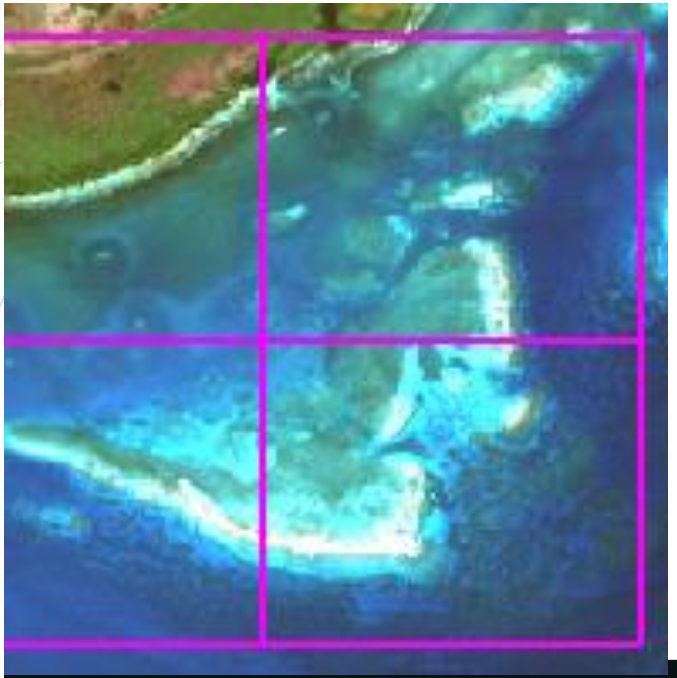
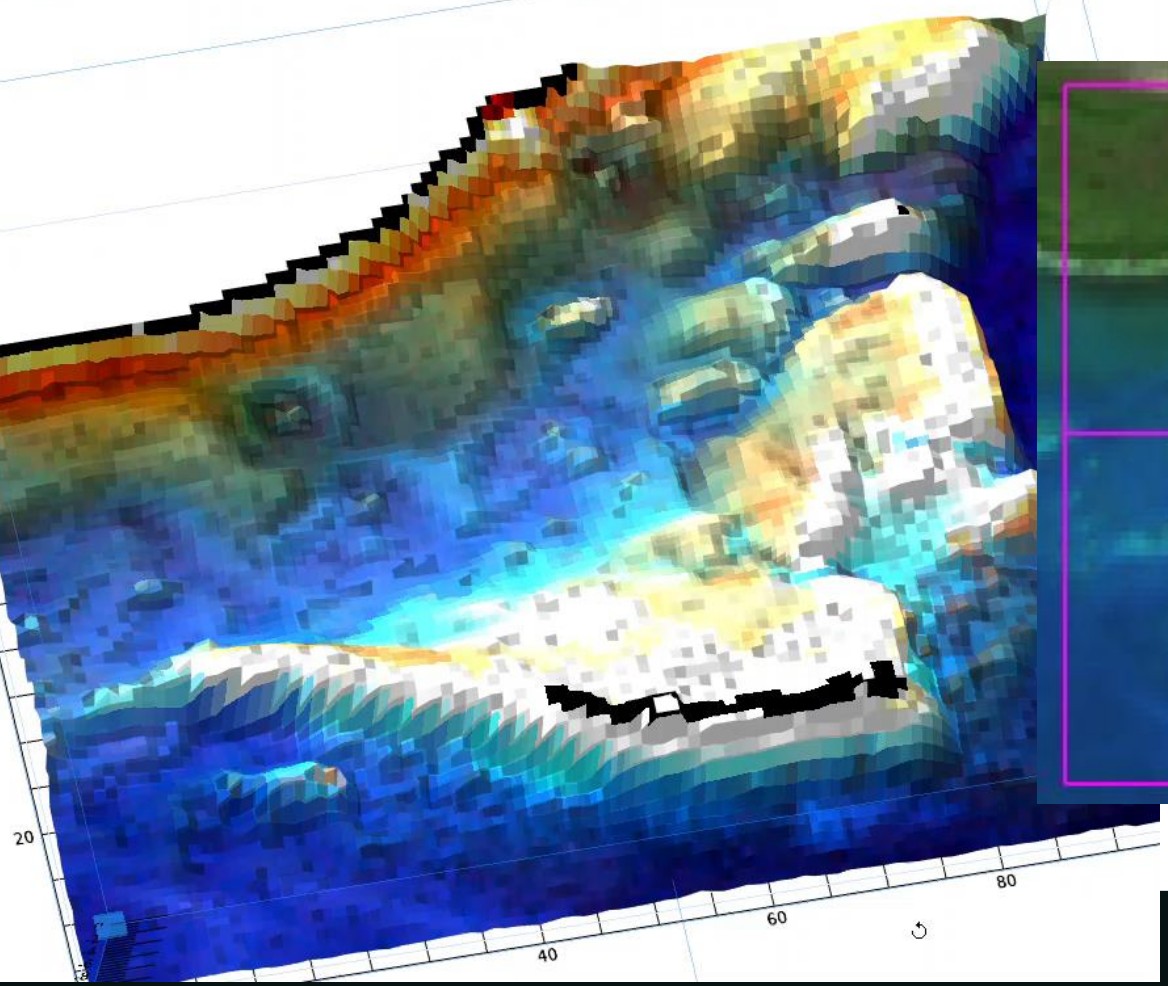
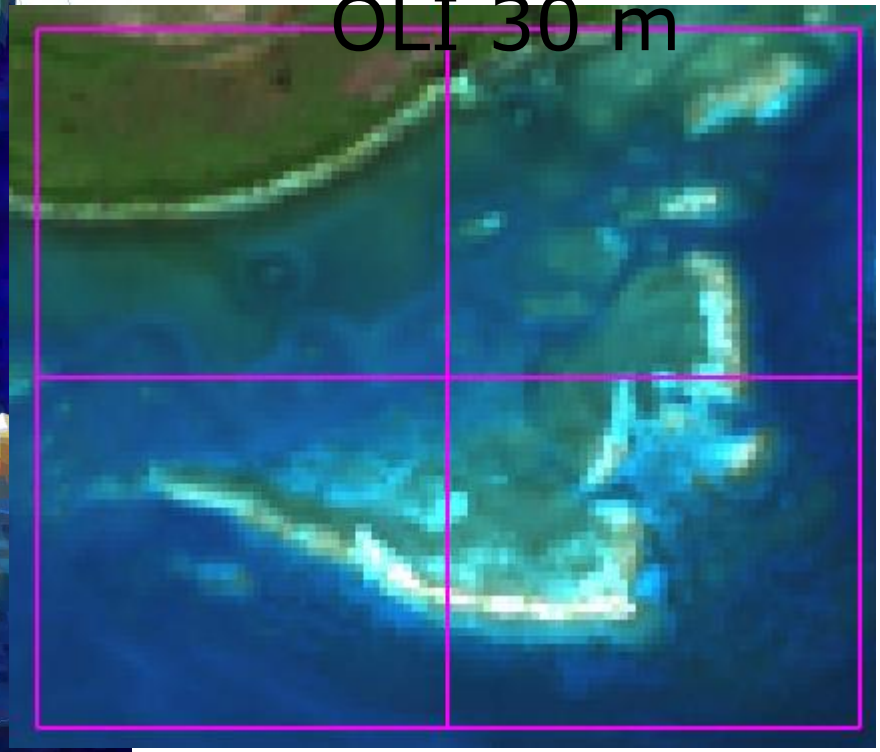
# MSI 10 m



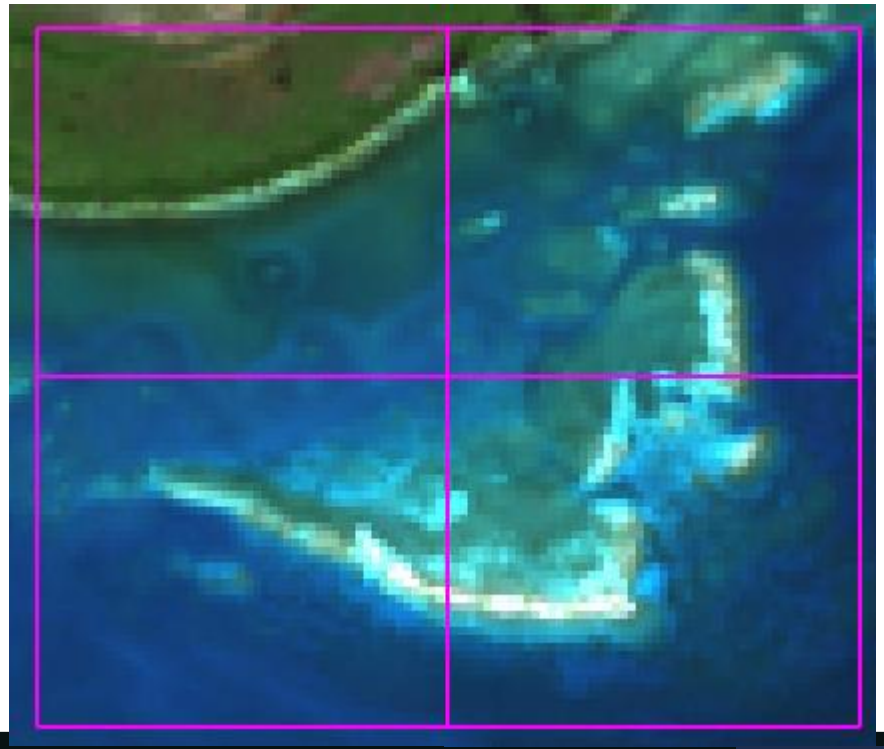



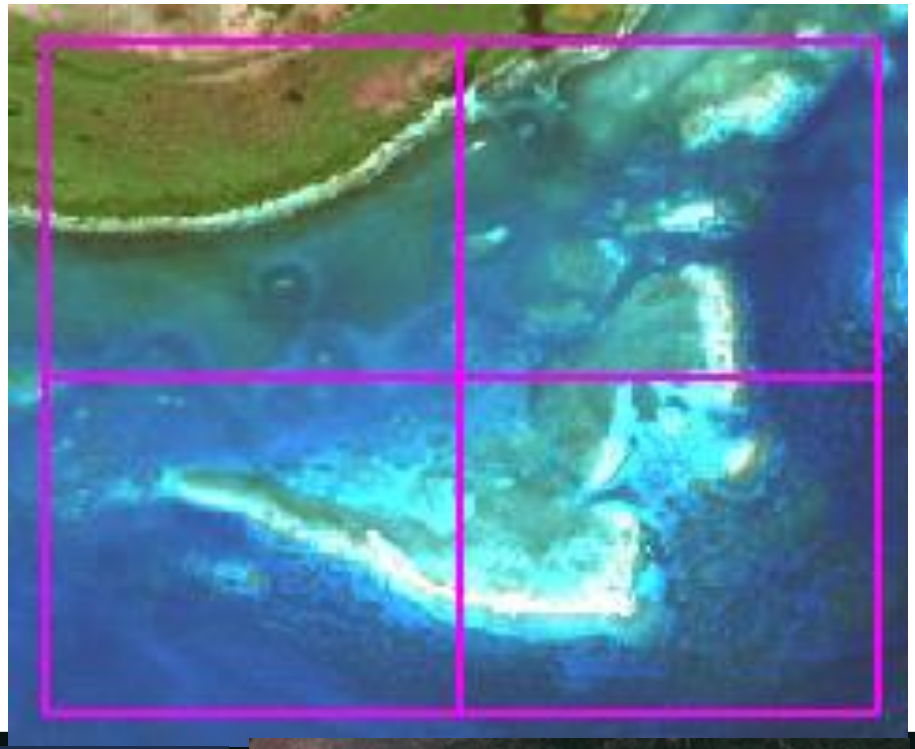

20
40
60
80


OLI 30 m

OLI 30 m

MSI 10 m





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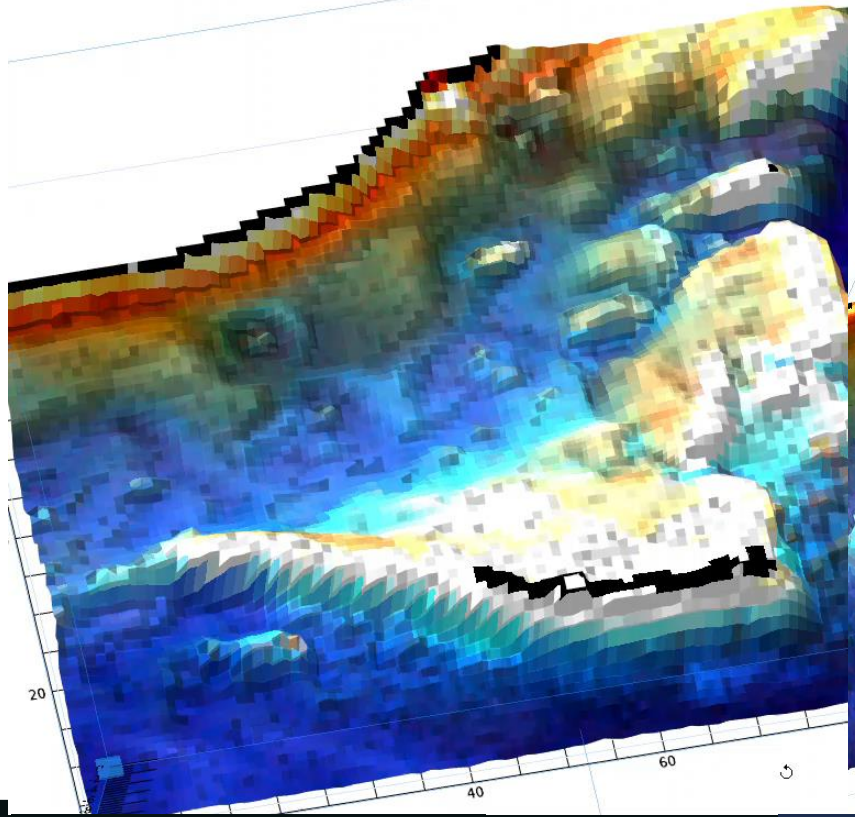
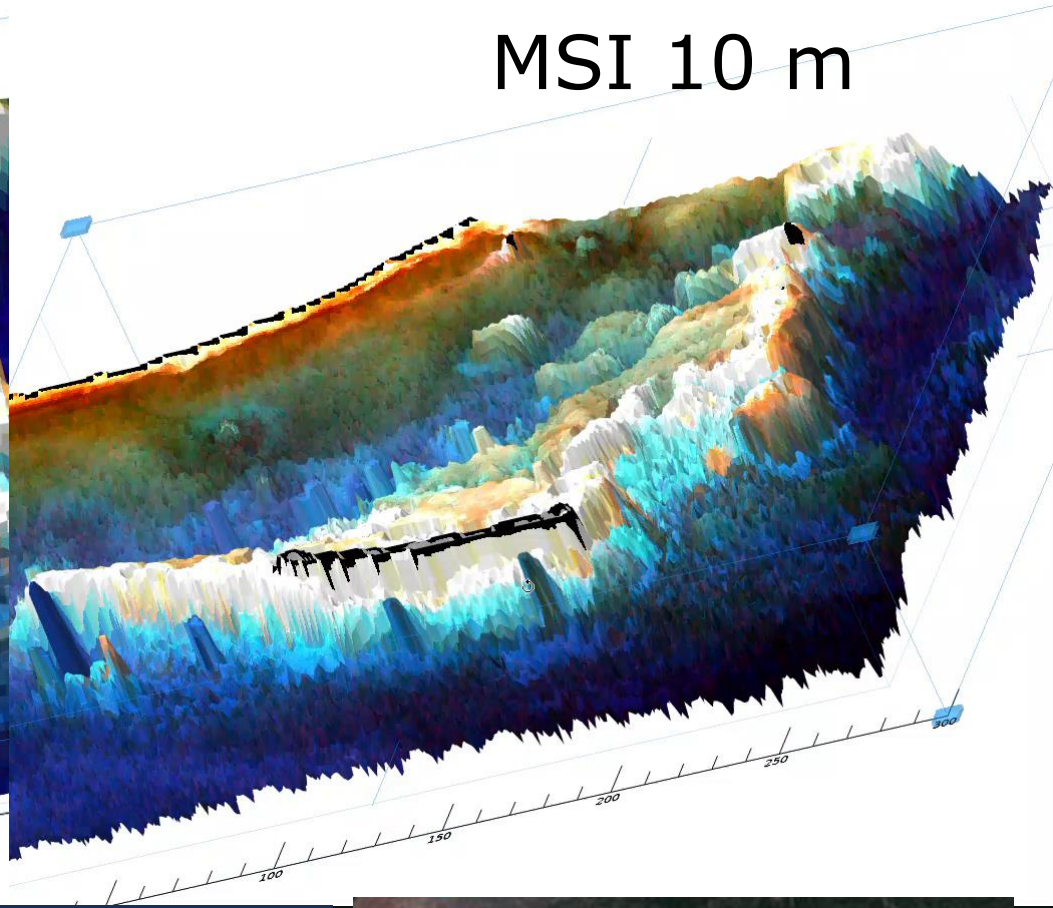
OLI 30 m

MSI 10 m

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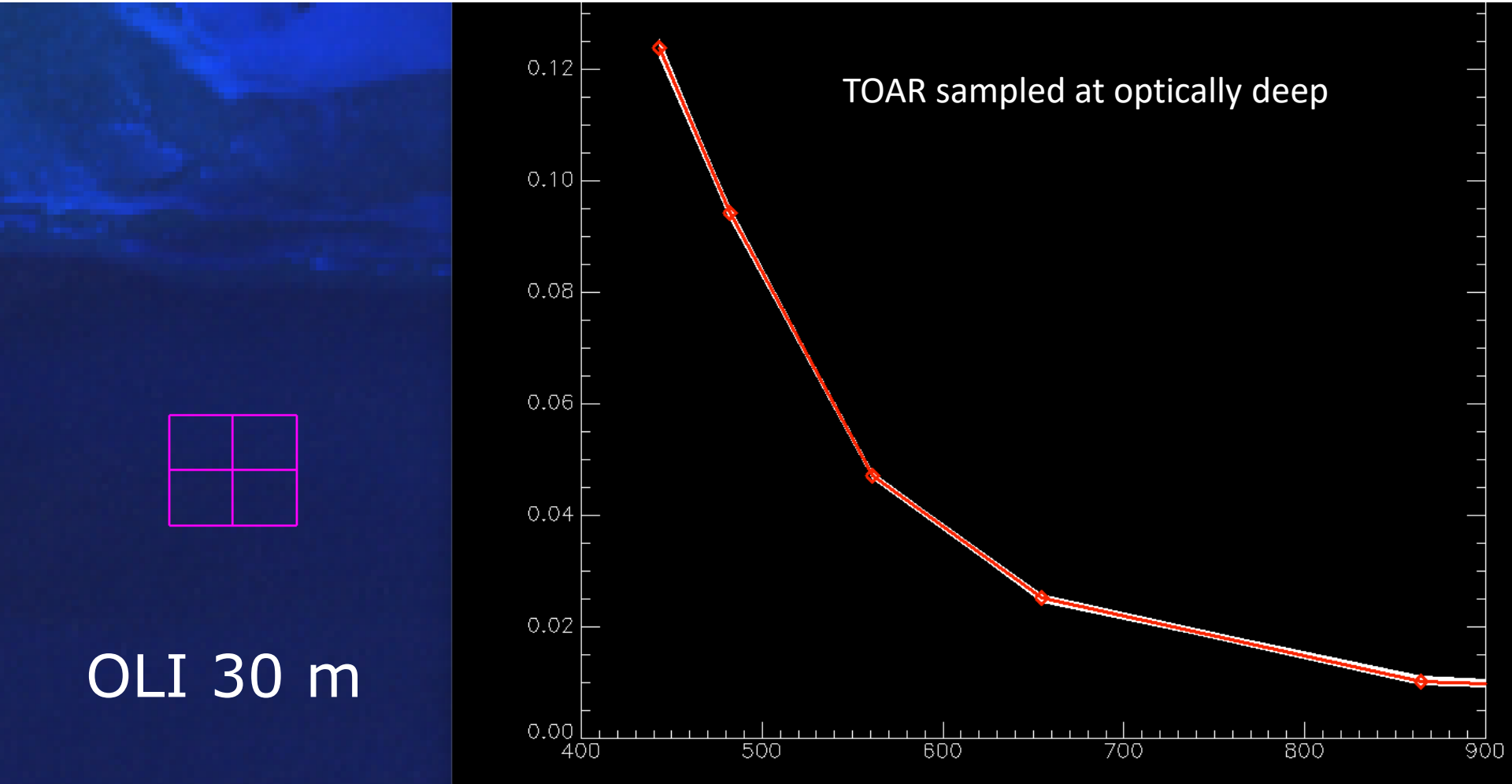
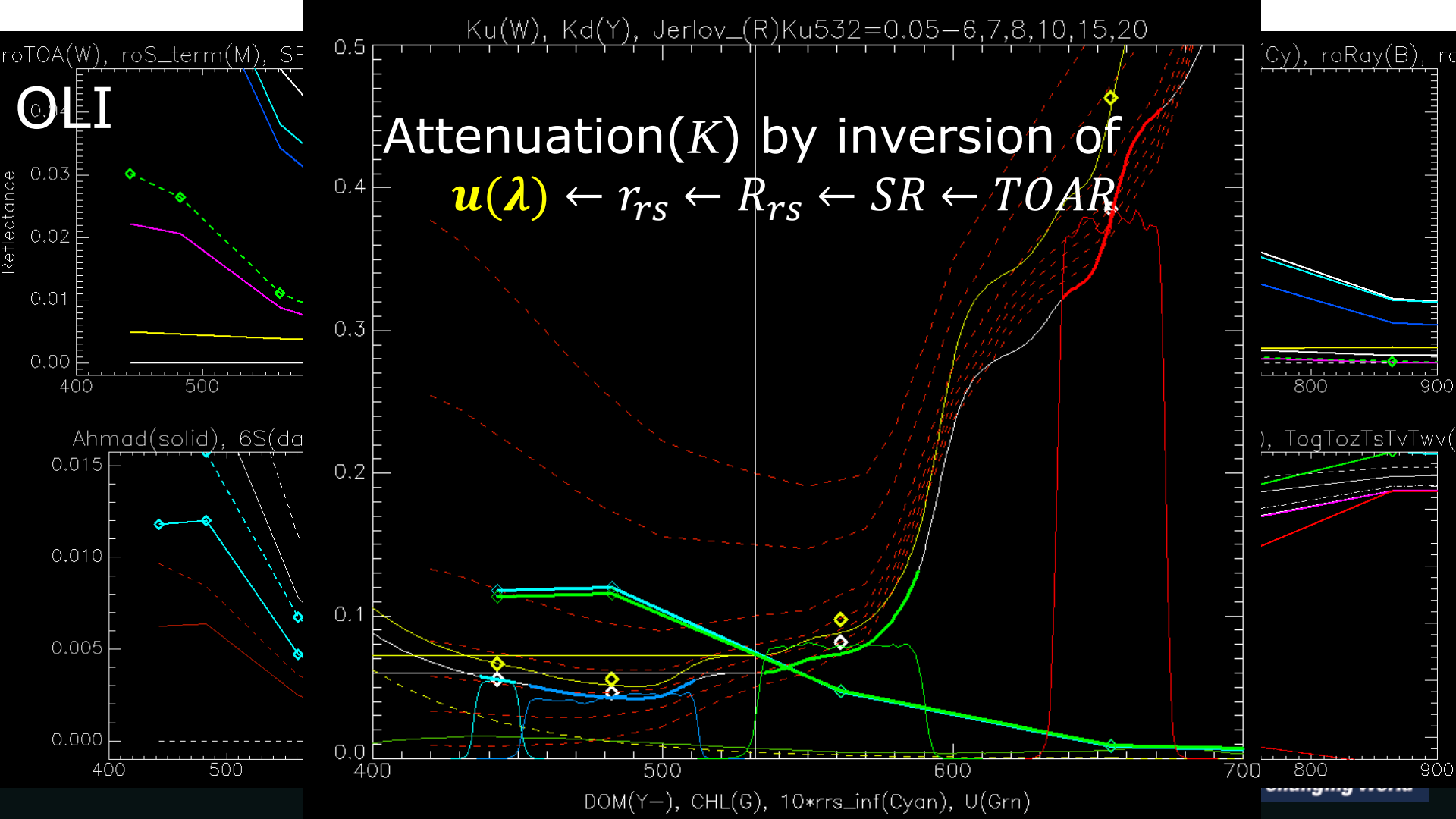
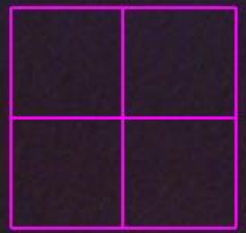
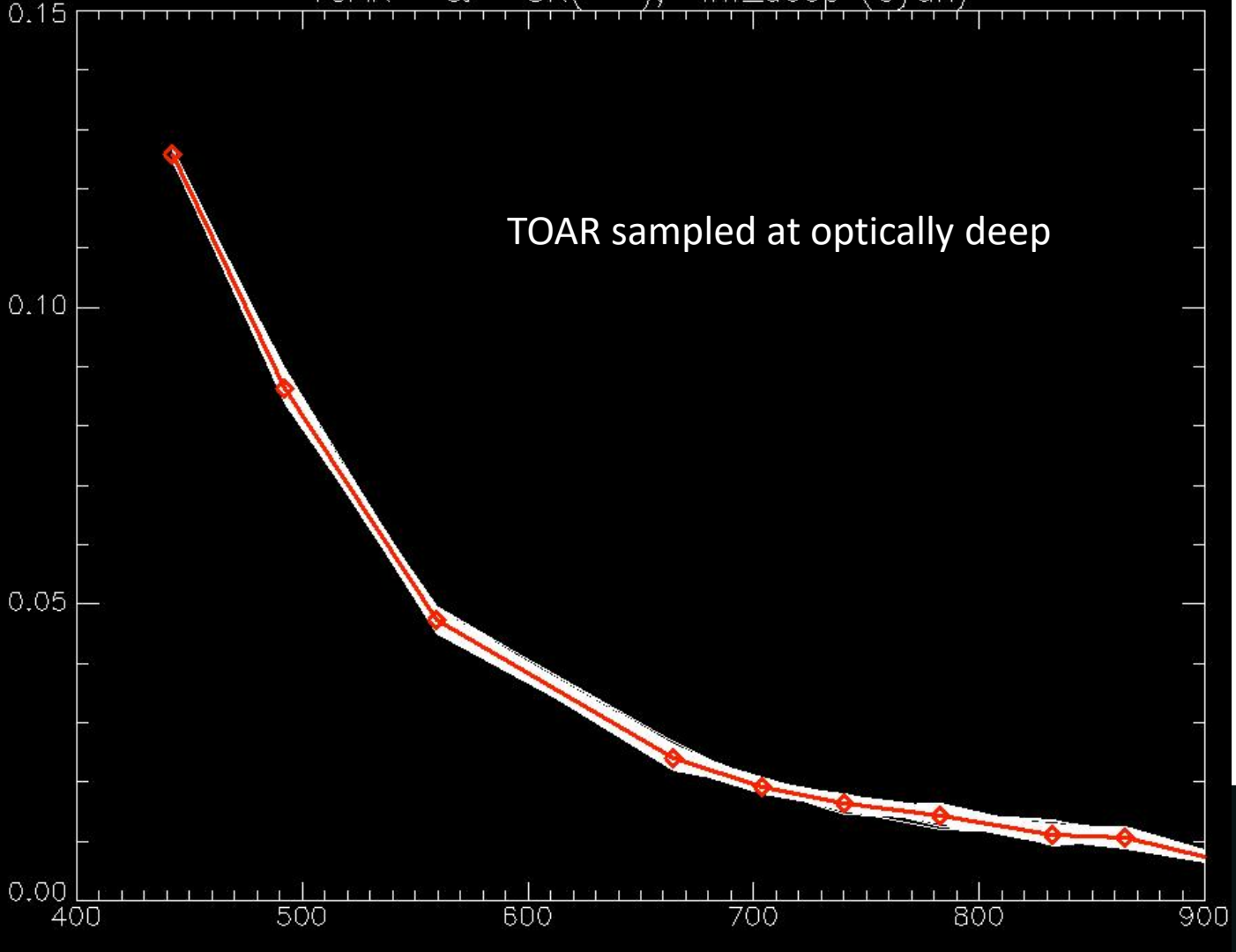

TOAR sampled at optically deep
0.12
0.10
0.08
0.06
0.04
0.02
0.00
400
500
600
700
800
900
OLI 30 m

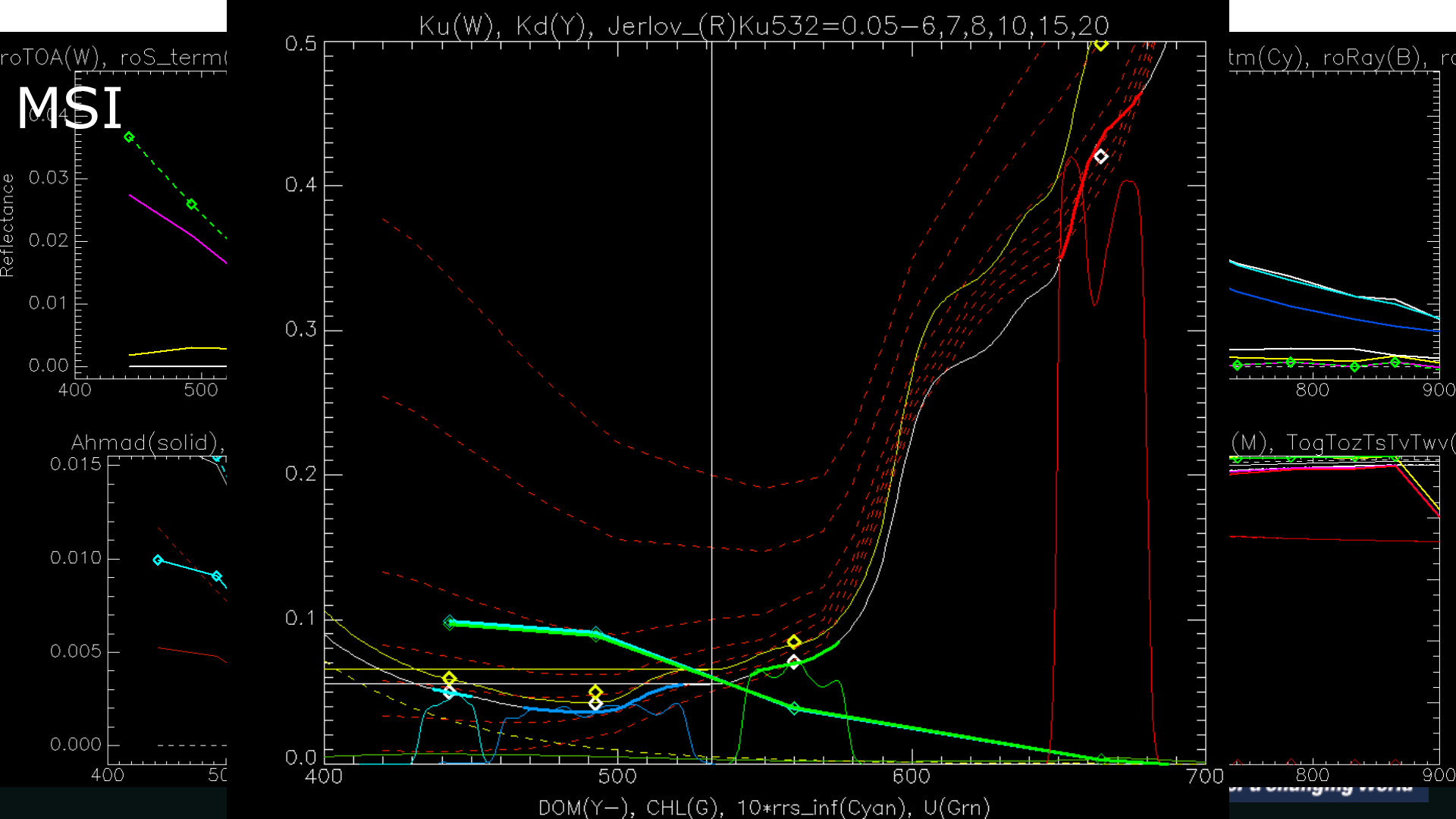

Ku(W), Kd(Y), Jerlov_(R)Ku532=0.05−6,7,8,10,15,20
roTOA(W), roS_term(M), SF
Cy), roRay(B), ro
OLI
Attenuation($K$) by inversion of
$\boldsymbol{u(\lambda)} \leftarrow r_{rs} \leftarrow R_{rs} \leftarrow SR \leftarrow TOAR$
Reflectance
Ahmad(solid), 6S(da
), TogTozTsTvTwv(
DOM(Y−), CHL(G), 10*rrs_inf(Cyan), U(Grn)

MSI 10 m

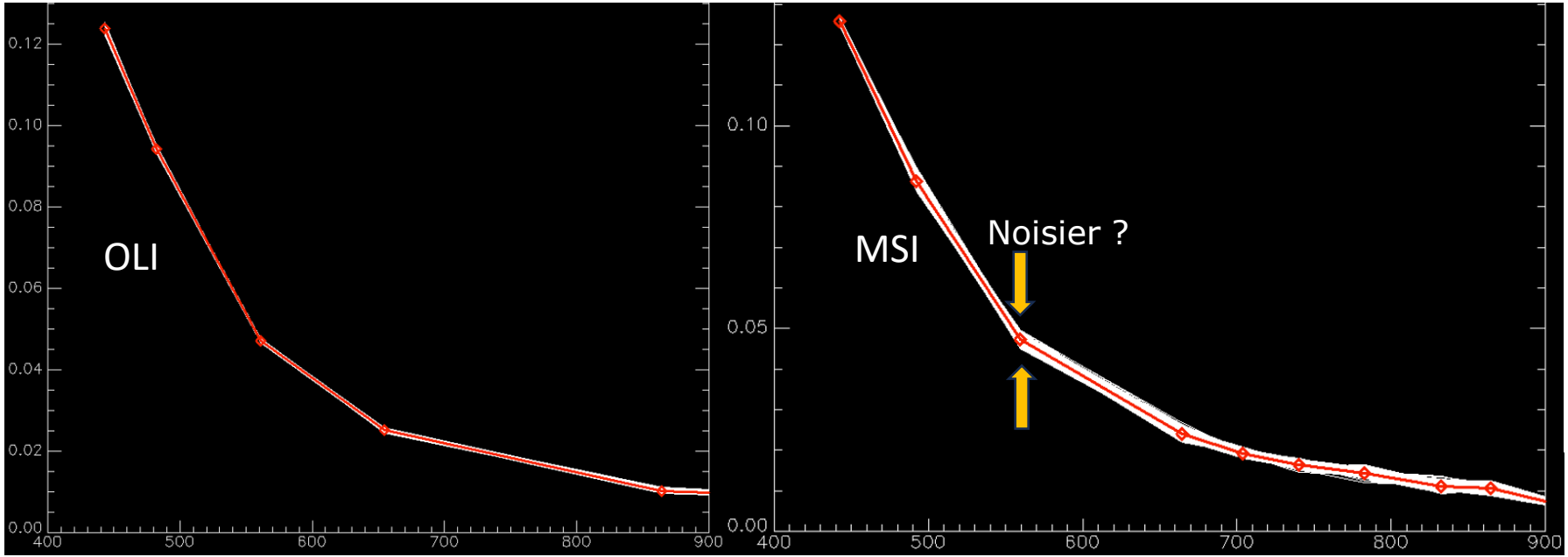
Noisier ?





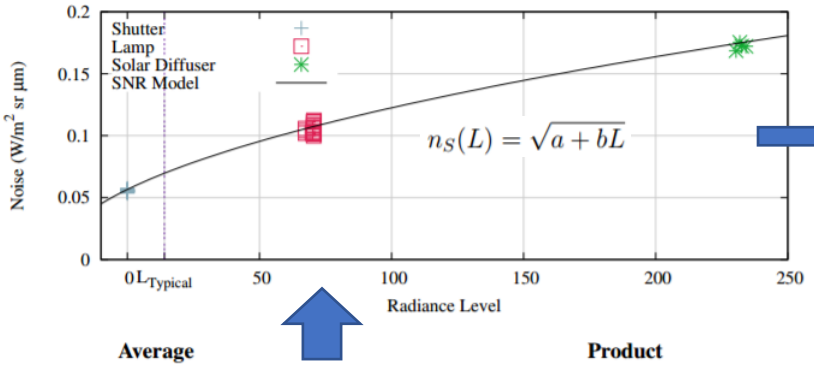

MSI
Ku(W), Kd(Y), Jerlov_(R)Ku532=0.05–6,7,8,10,15,20
roTOA(W), roS_term(
tm(Cy), roRay(B), ro
Reflectance
0.5
0.4
0.3
0.2
0.1
0.0
0.03
0.02
0.01
0.00
400
500
600
700
800
900
Ahmad(solid),
(M), TogTozTsTvTwv(
0.015
0.010
0.005
0.000
DOM(Y–), CHL(G), 10*rrs_inf(Cyan), U(Grn)

# TOAR comparison ( OLI vs MSI , same day ), benefit of MSI's +4 bands ??



# Noise of Landsat 8 OLI (Operational Land Imager)

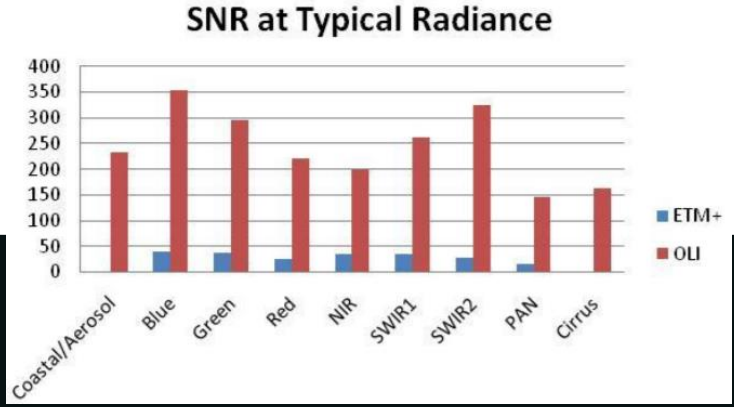
Ball Aerospace



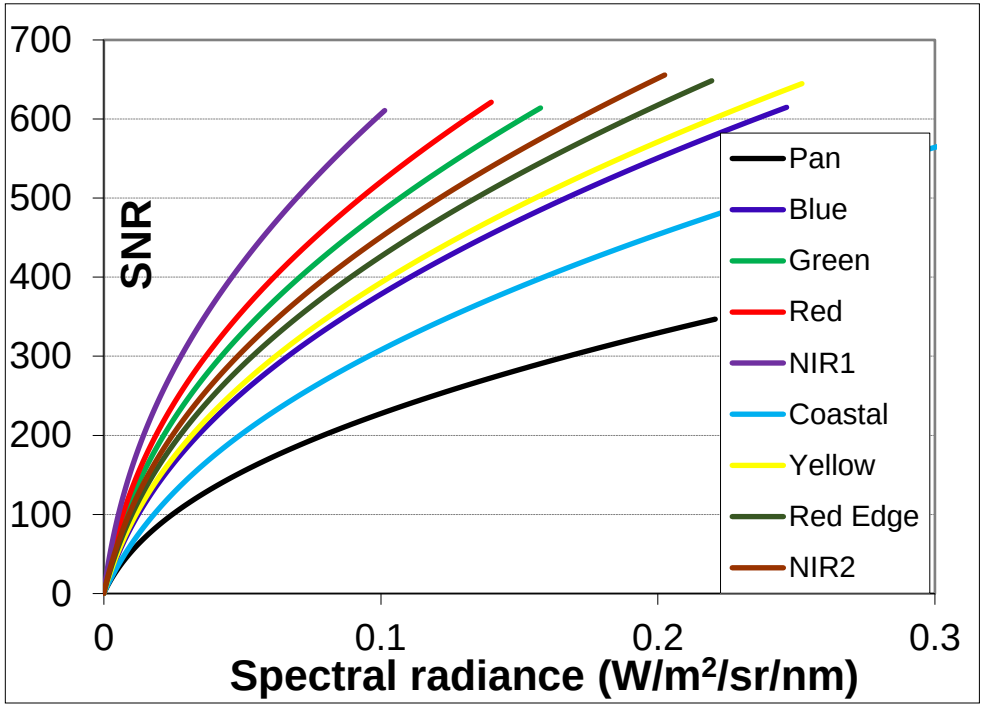

$$n_T(L) = \sqrt{0.8 \cdot n_S(L)^2 + \epsilon_q^2}$$

$$SNR \approx L / n_T(L)$$

| Band Name | Average Dark Noise $\left(\frac{W}{m^2 sr \mu m}\right)$ | Noise Model Coefficients $a\left(\left(\frac{W}{m^2 sr \mu m}\right)^2\right)$ | Noise Model Coefficients $b\left(\frac{W}{m^2 sr \mu m}\right)$ | Product Quantization Noise ($\epsilon_q$) | $L_{Typical}$ $\left(\frac{W}{m^2 sr \mu m}\right)$ | $L_{High}$ $\left(\frac{W}{m^2 sr \mu m}\right)$ |
|---|---|---|---|---|---|---|
| Coastal Aerosol | 0.11 | 0.012 | 0.00042 | 0.0047 | 40 | 190 |
| Blue | 0.089 | 0.0082 | 0.000094 | 0.0048 | 40 | 190 |
| Green | 0.084 | 0.0073 | 0.000089 | 0.0035 | 30 | 194 |
| Red | 0.083 | 0.0071 | 0.00011 | 0.0039 | 22 | 150 |
| NIR | 0.056 | 0.0032 | 0.00012 | 0.0028 | 14 | 150 |
| SWIR 1 | 0.011 | 0.00013 | 0.000026 | 0.00055 | 4.0 | 32 |
| SWIR 2 | 0.0034 | 0.000011 | 0.0000091 | 0.00025 | 1.7 | 11 |
| Pan | 0.086 | 0.0078 | 0.00069 | 0.0033 | 23 | 156 |
| Cirrus | 0.025 | 0.00059 | 0.00014 | 0.00070 | 6.0 | N/A |

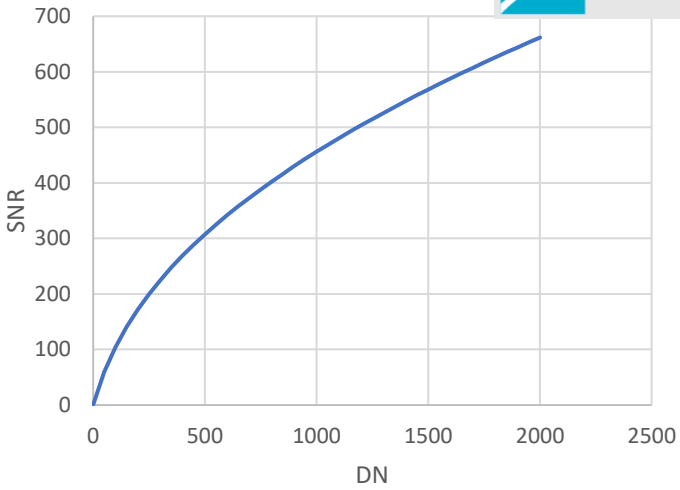



*Remote Sens.* **2015**, *7*, 2208-2237; doi:10.3390/rs70202208




$$SNR = \frac{mean(signal)}{stddev(signal)}$$

Ball Aerospace

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# SENTINEL-2 User Handbook

Radiometric resolution is routinely expressed as a bit number, typically in the range of 8 to 16 bits. The radiometric resolution of the MSI instrument is 12 bit, enabling the image to be acquired over a range of 0 to 4 095 potential light intensity values. The radiometric accuracy is less than 5% (goal 3%). Radiometric resolution is also dependent upon the Signal to Noise Ratio (SNR) of the detector.

*Table 3:10 m Spatial Resolution Bands and associated Signal to Noise ratio (SNR)*

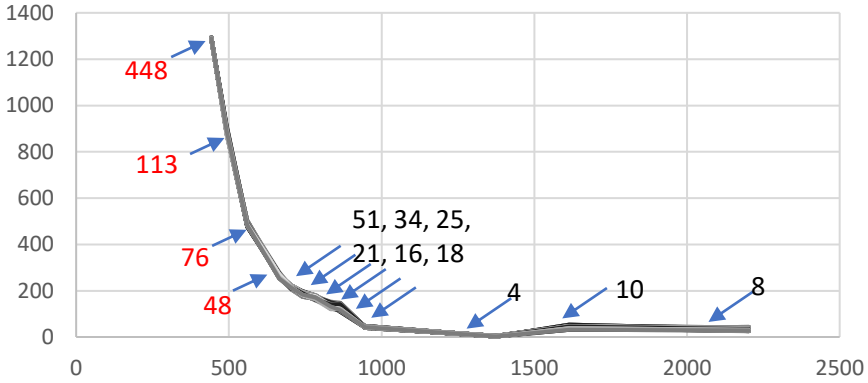
| Band number | Central wavelength (nm) | Bandwidth (nm) | Lref (reference radiance) (W m−2 sr−1 µm−1) | MSI SNR @ Lref |
|---|---|---|---|---|
| 2 | 490 | 65 | 128 | 154 |
| 3 | 560 | 35 | 128 | 168 |
| 4 | 665 | 30 | 108 | 142 |
| 8 | 842 | 115 | 103 | 172 |

Ball Aerospace

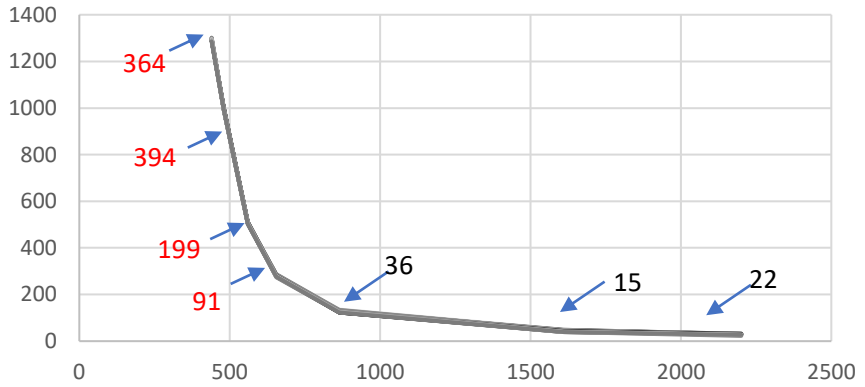
| OLI L_typical | OLI SNR L_typical |
|---|---|
| 40 | 350 |
| 30 | 300 |
| 22 | 220 |
| 14 | 200 |

# Optically Deep-Water SNR

## S2-MSI (10m)




## L8/9-OLI (30m)

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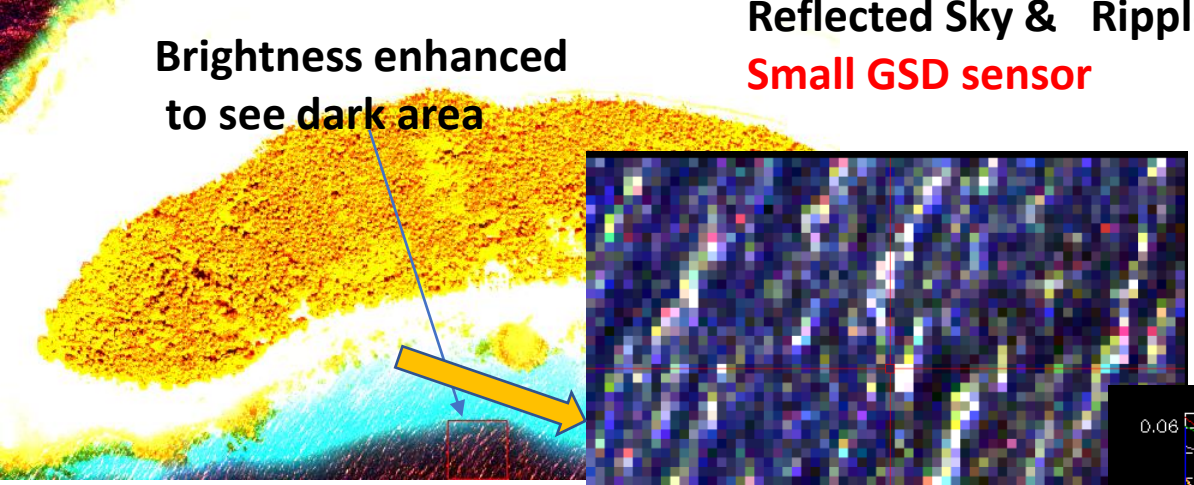
Brightness enhanced
to see dark area

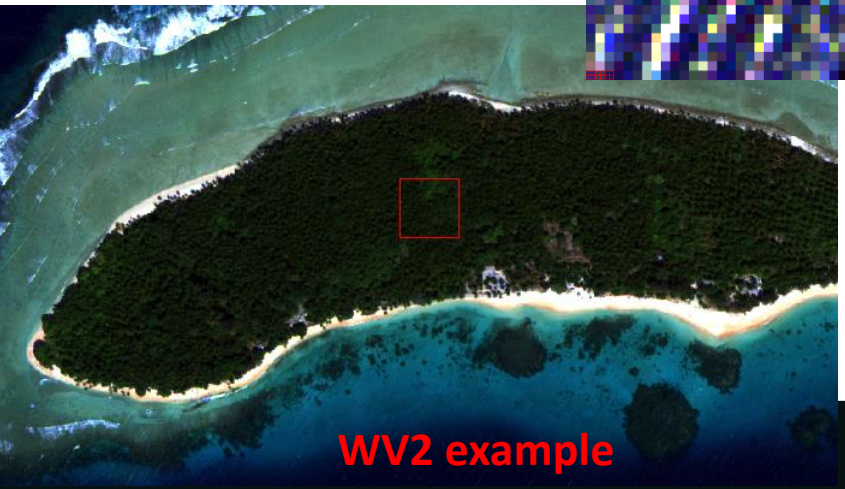
Reflected Sky & Ripples

Small GSD sensor

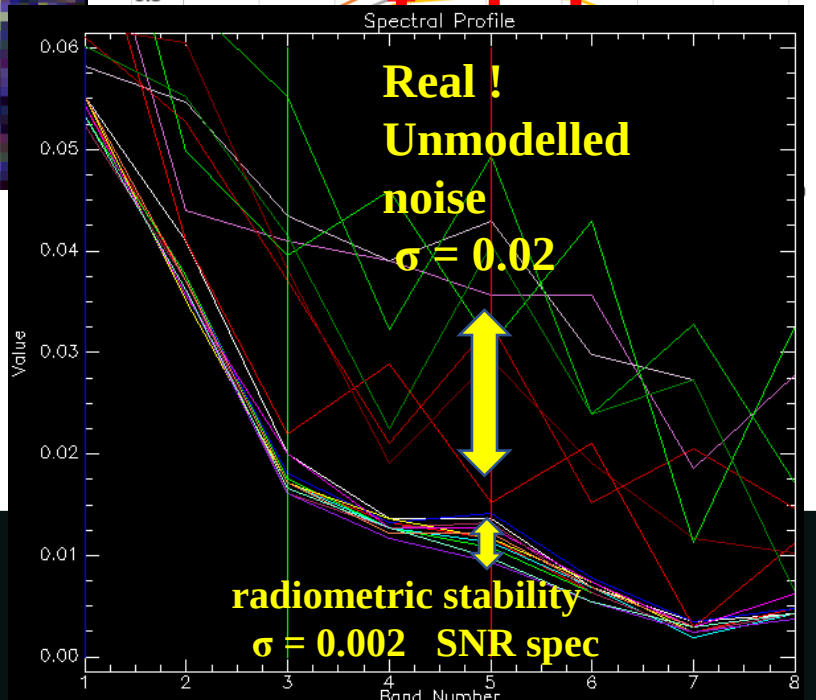





Curse of small pixel



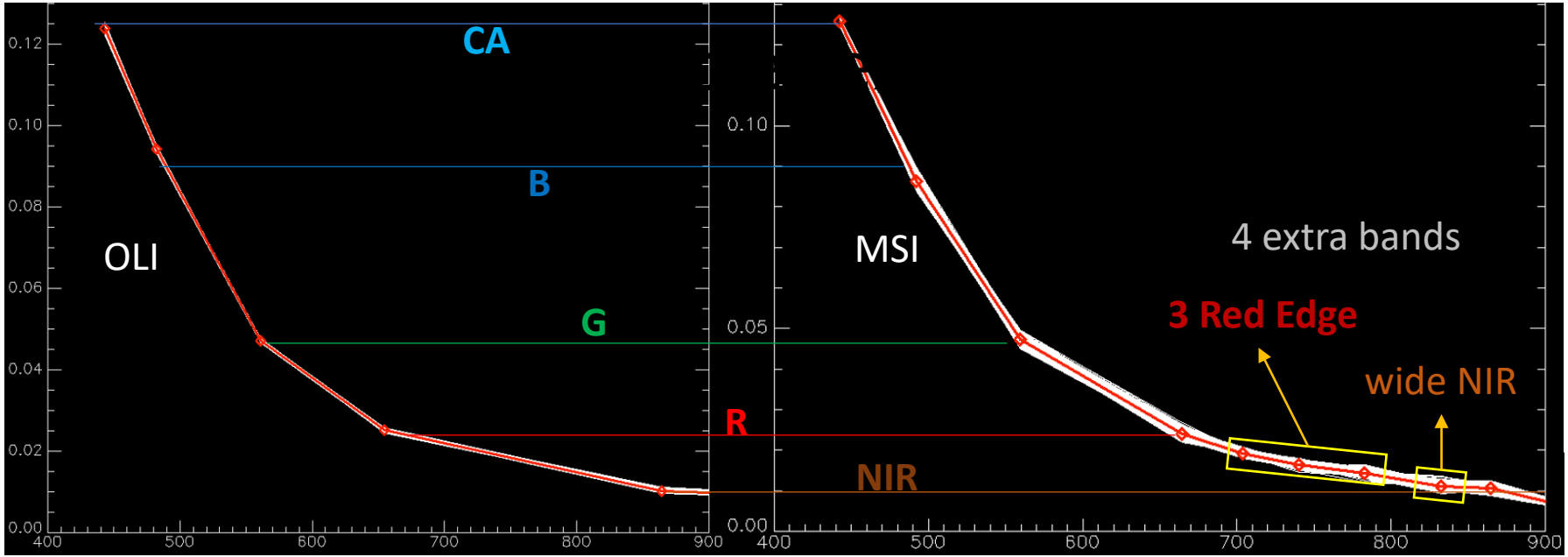
WV2 example




Real !
Unmodelled
noise
σ = 0.02

radiometric stability
σ = 0.002 SNR spec

# TOAR comparison ( OLI vs MSI , same day ), benefit of MSI's +4 bands ??

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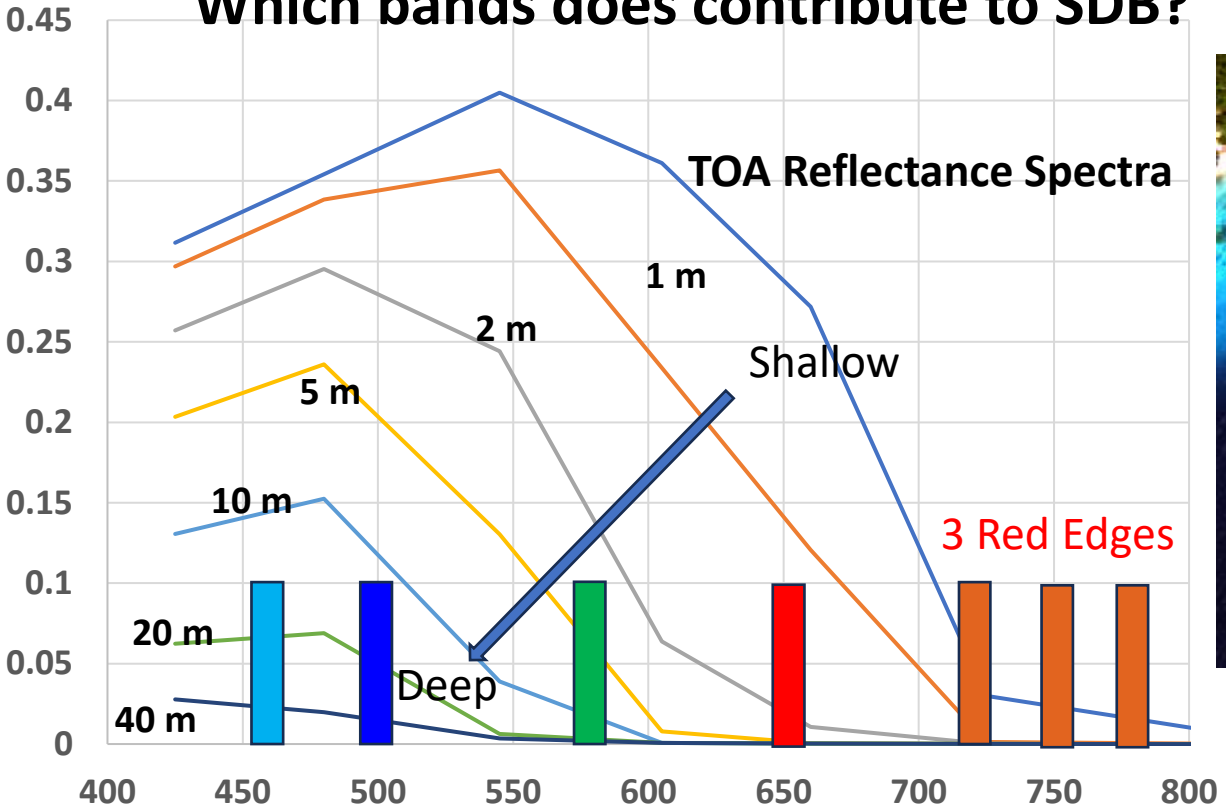
# Which bands does contribute to SDB?

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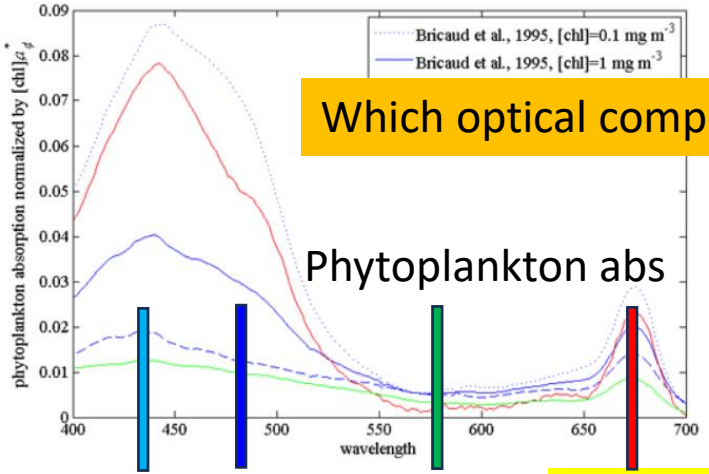
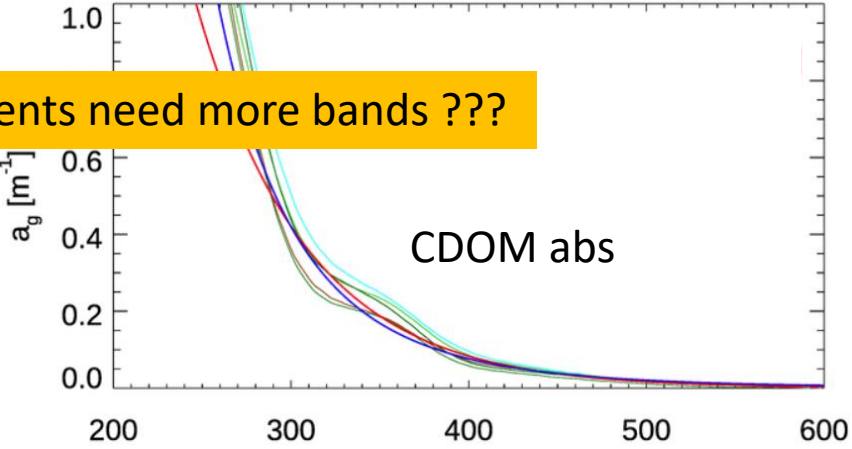
Which optical components need more bands ???

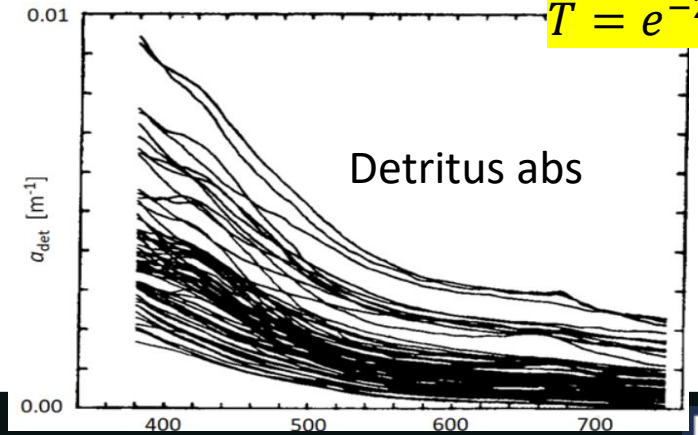



Phytoplankton abs

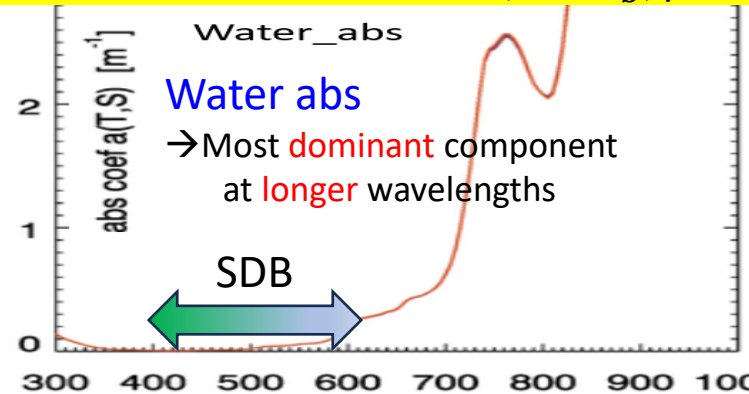



CDOM abs

$T = e^{-2 \cdot OD} \leftarrow OD = K \cdot z \leftarrow K = (a + b_b)/cos\theta_s$



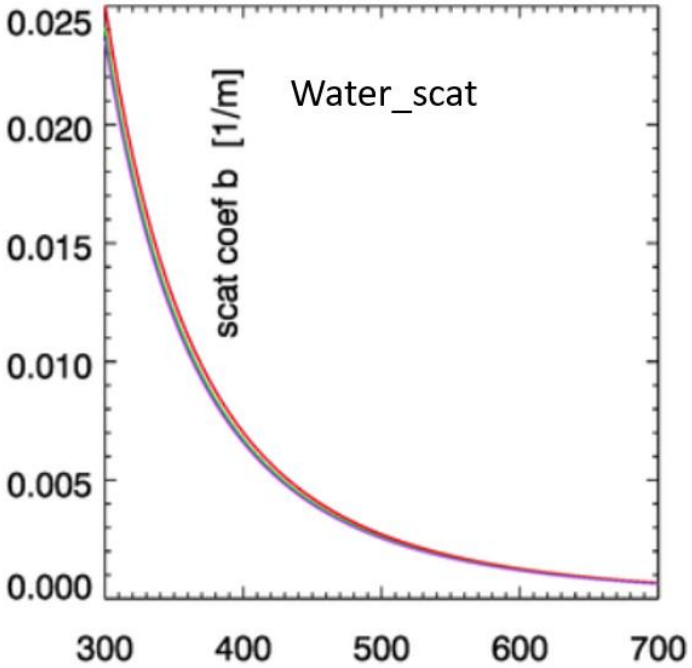

Detritus abs

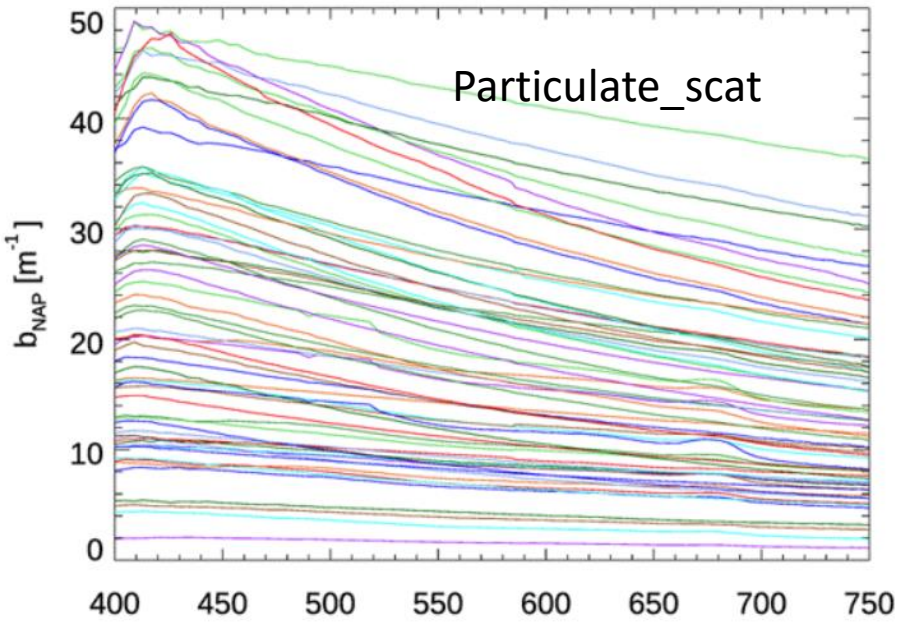



Water abs

→Most dominant component at longer wavelengths

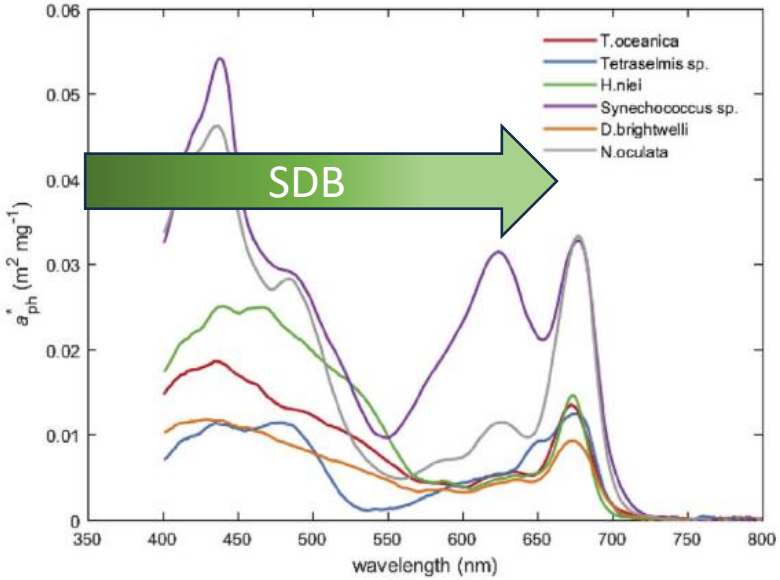
SDB

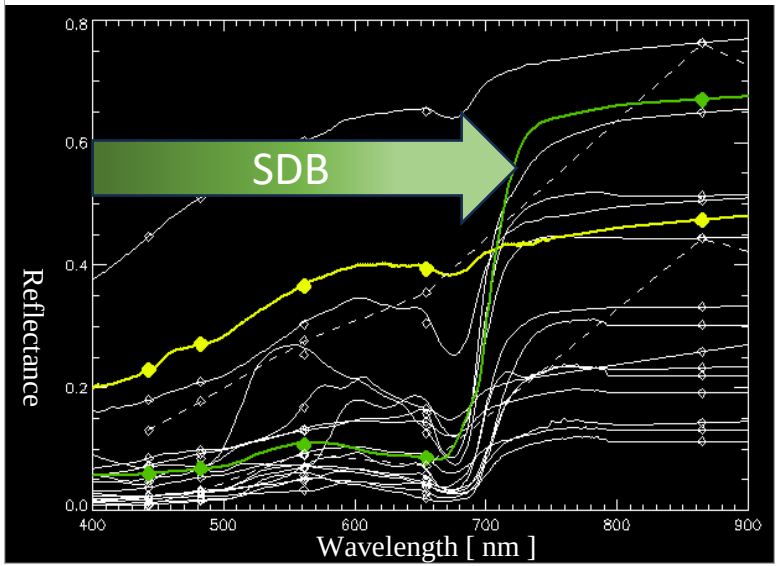



# Seeking SDB-sensitive bands, what are relevant optical properties?

Phytoplankton species




Bottom Reflectance Library




Above two components get benefit from more bands.

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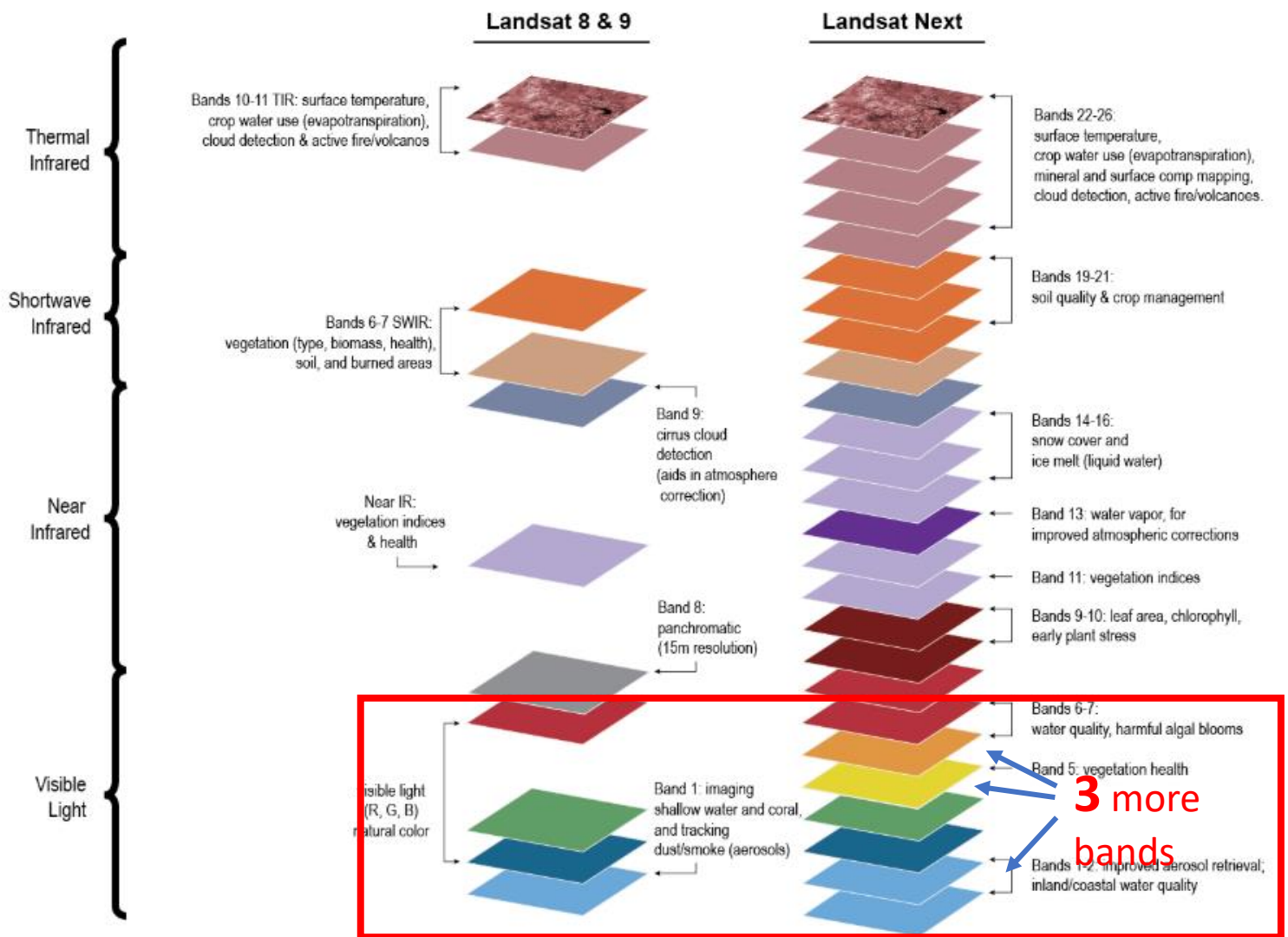
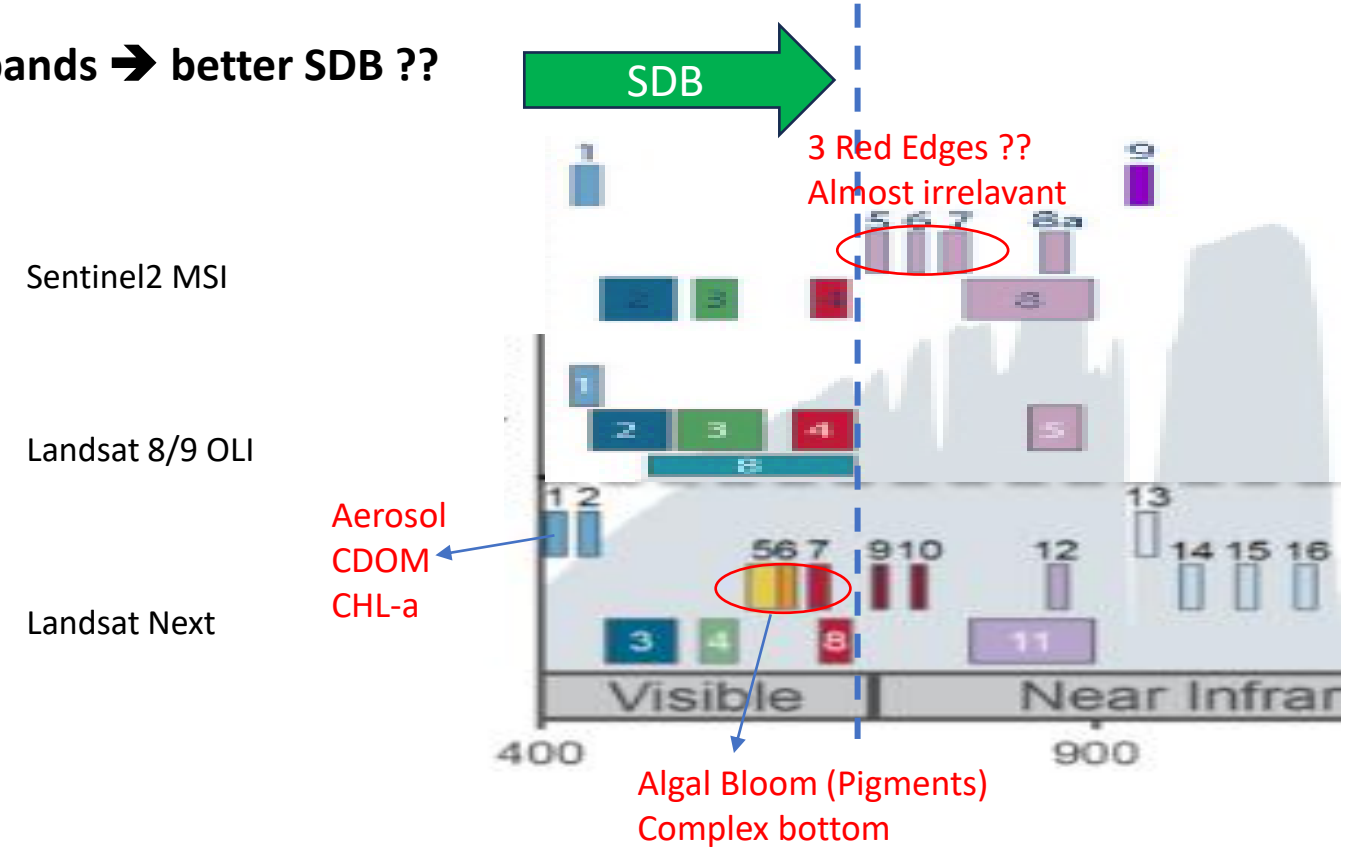

Landsat 8 & 9
Landsat Next
Thermal Infrared
Shortwave Infrared
Near Infrared
Visible Light
Bands 10-11 TIR: surface temperature, crop water use (evapotranspiration), cloud detection & active fire/volcanos
Bands 6-7 SWIR: vegetation (type, biomass, health), soil, and burned areas
Band 9: cirrus cloud detection (aids in atmosphere correction)
Near IR: vegetation indices & health
Band 8: panchromatic (15m resolution)
isible light (R, G, B) atural color
Band 1: imaging shallow water and coral, and tracking dust/smoke (aerosols)
Bands 22-26: surface temperature, crop water use (evapotranspiration), mineral and surface comp mapping, cloud detection, active fire/volcanoes.
Bands 19-21: soil quality & crop management
Bands 14-16: snow cover and ice melt (liquid water)
Band 13: water vapor, for improved atmospheric corrections
Band 11: vegetation indices
Bands 9-10: leaf area, chlorophyll, early plant stress
Bands 6-7: water quality, harmful algal blooms
Band 5: vegetation health
Bands 1-2: improved aerosol retrieval; inland/coastal water quality
3 more bands

**More bands ➔ better SDB ??**



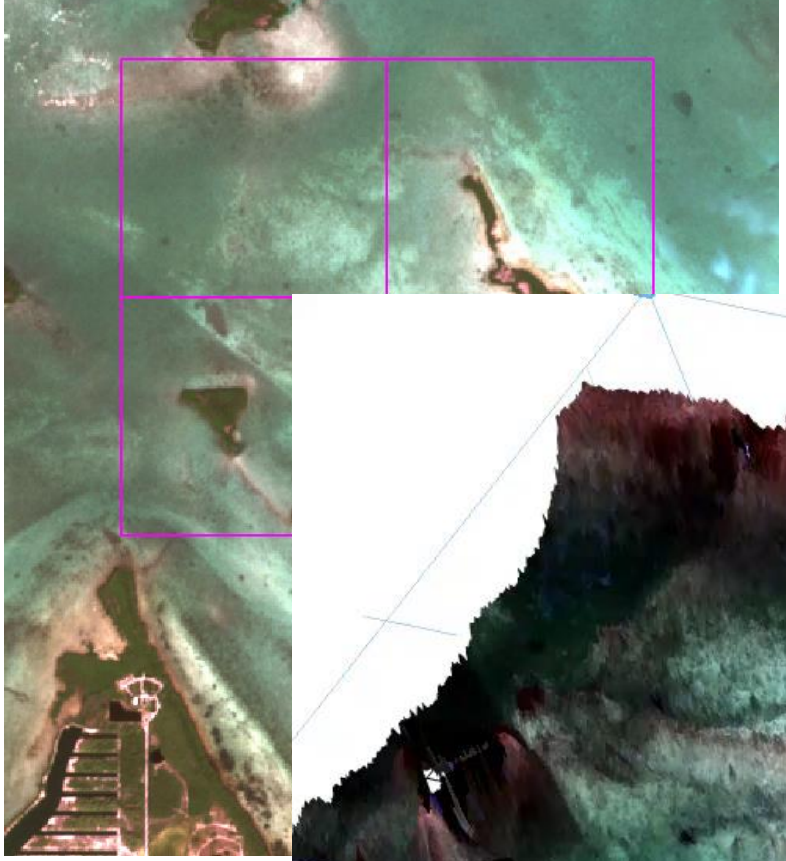
# OLI/MSI SDB summary

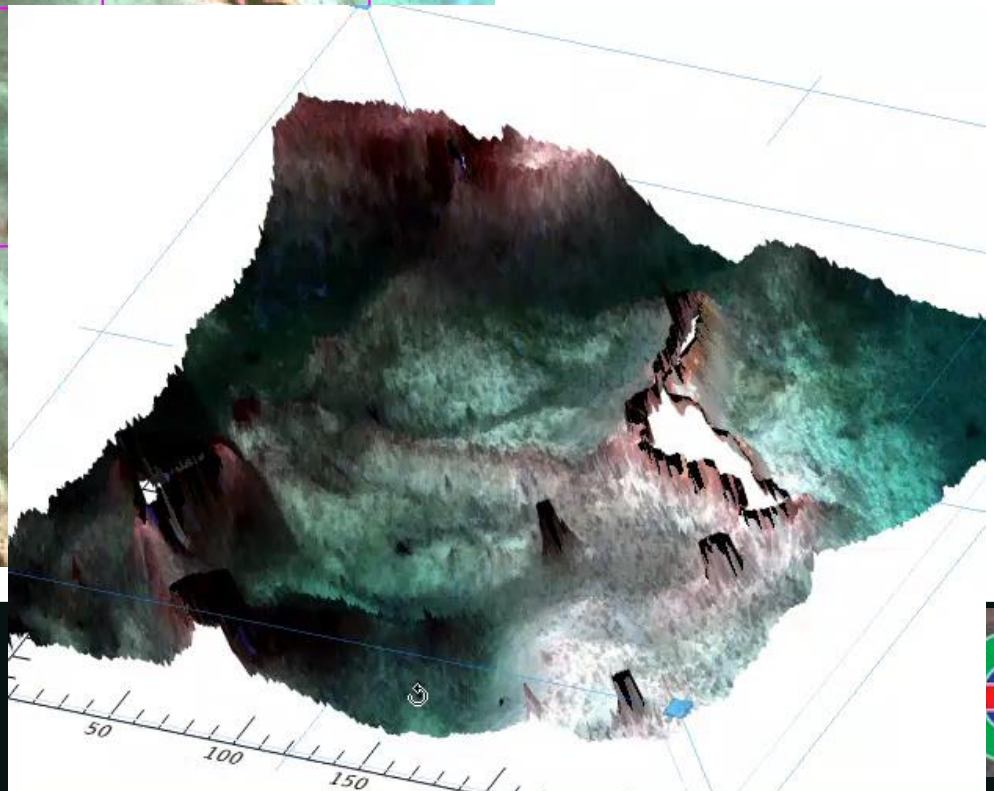
Landsat 8/9 OLI & Sentinel-2 MSI are suitable sensors for SDB
due to high radiometric fidelity over optically shallow coastal water.

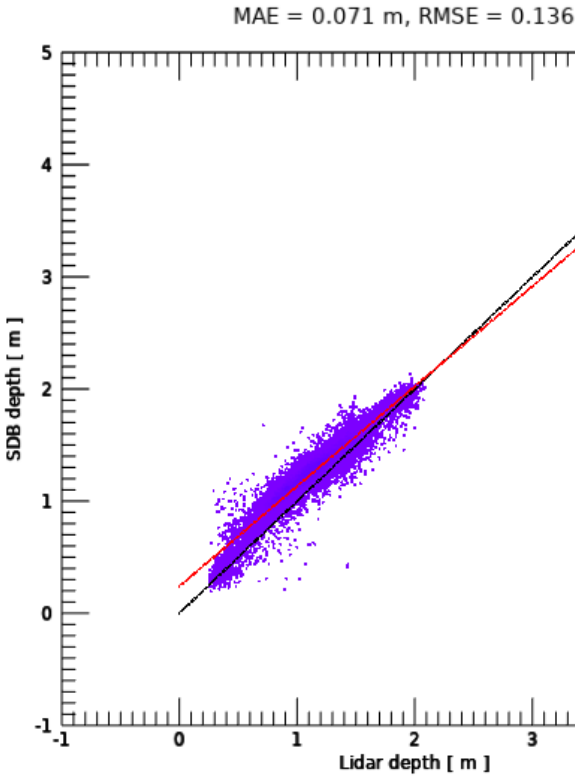
MSI 10 m can reveal more spatial details than OLI 30 m due to 3x smaller GSD.

MSI scene is a bit noisier mainly due to smaller pixel size. ← MSI vs OLI SNR
Accordingly high-res imagery will suffer from the same problem, SDB uncertainty increase
(1) Spectral smoothing ??? → multi-band too small # of points, NOT suitable for smoothing
(2) Spatial smoothing ??? → degrades the benefit of smaller GSD

Physics-based SDB would get benefit from Landsat-Next sensor
(1) additional 3 VIS bands (2) improved GSD ( 10 m ).



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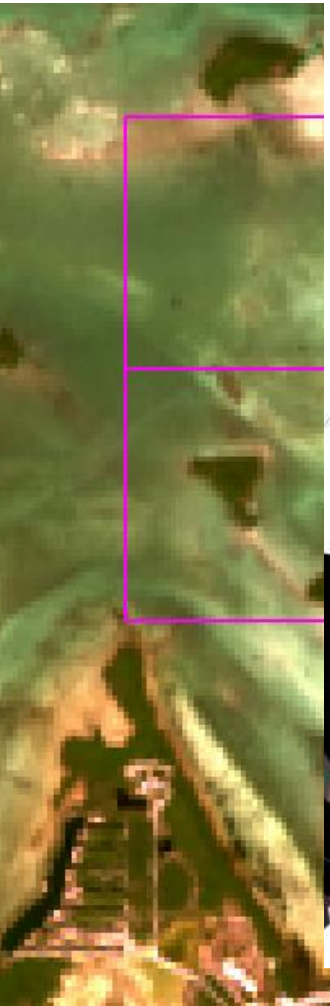
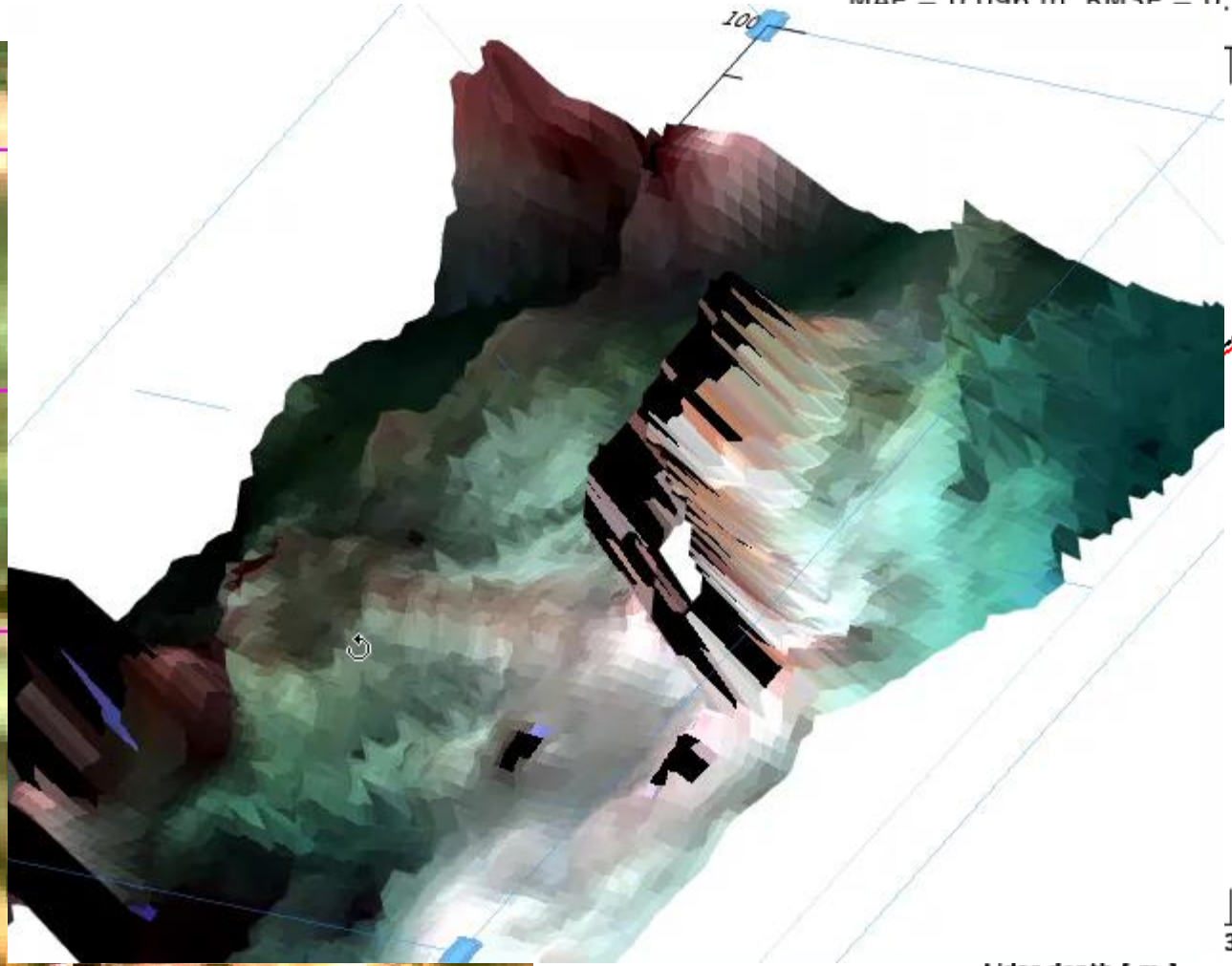
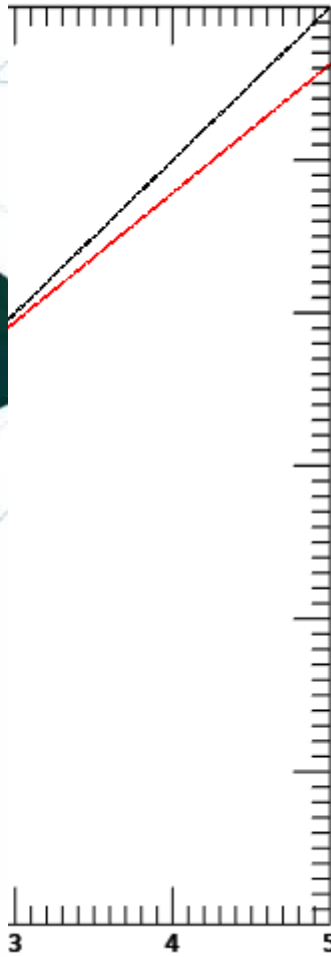
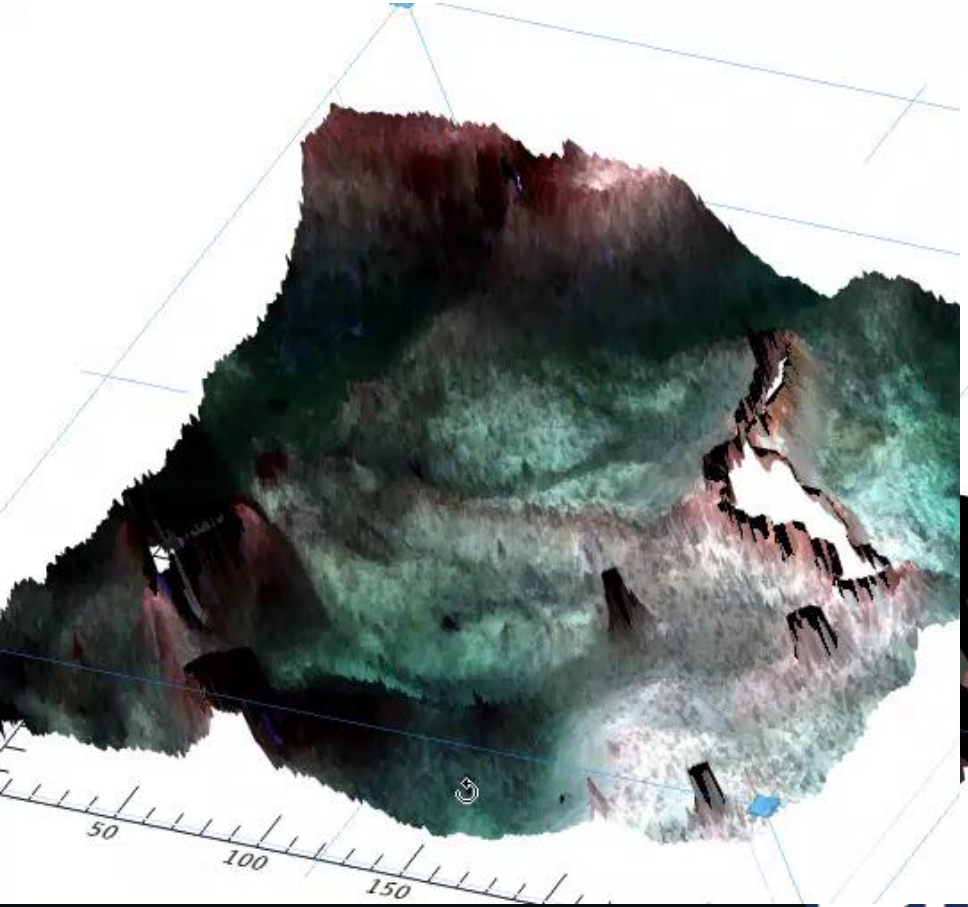
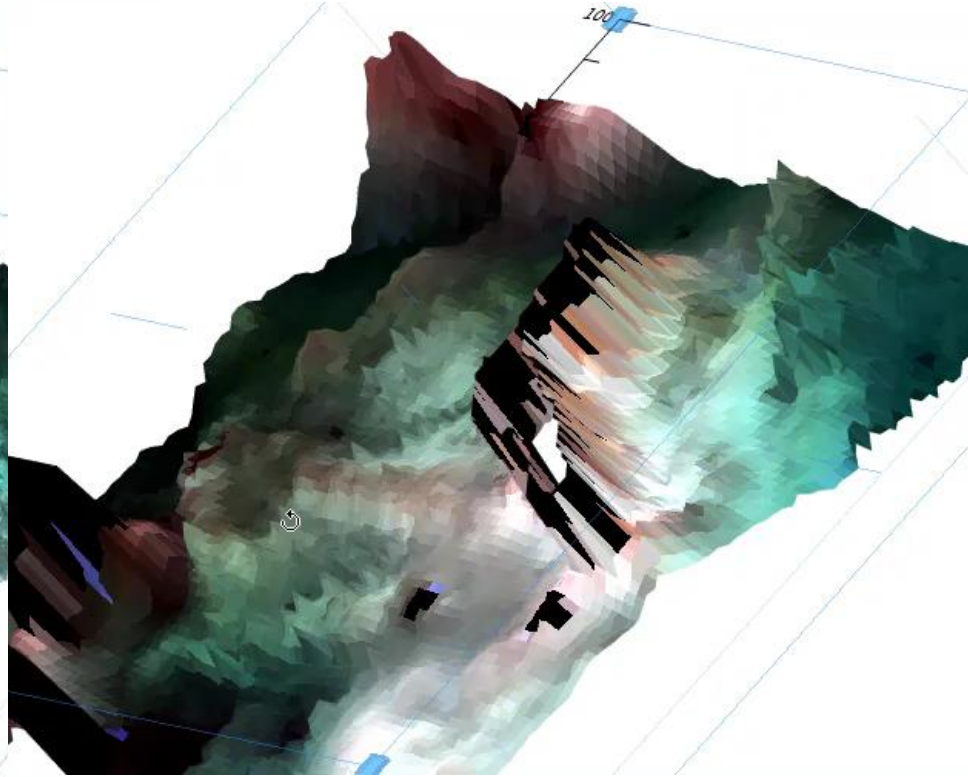



MAE = 0.096 m RMSE = 0.183 m
100


3
4
Lidar depth [ m ]

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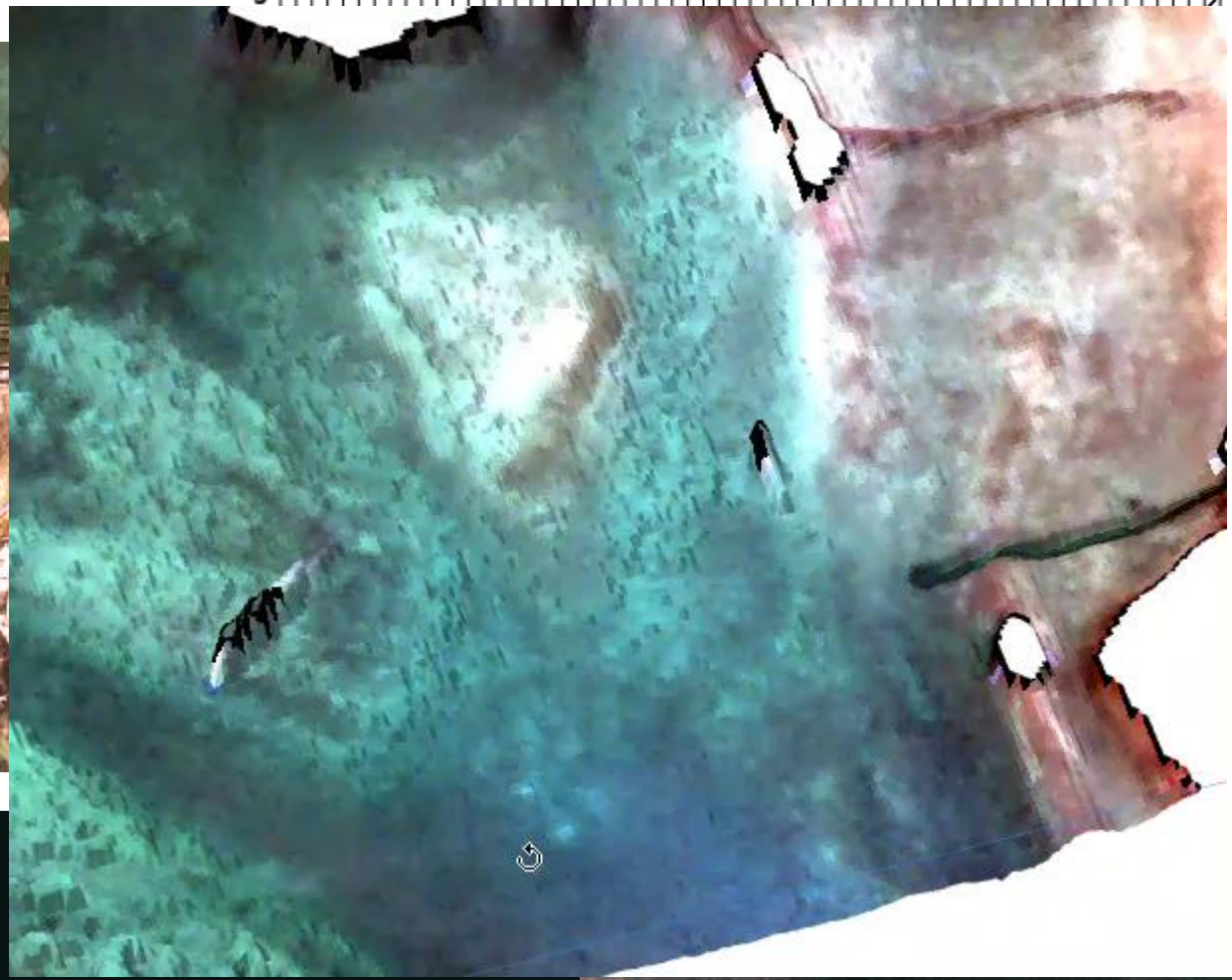
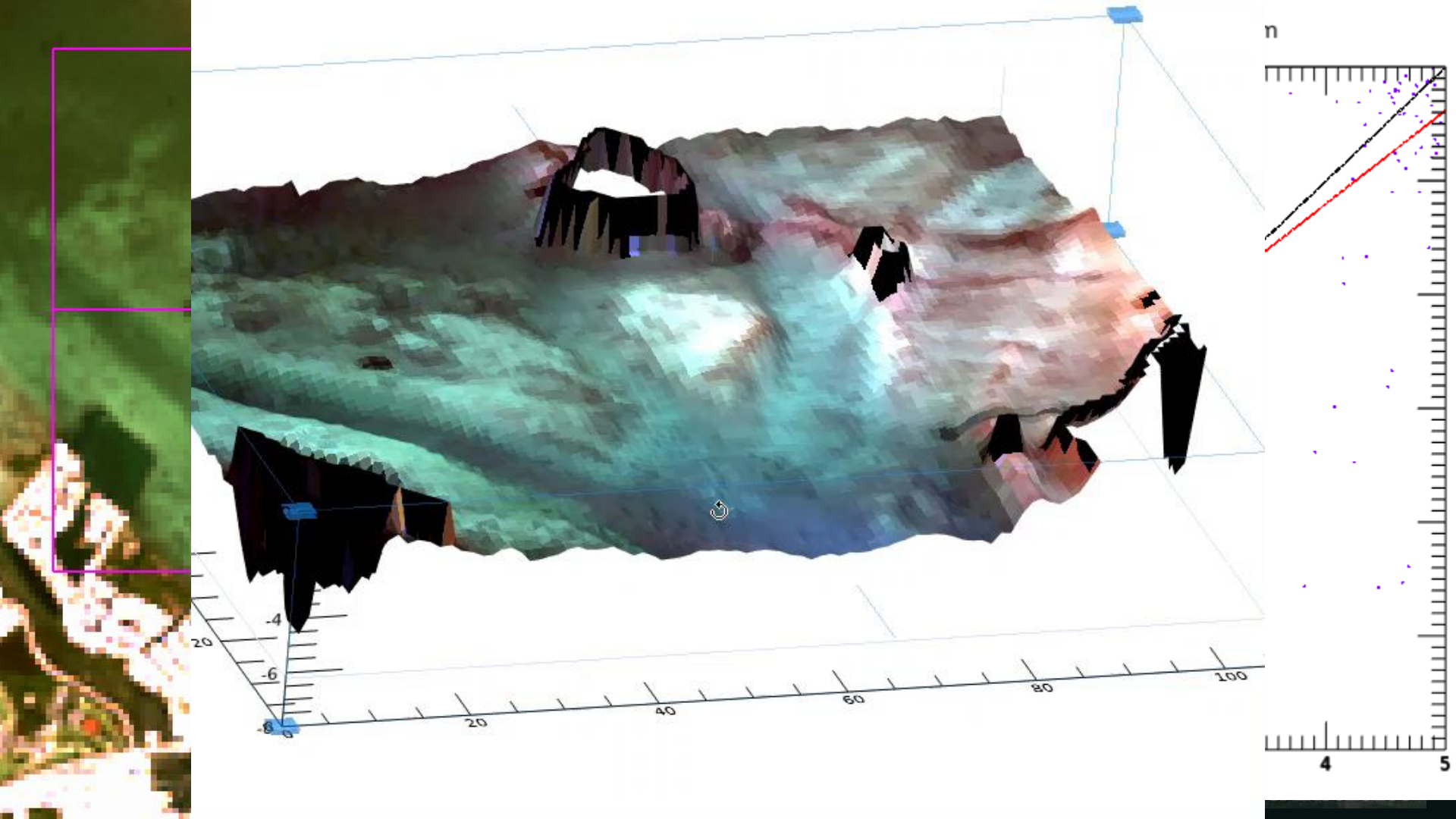
MAE = 0.215 m, RMSE = 0.226 m

5

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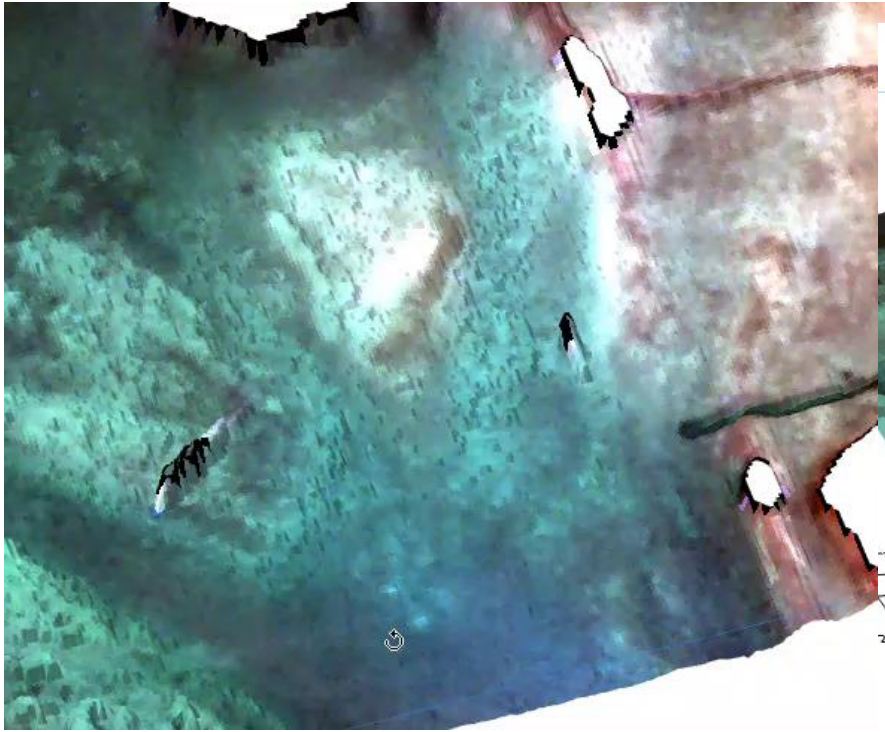

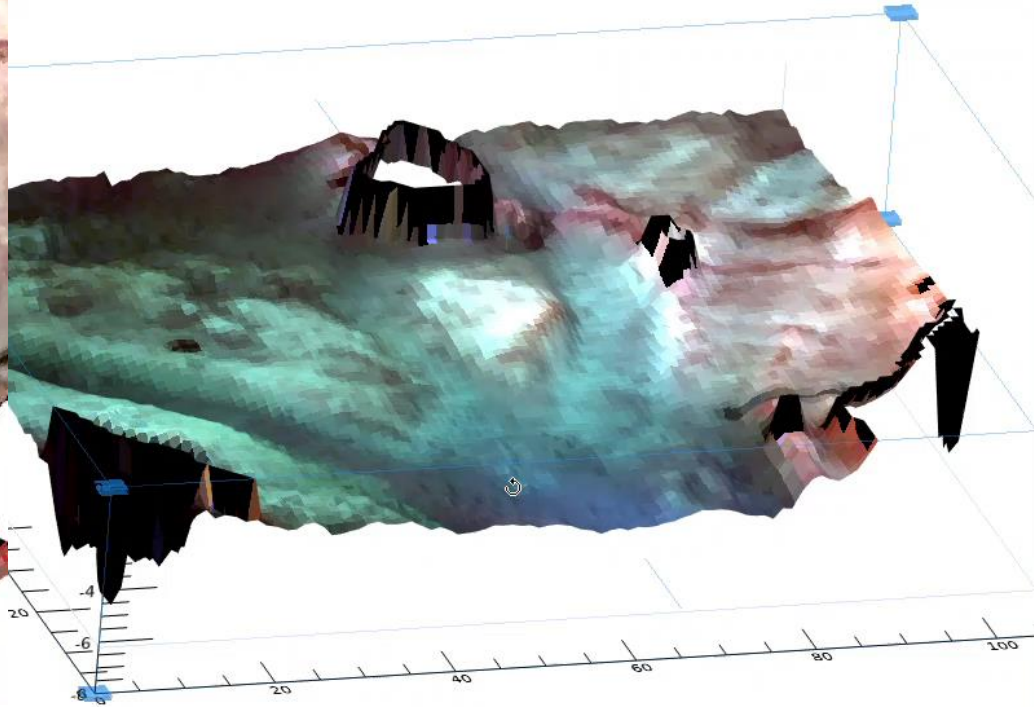


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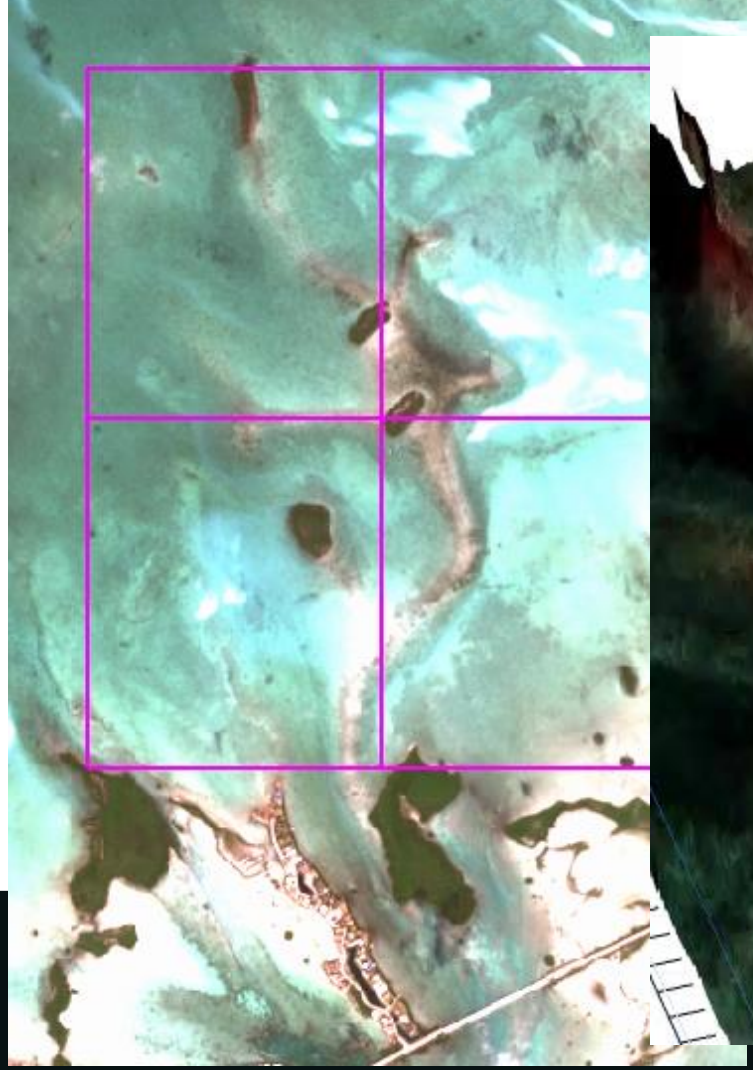

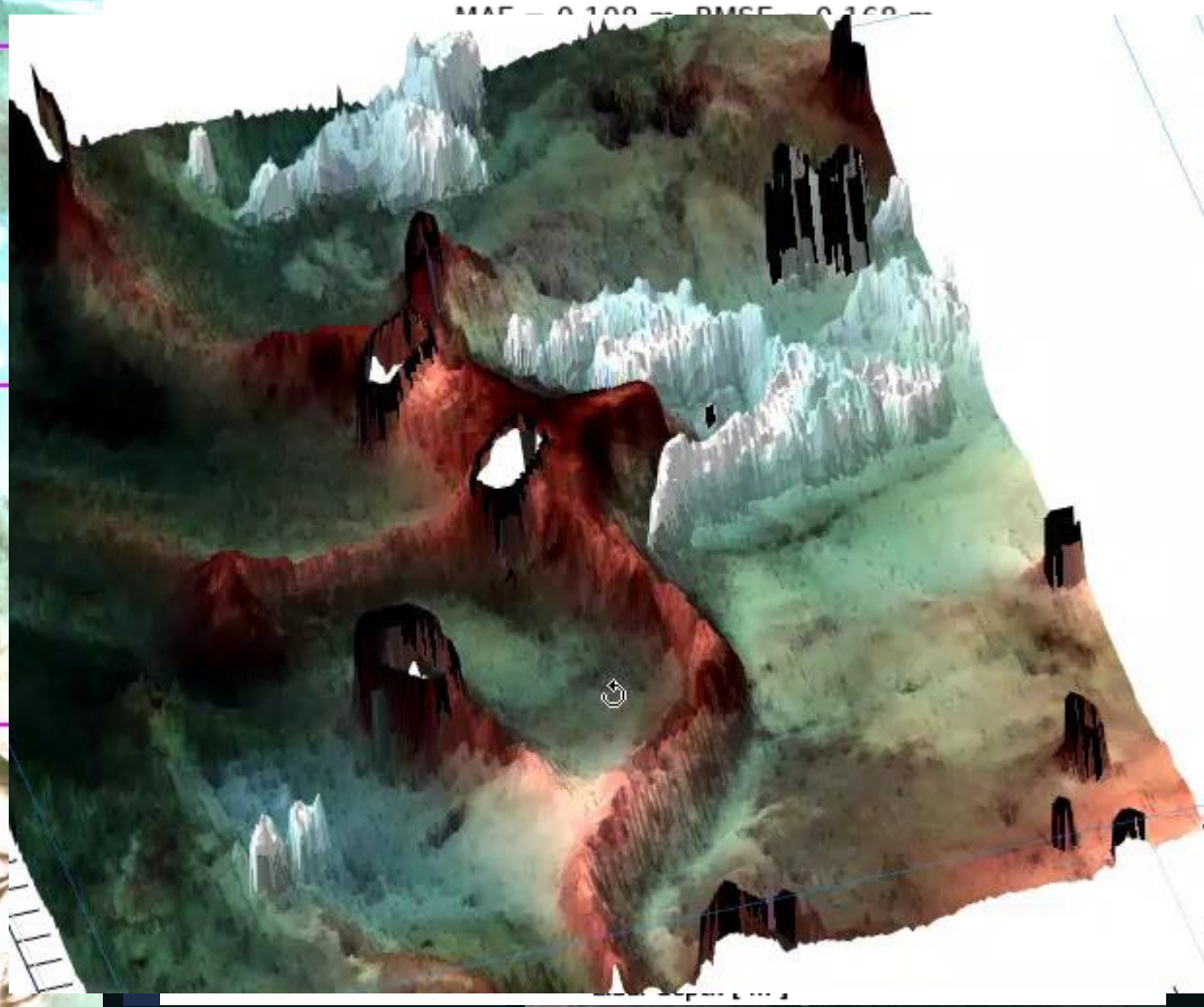

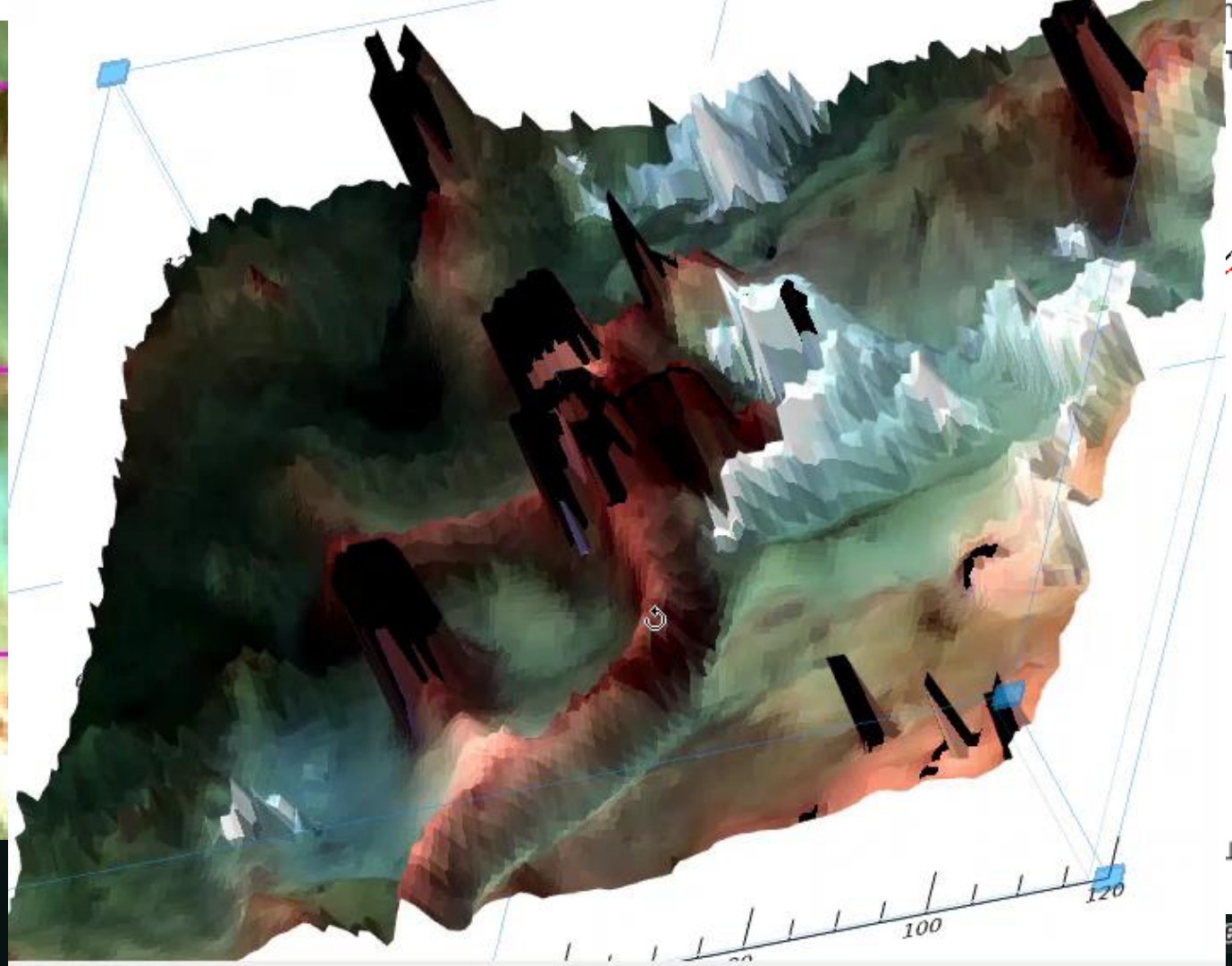



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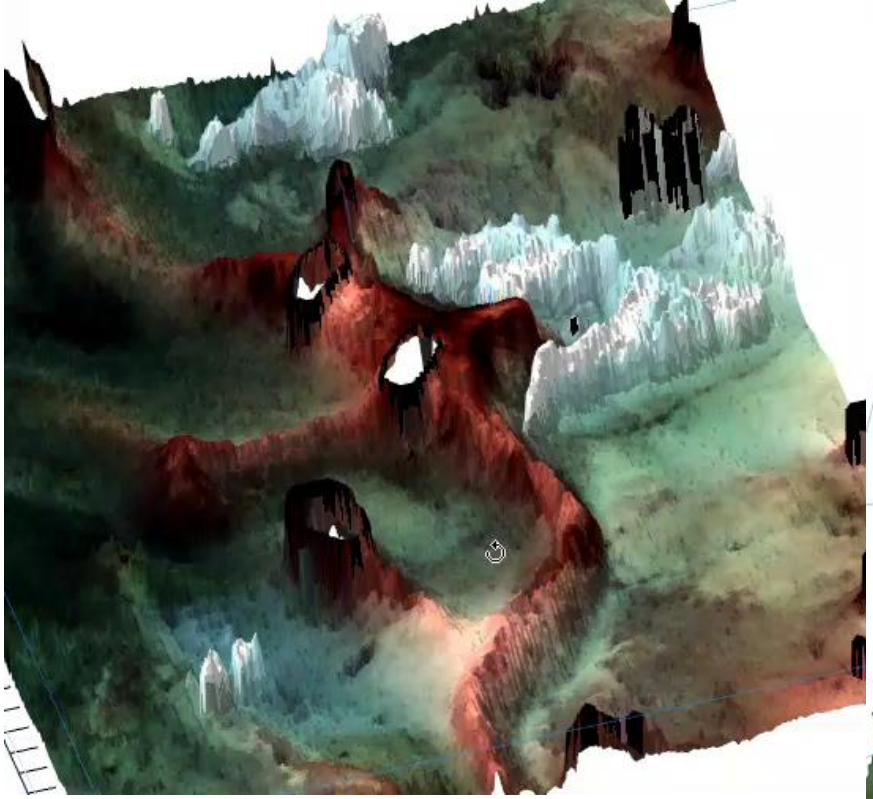

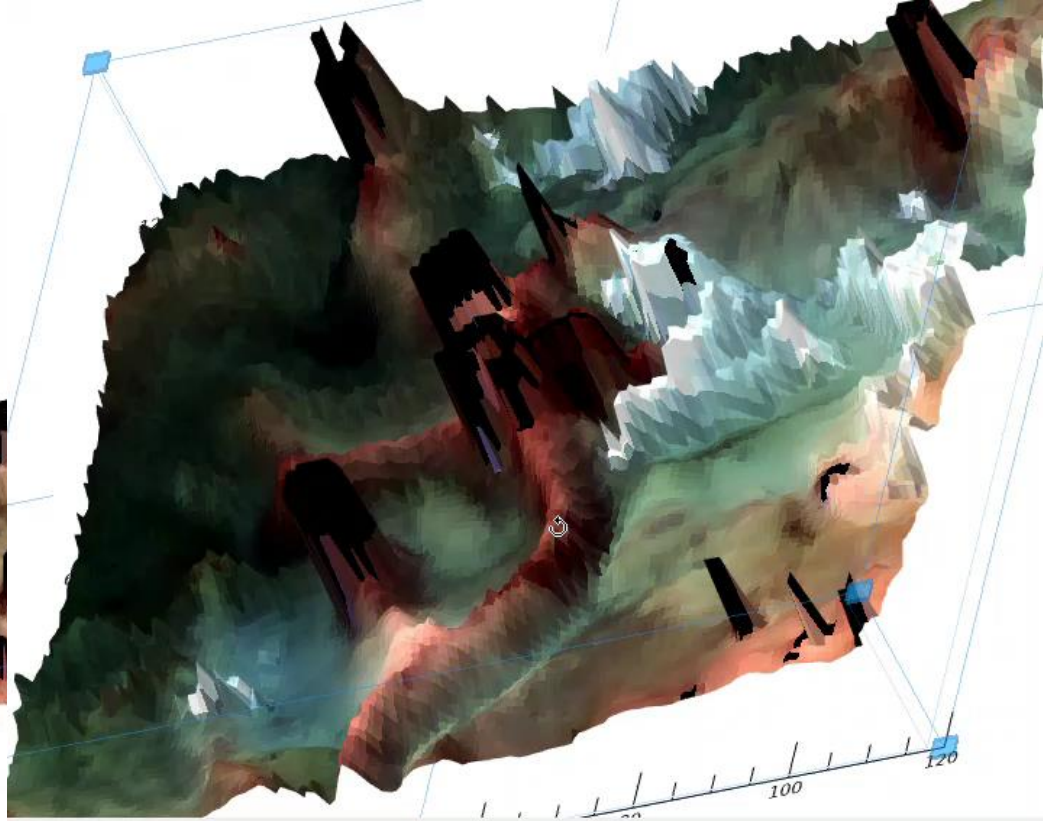


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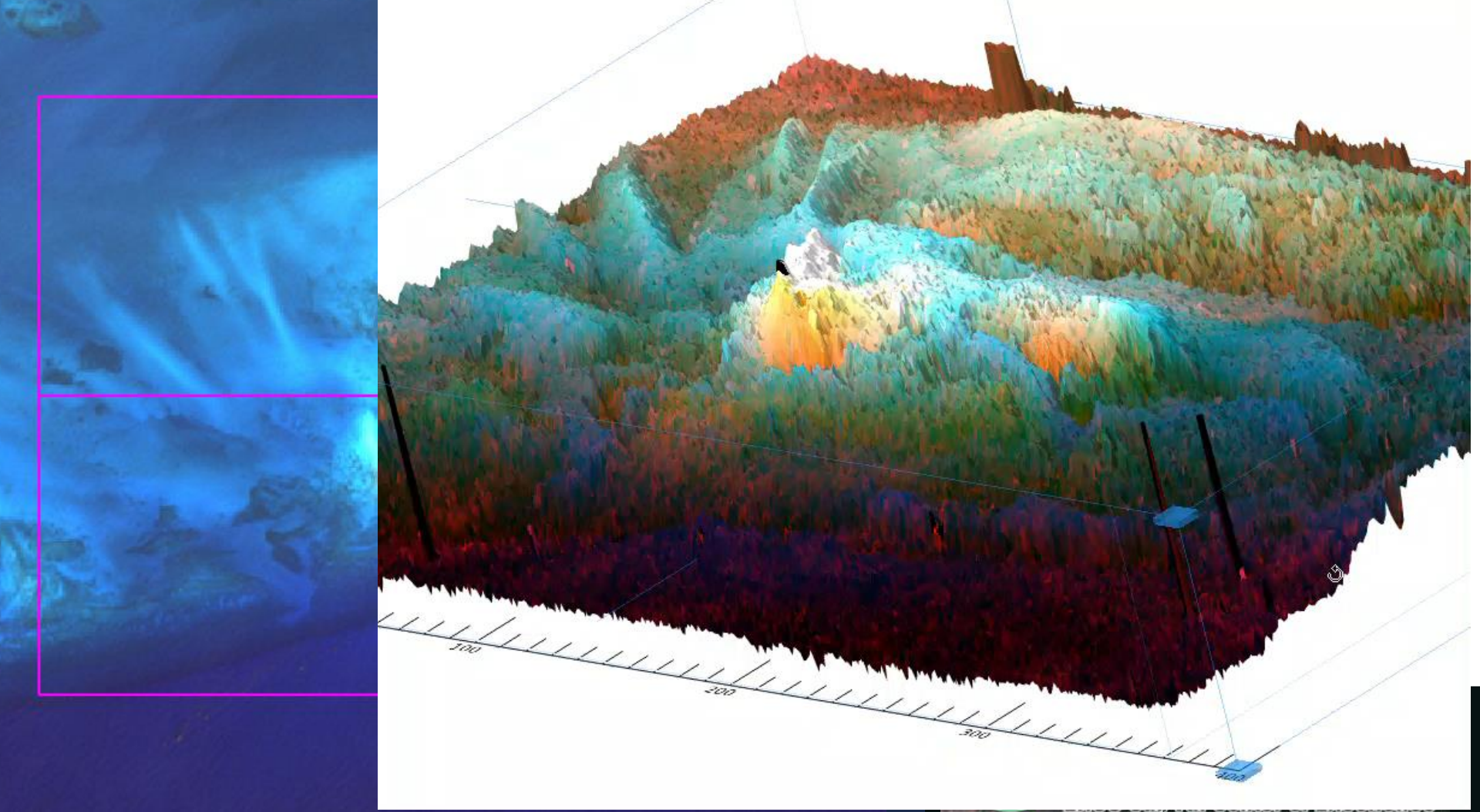
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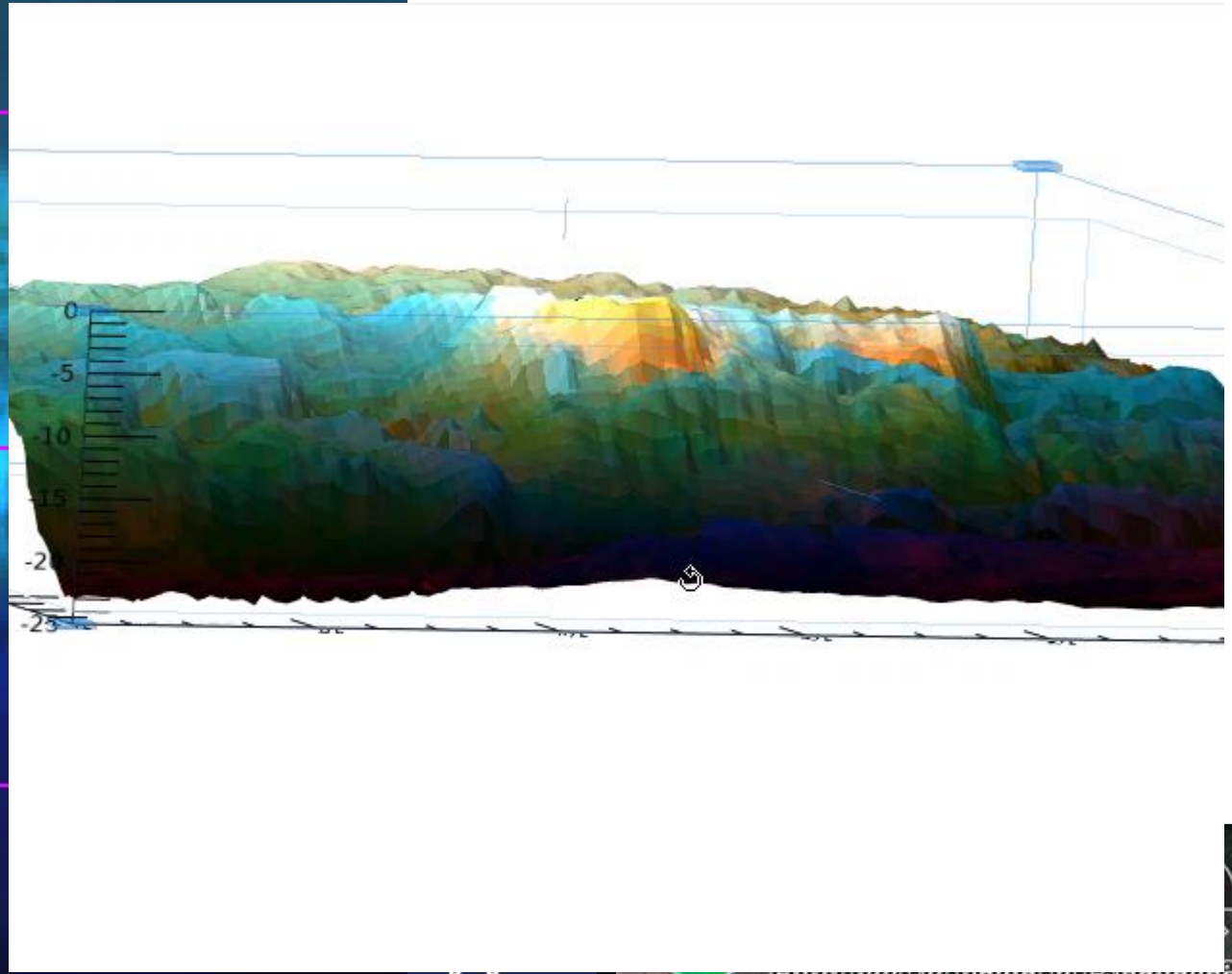
200
300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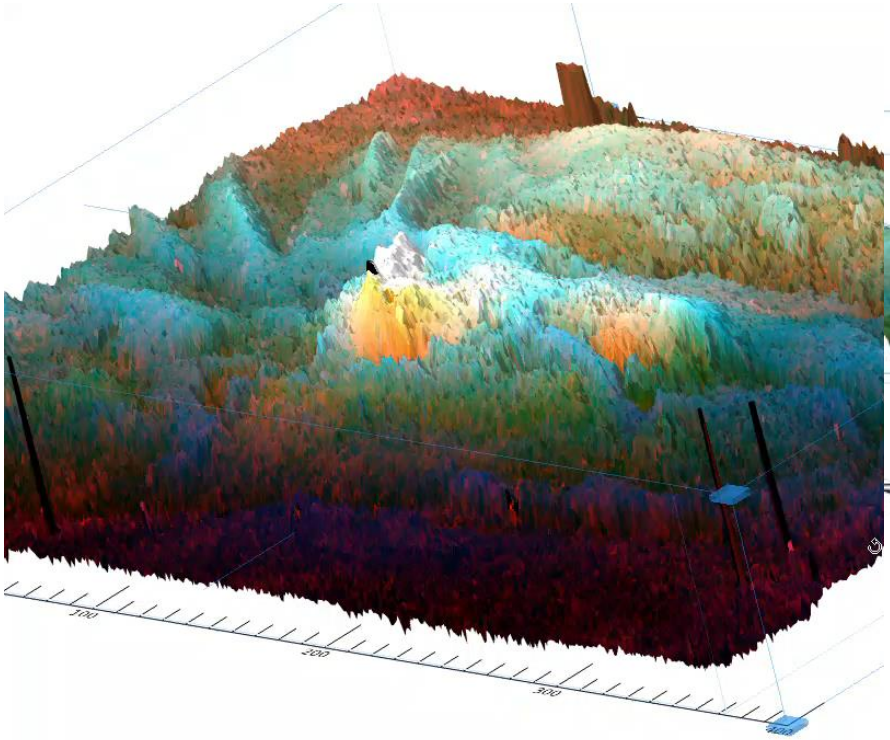


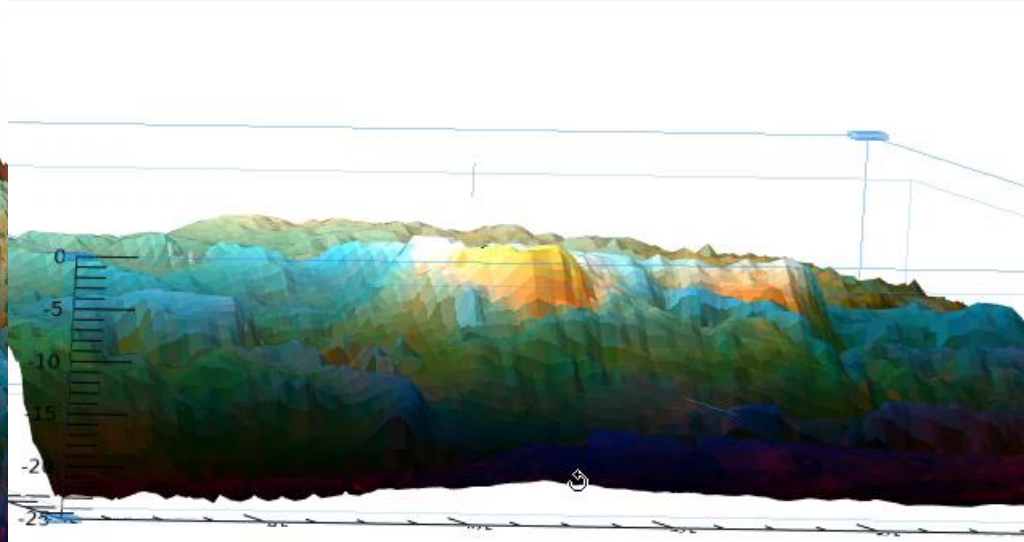

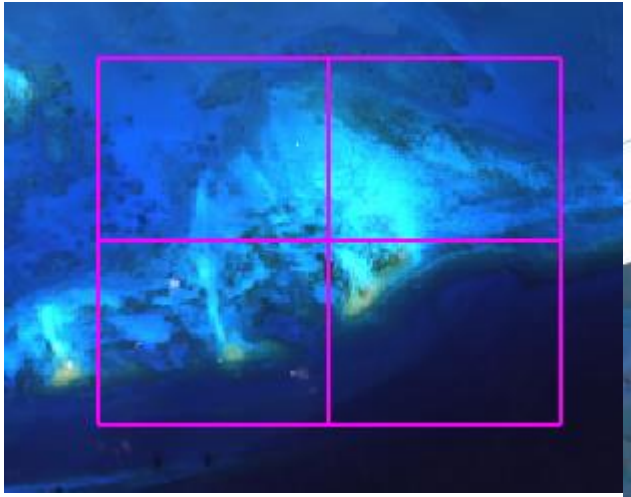

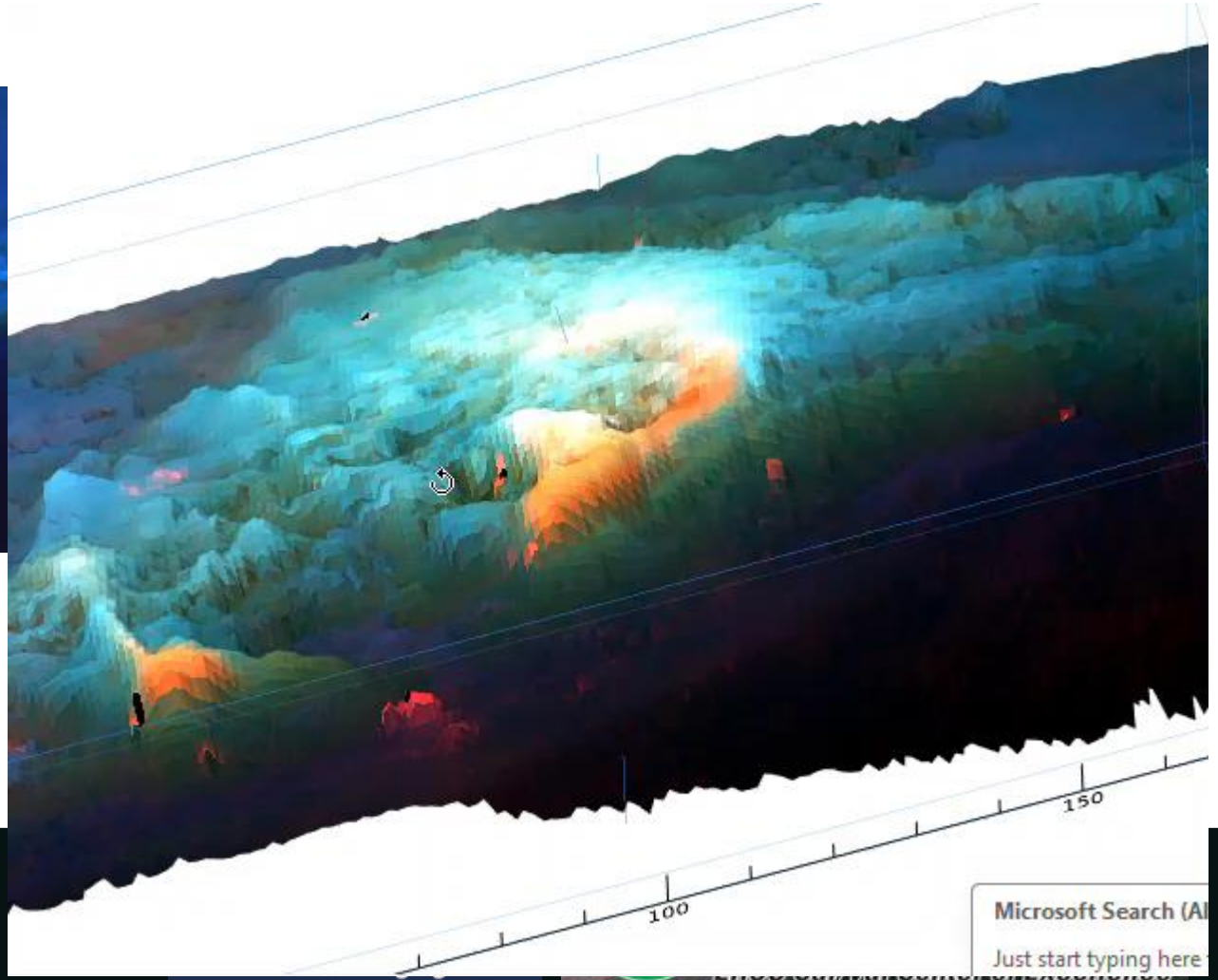


Microsoft Search (A

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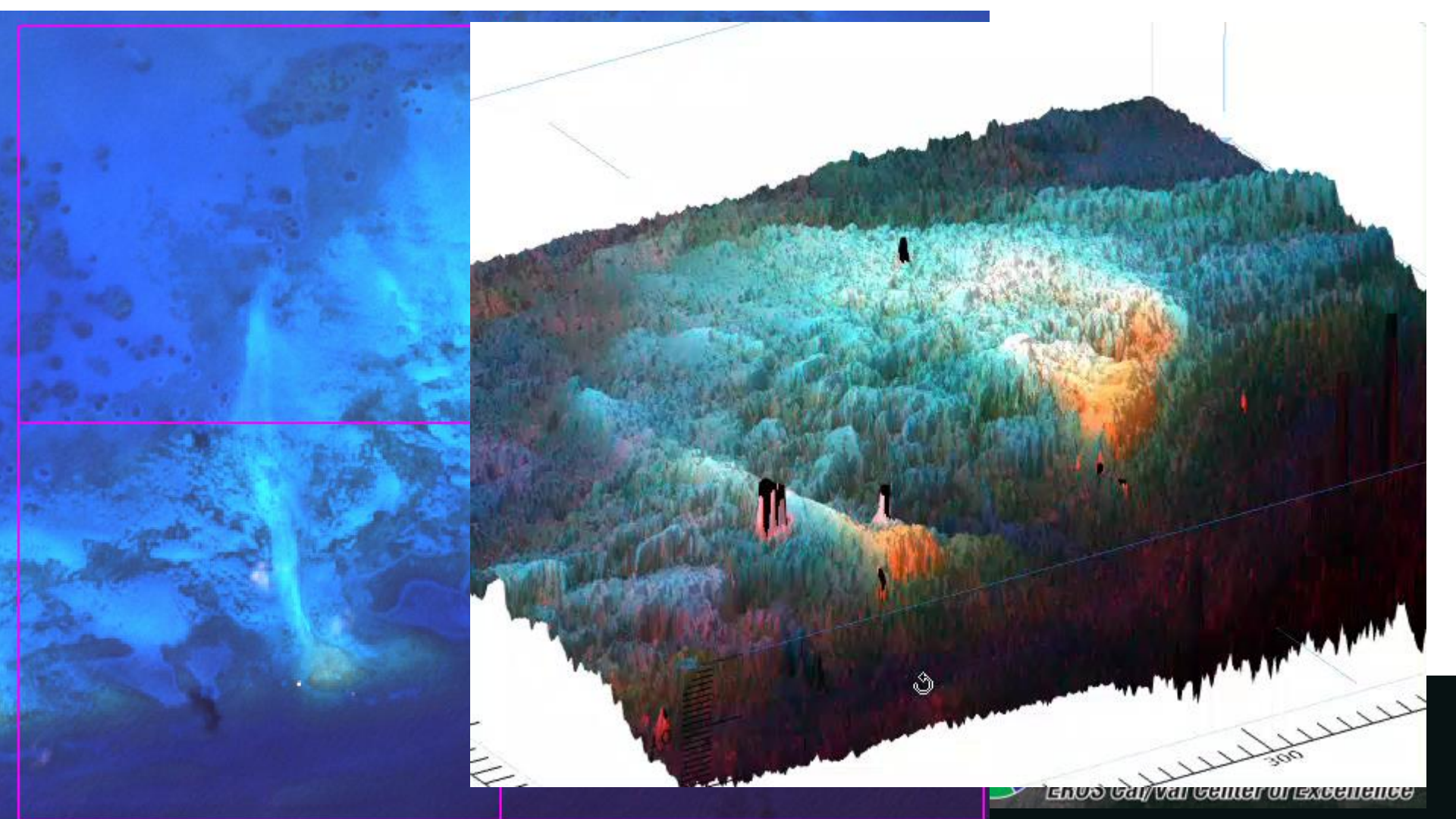
300
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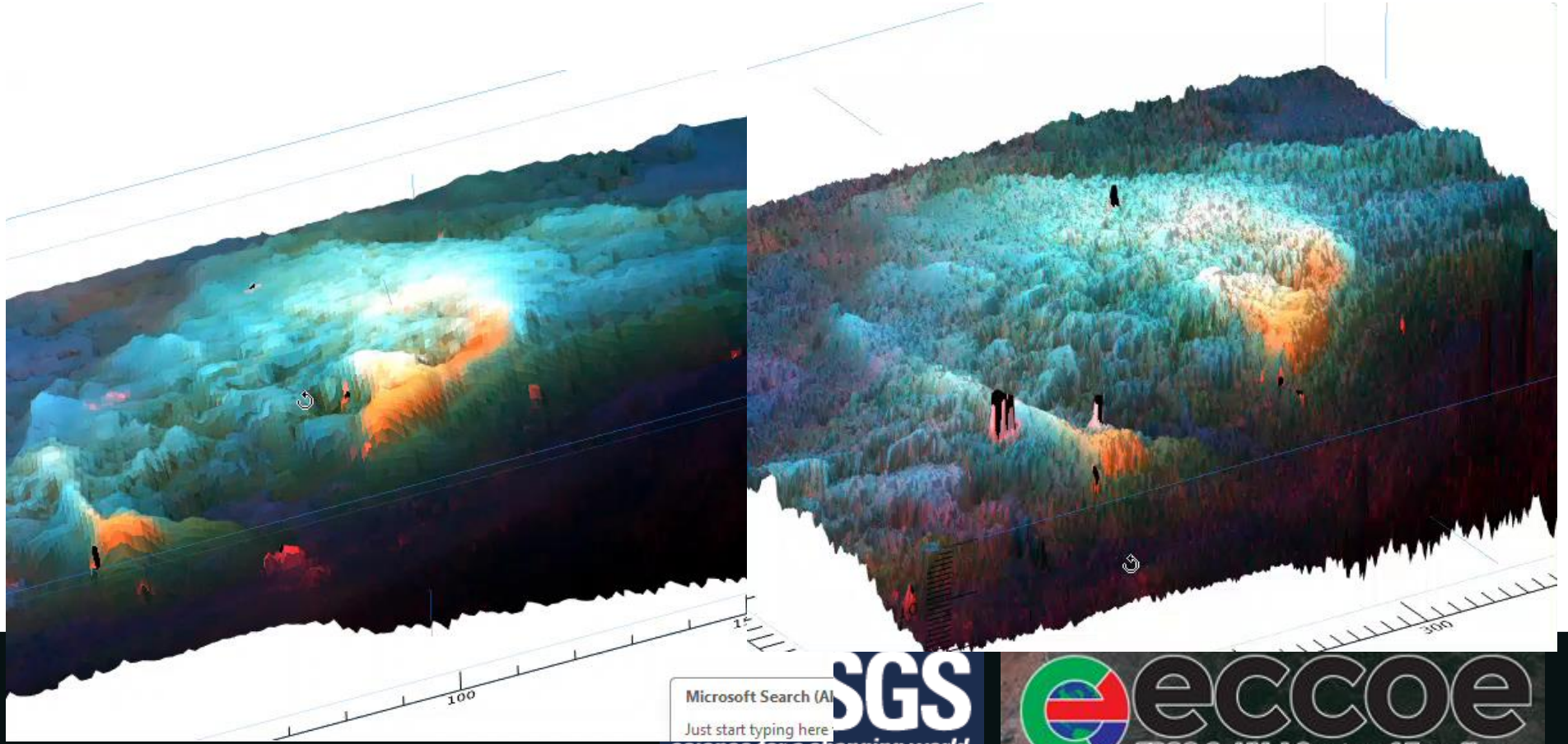


Microsoft Search (A

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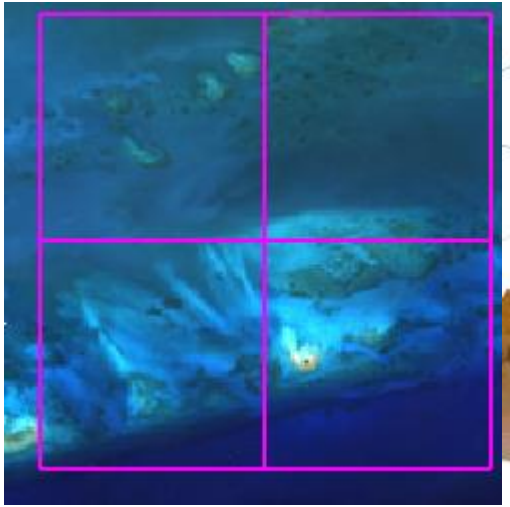

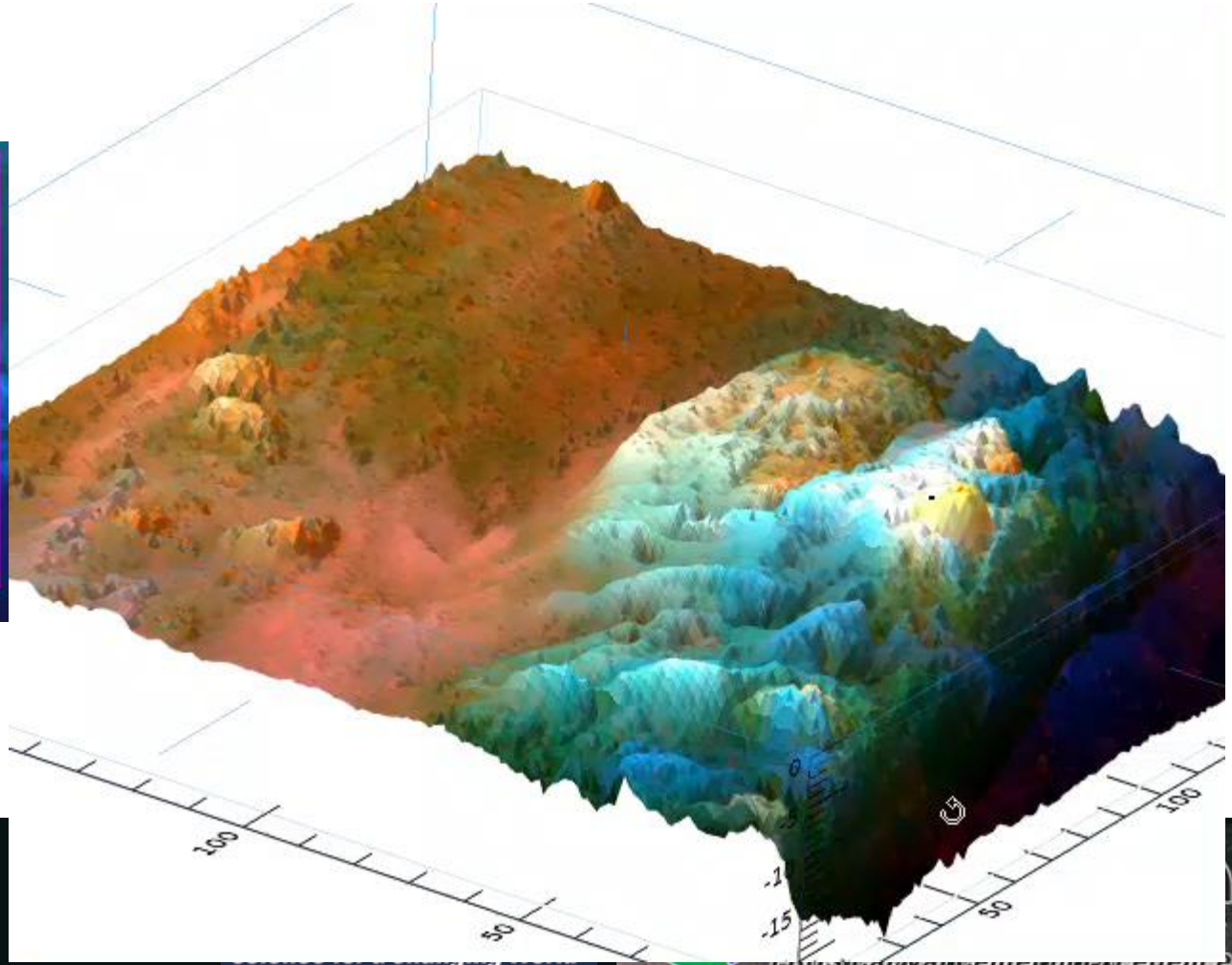
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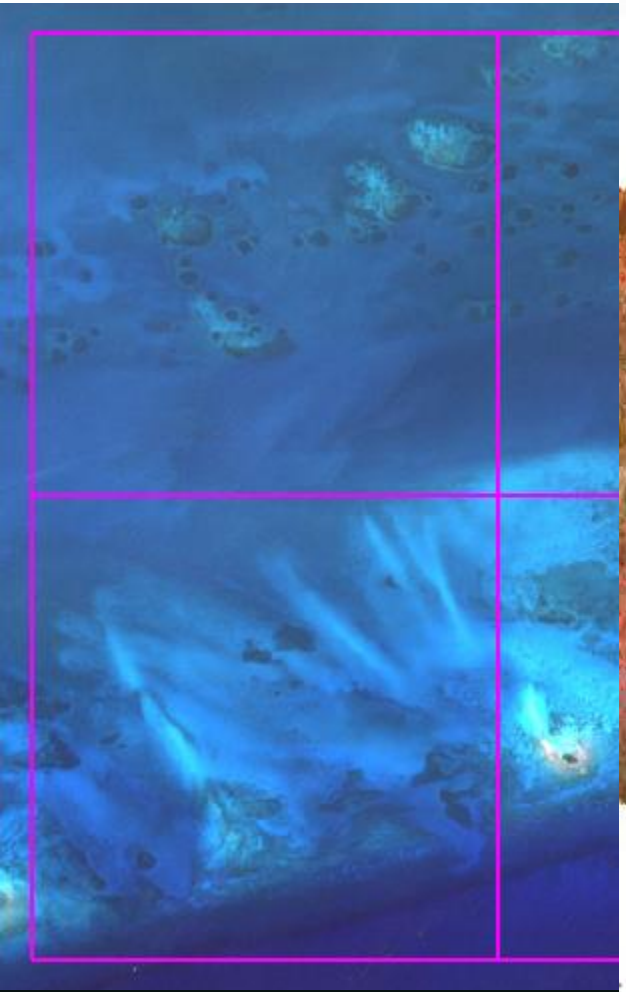

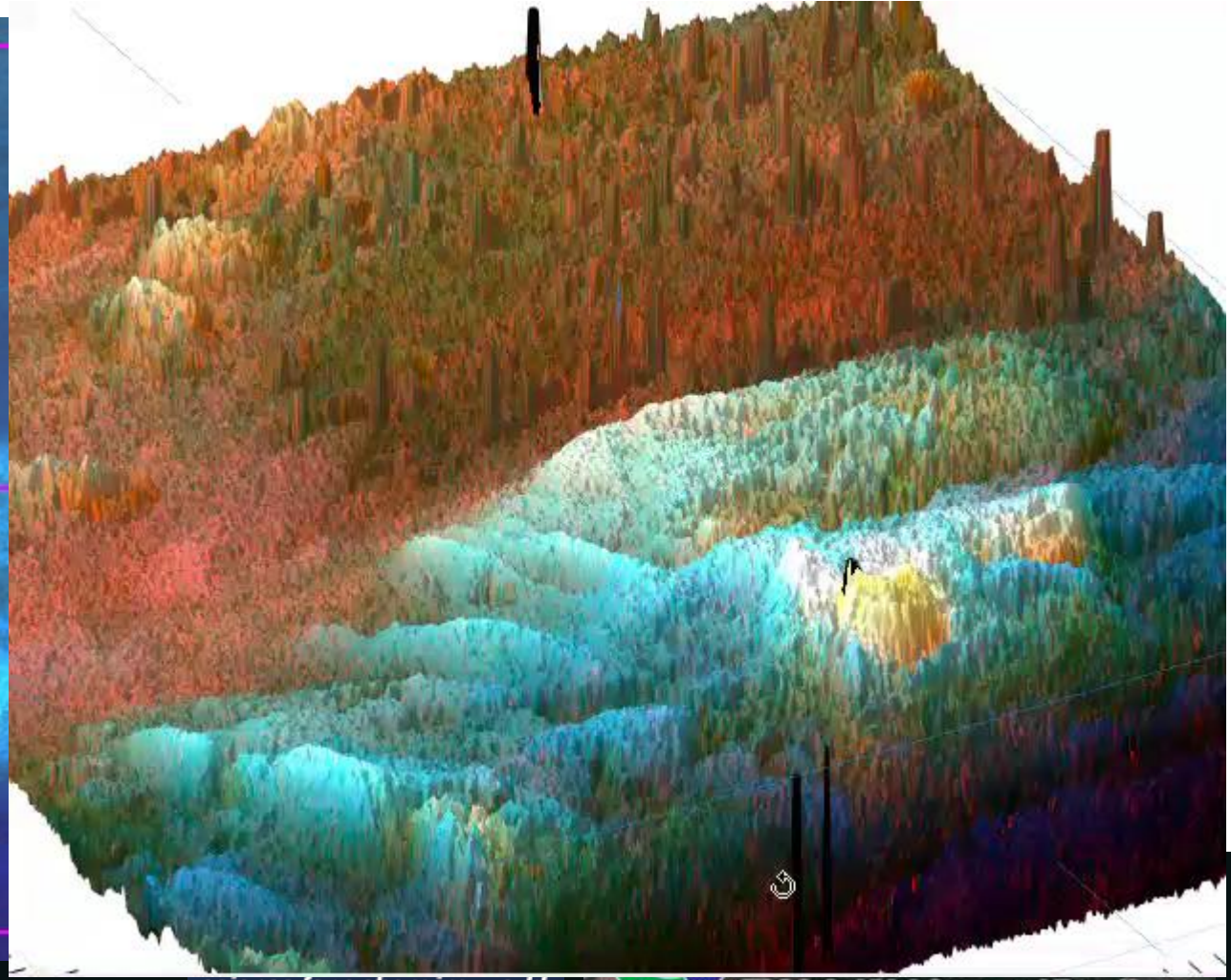

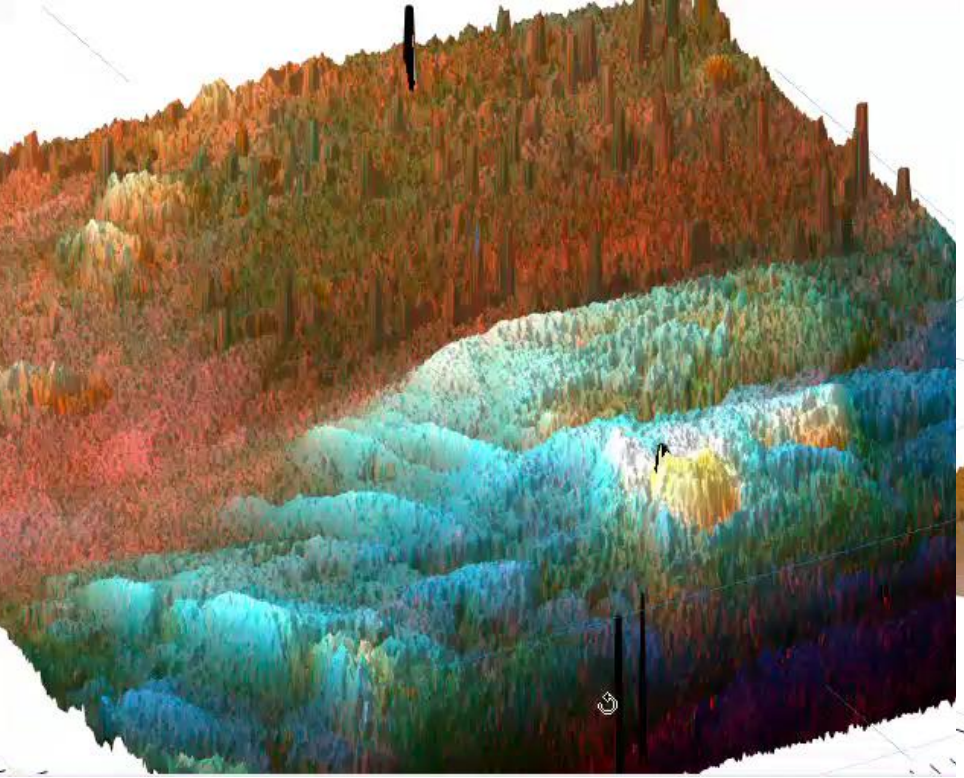

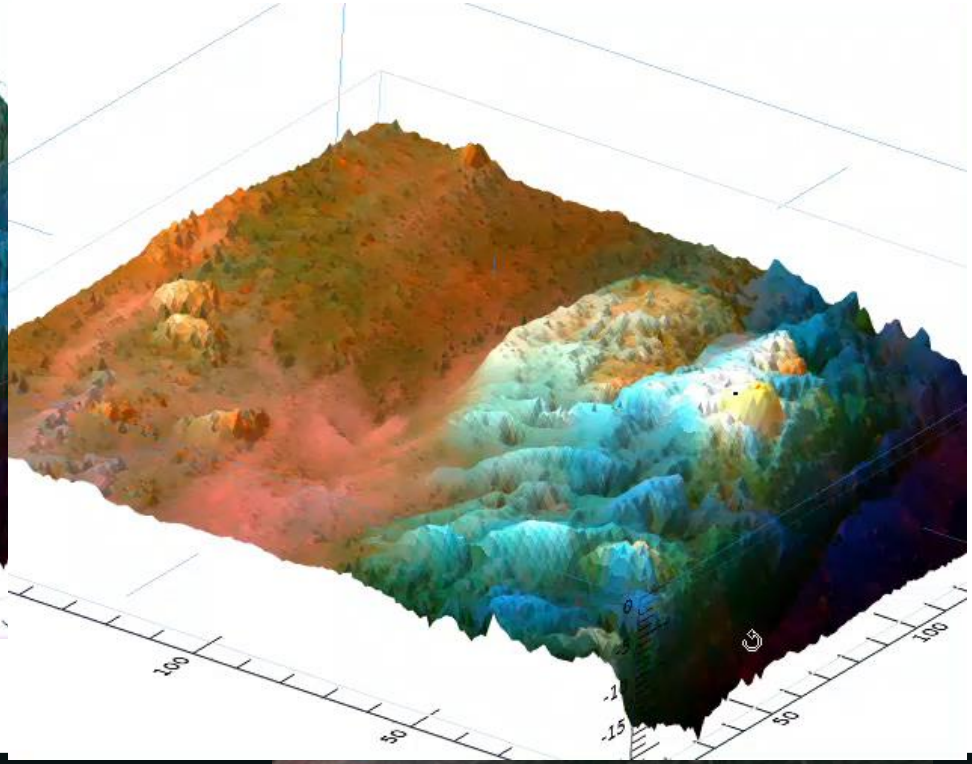


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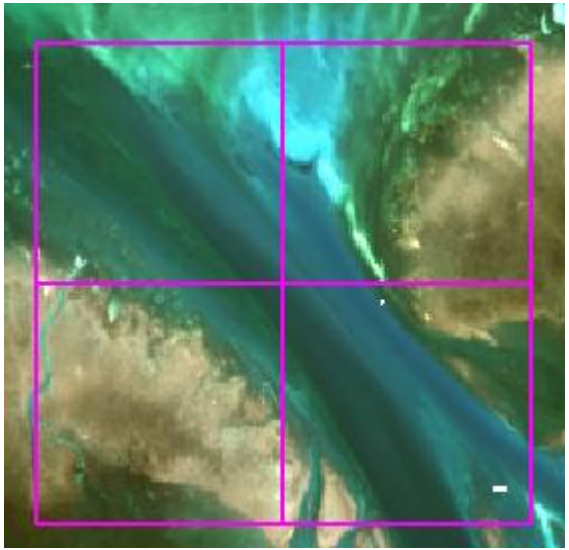

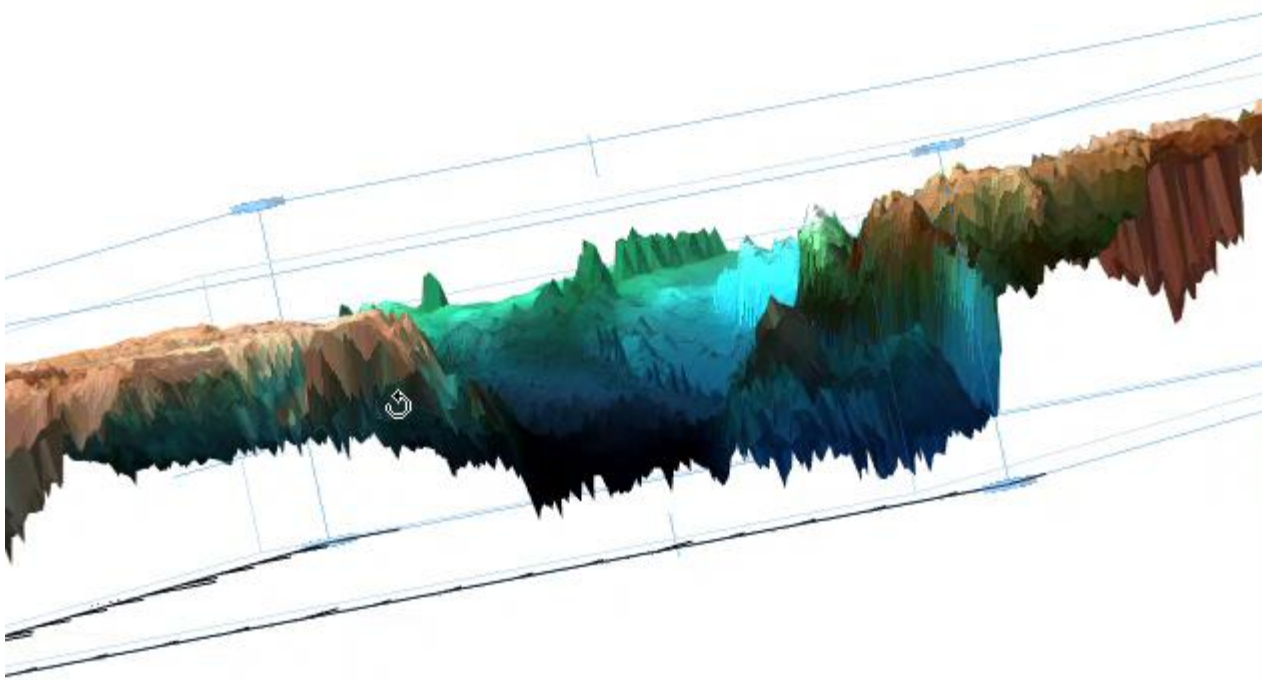

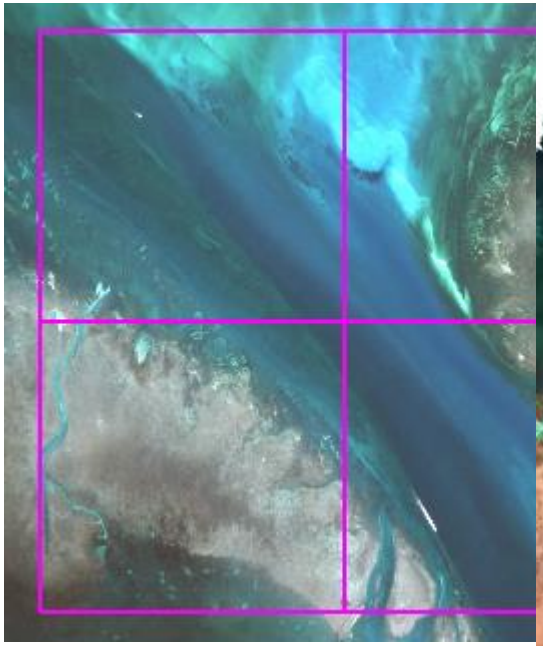

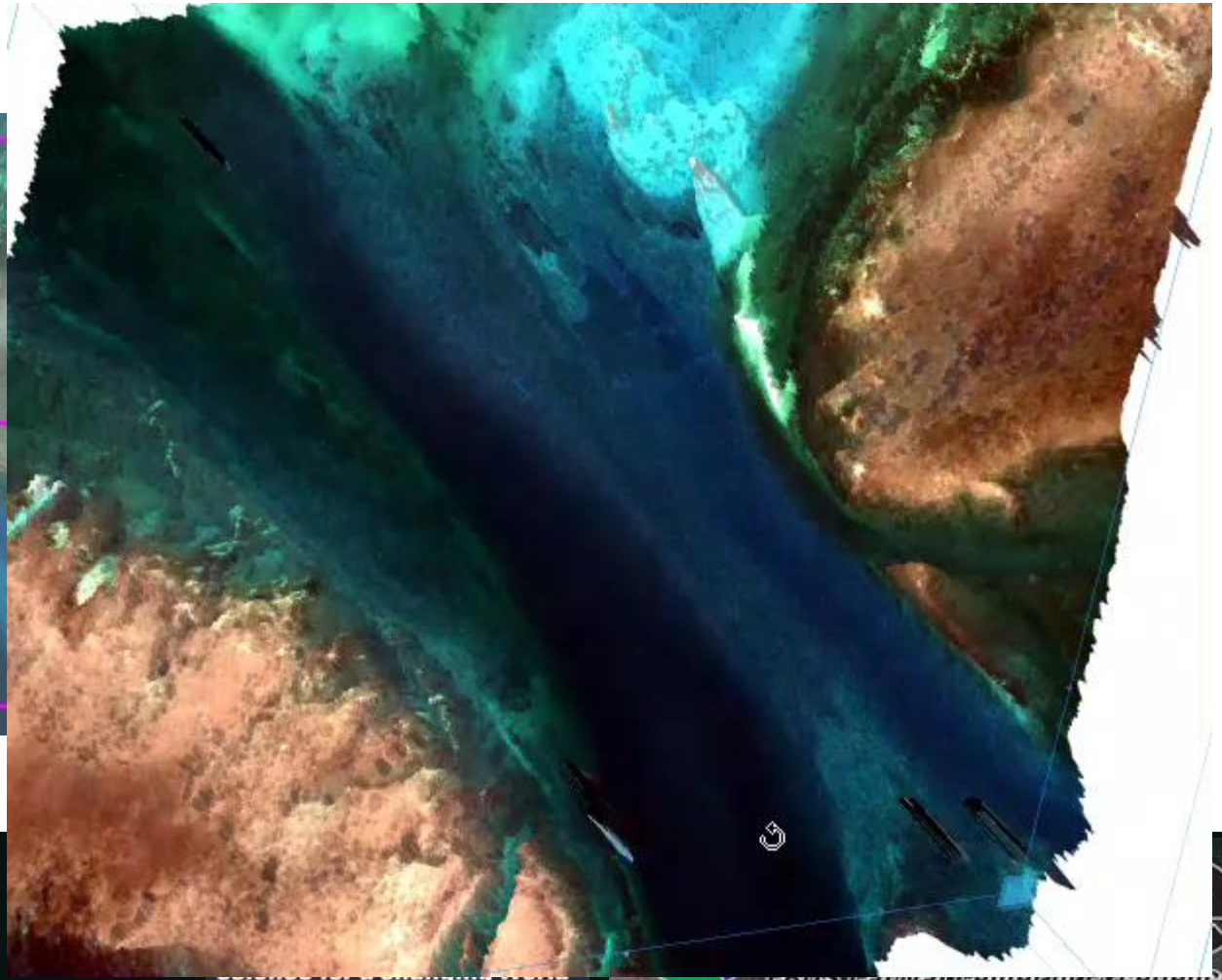

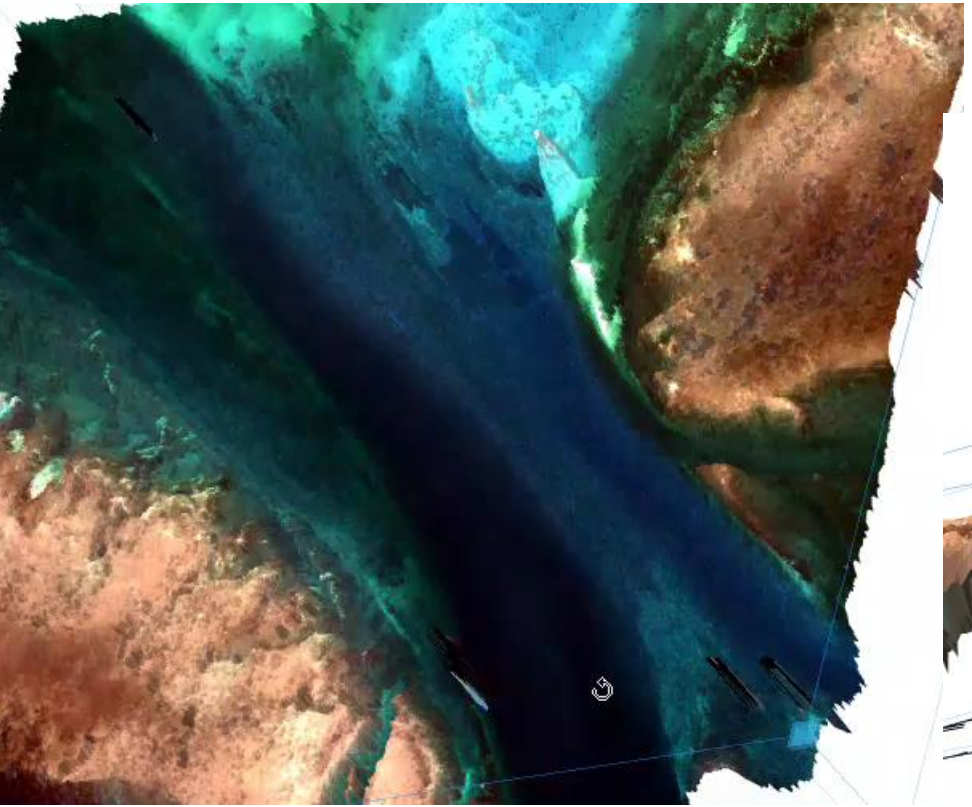

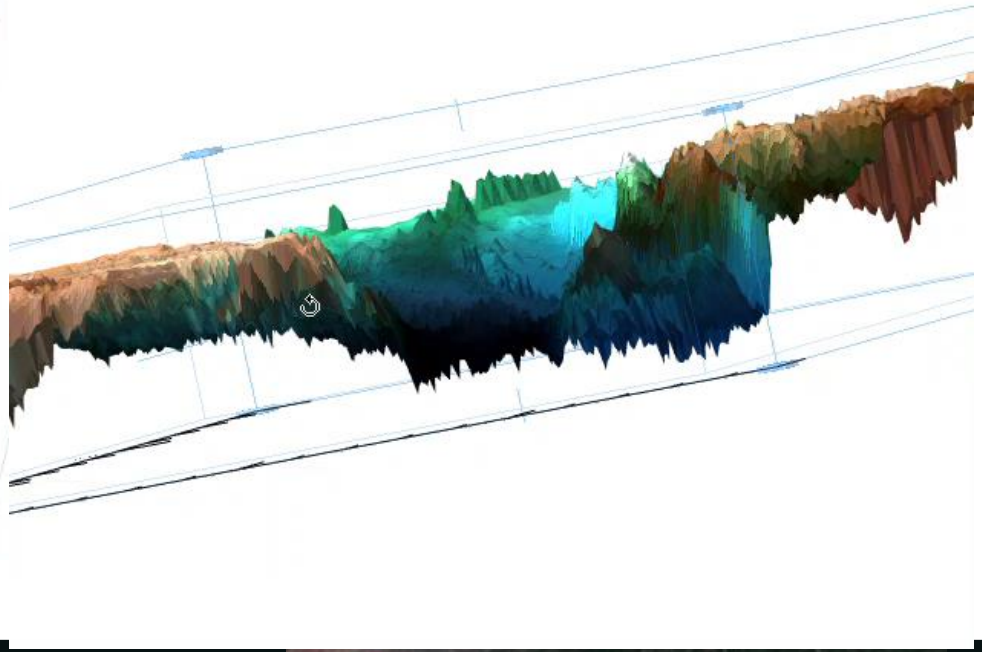

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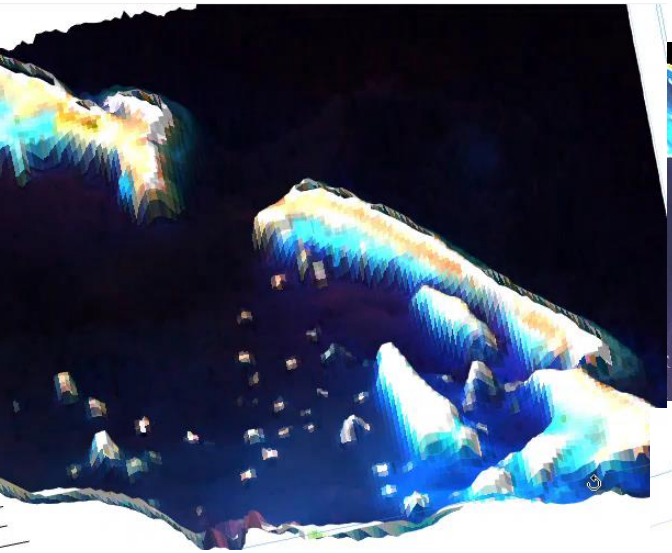
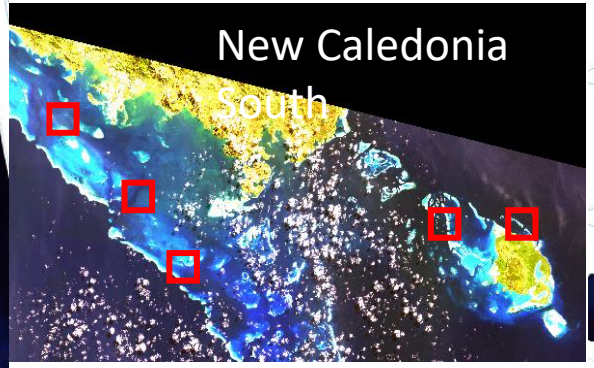
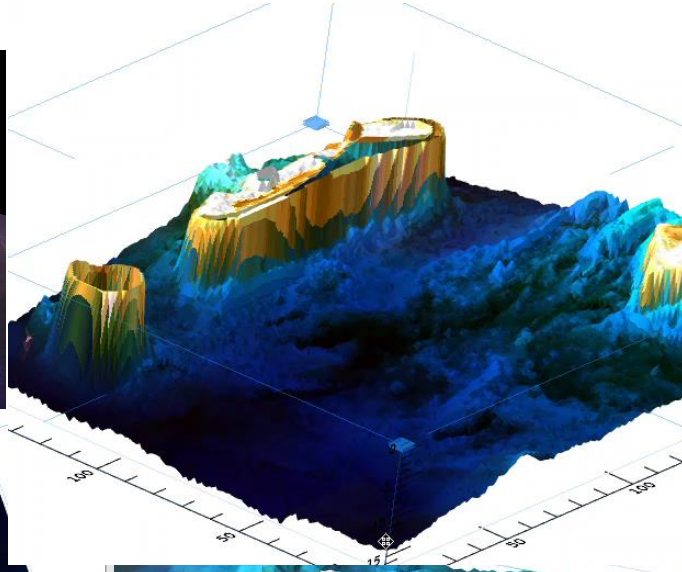
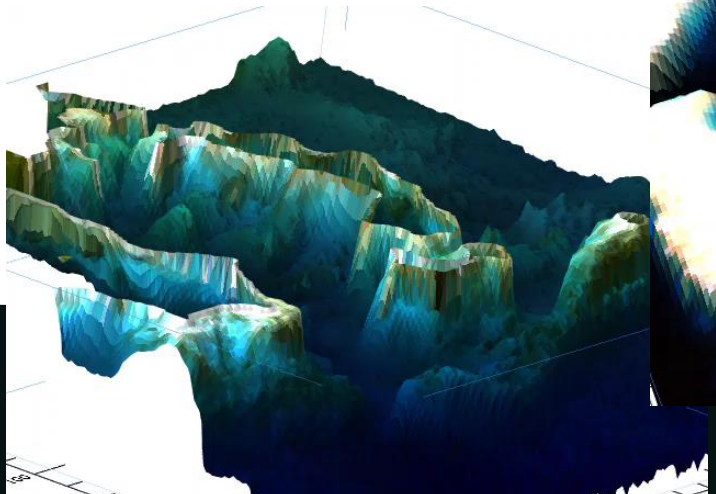
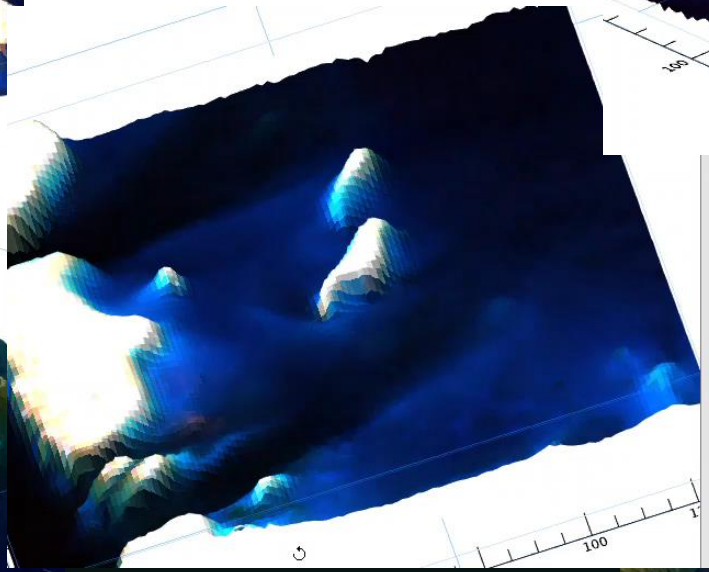
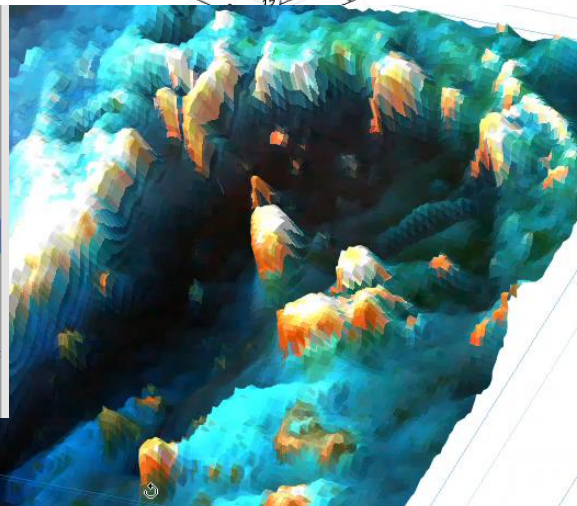



New Caledonia
South

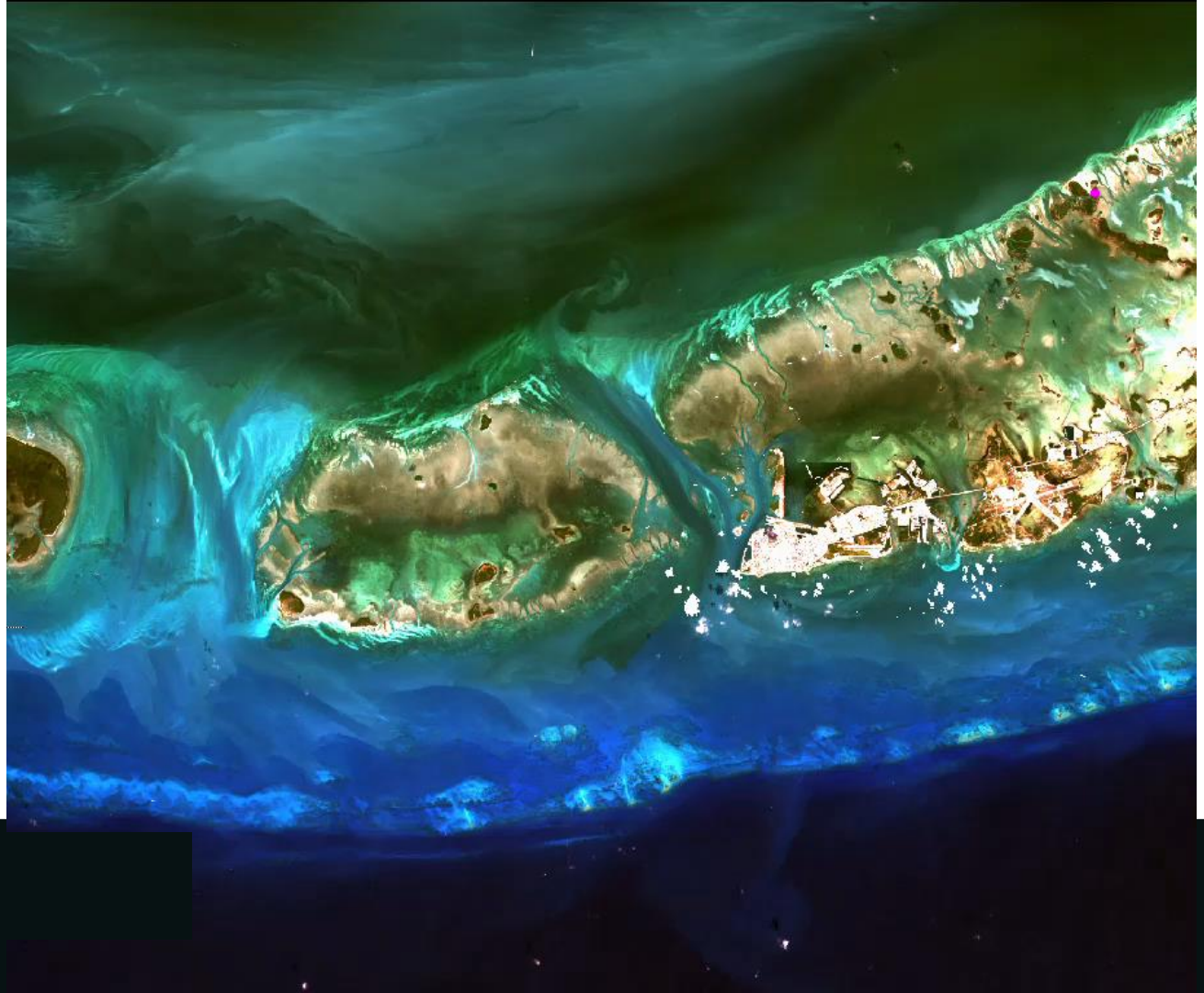


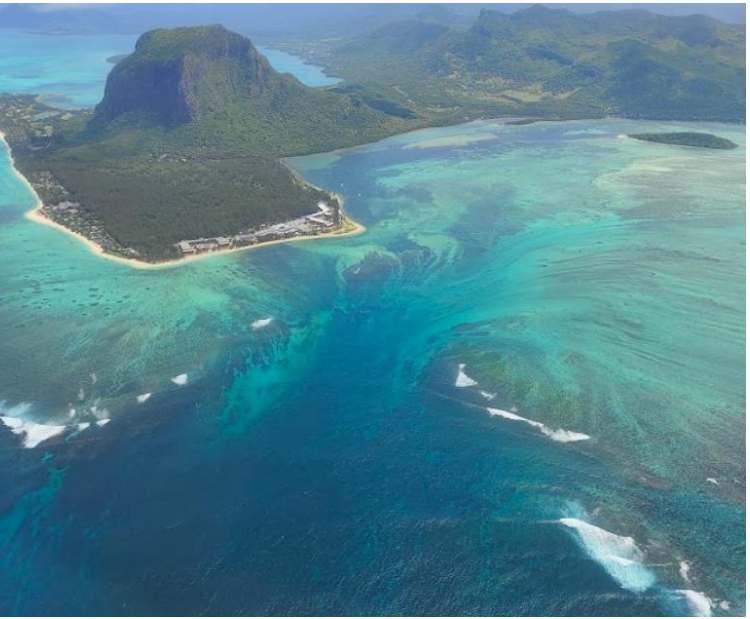






Key West
Florida





Underwater Waterfall