

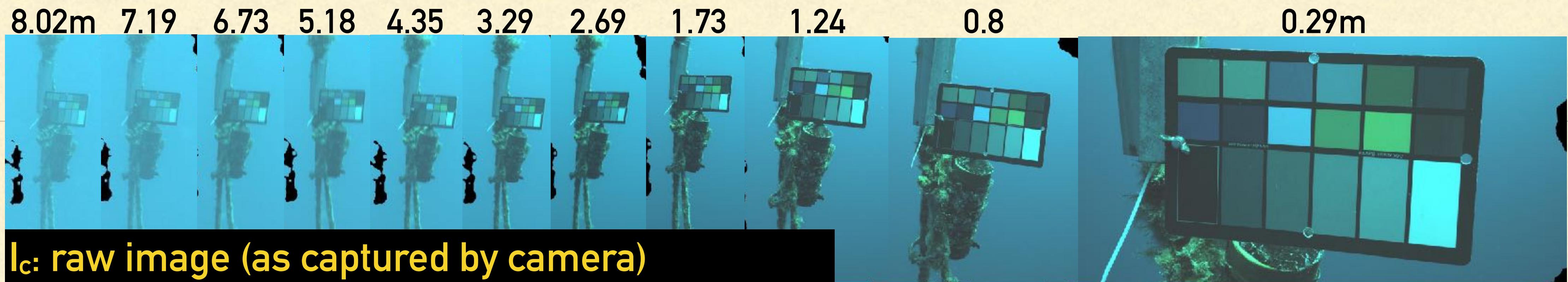


# UNDERWATER COLORIMETRY

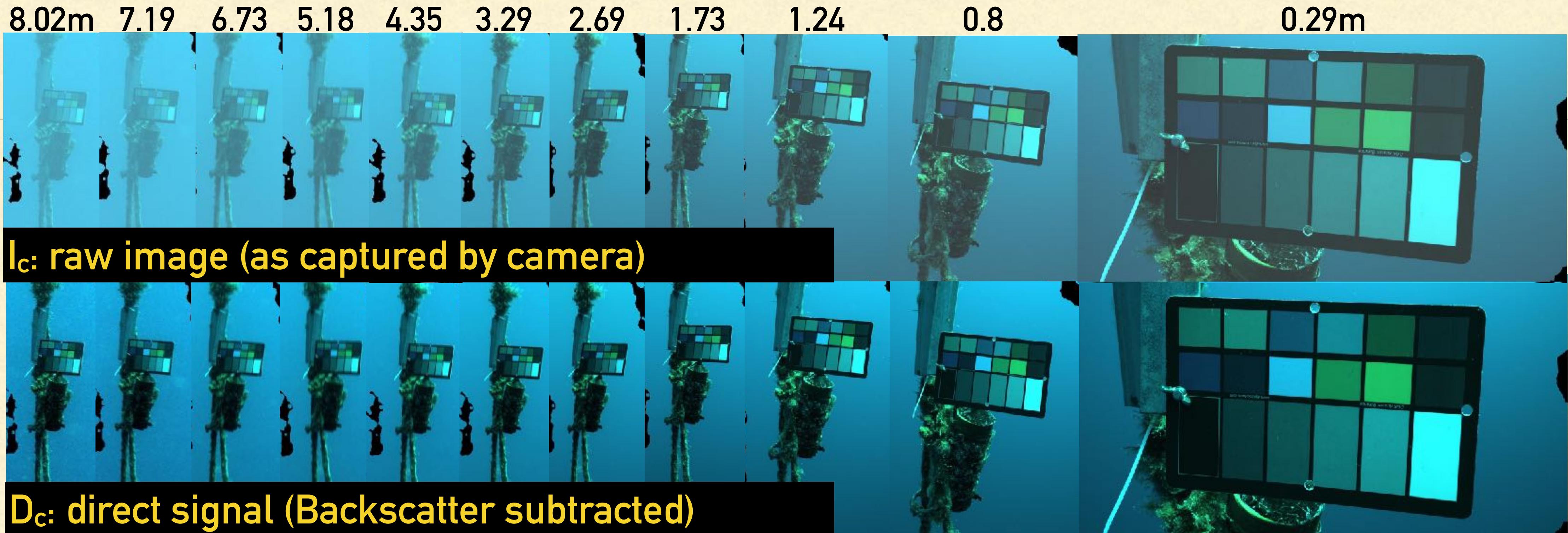
## COLORS IN THE OCEAN - III



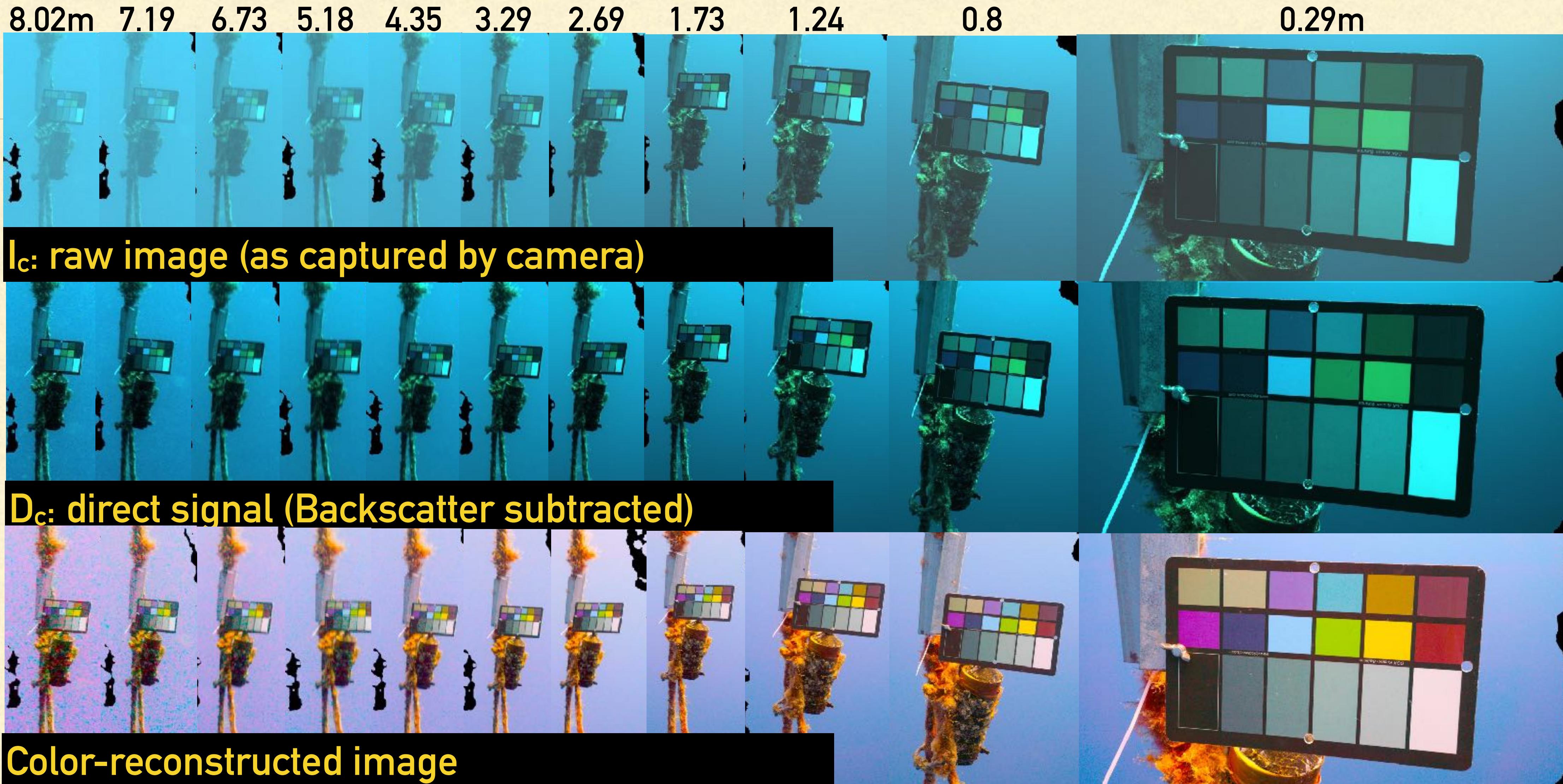
# Distance Dependency



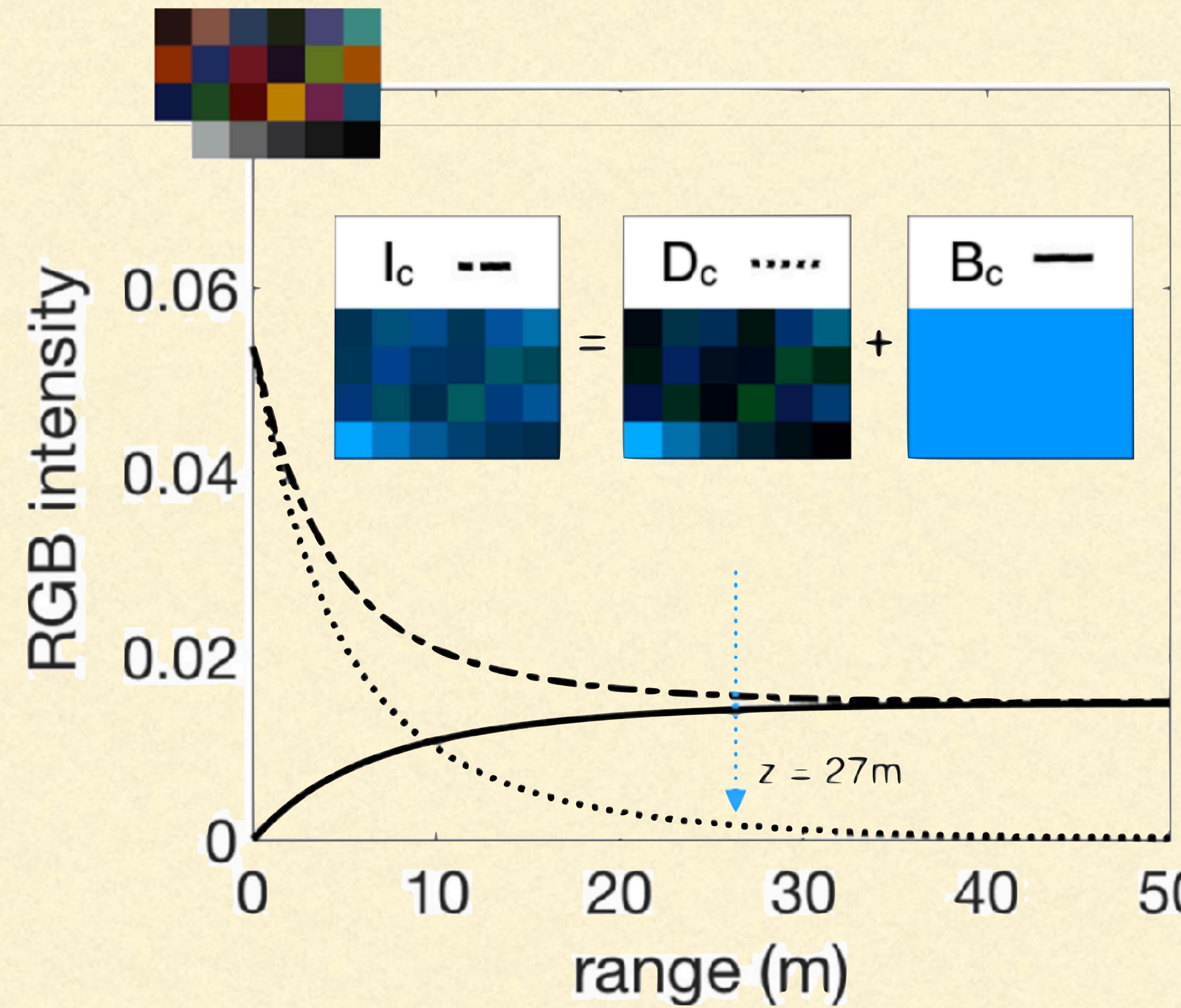
# Distance Dependency



# Distance Dependency

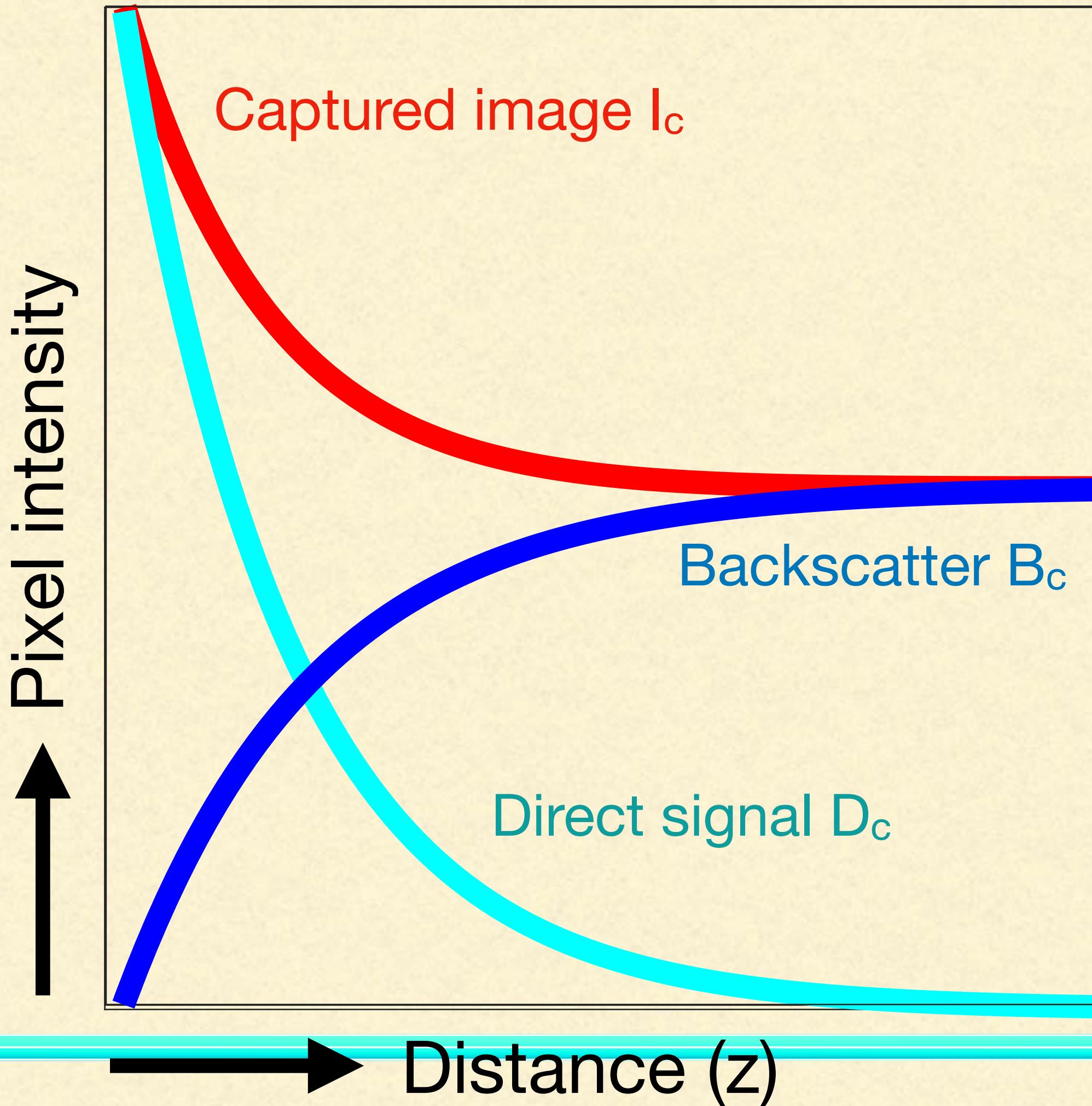


# Distance Dependency



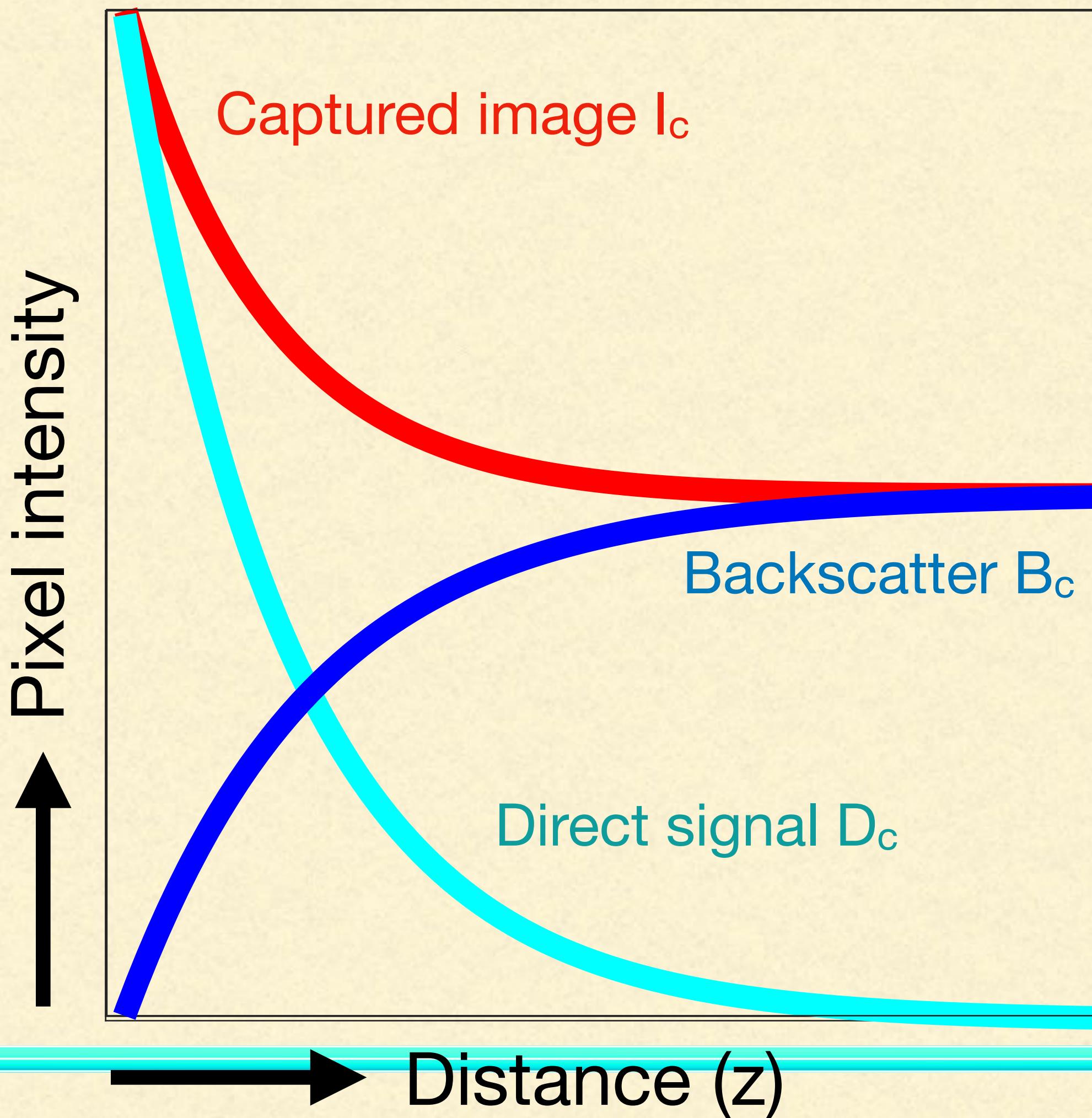
# Image Formation

Predicted by Akkaynak & Treibitz Model

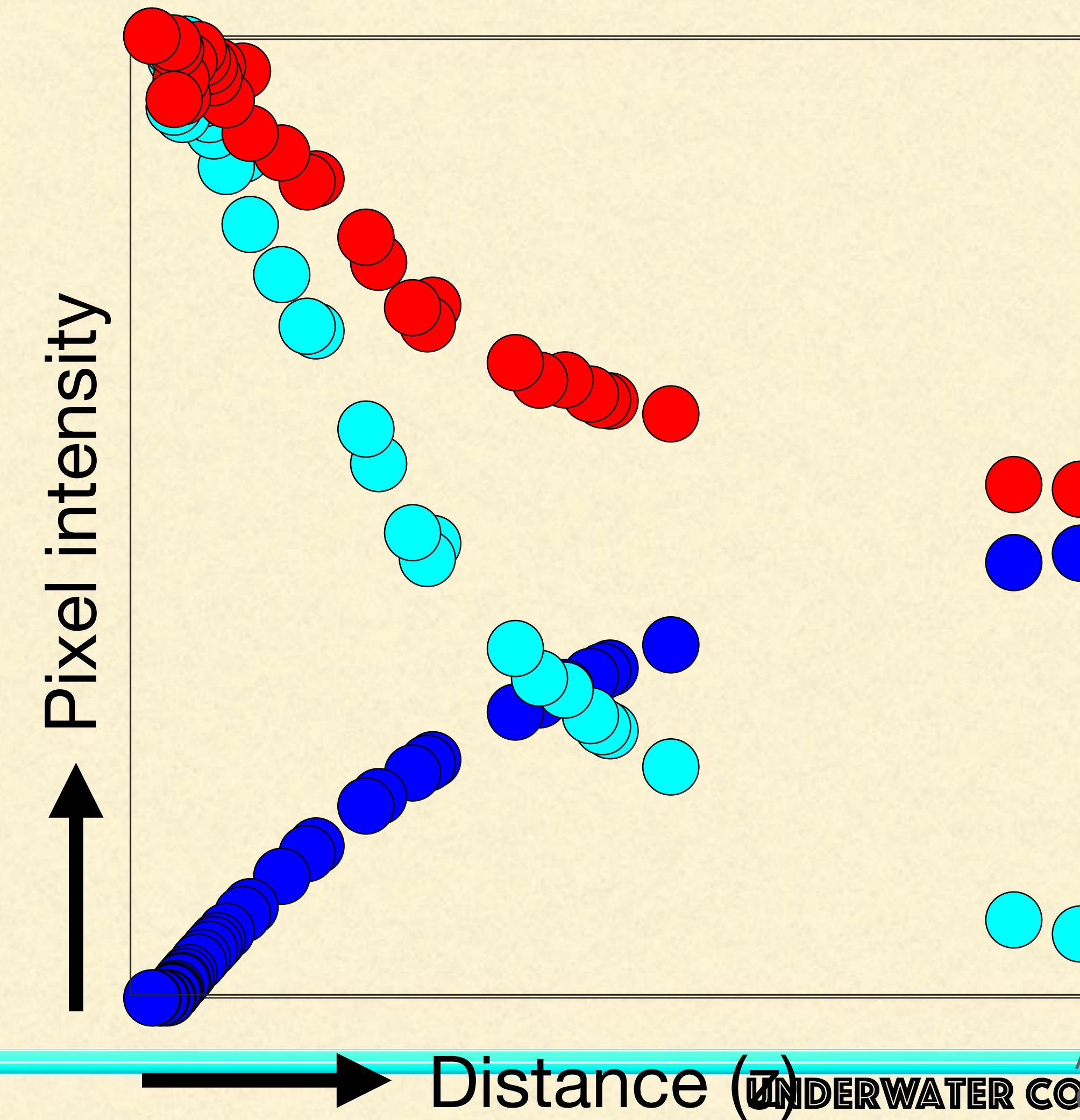


# Image Formation

Predicted by Akkaynak & Treibitz Model

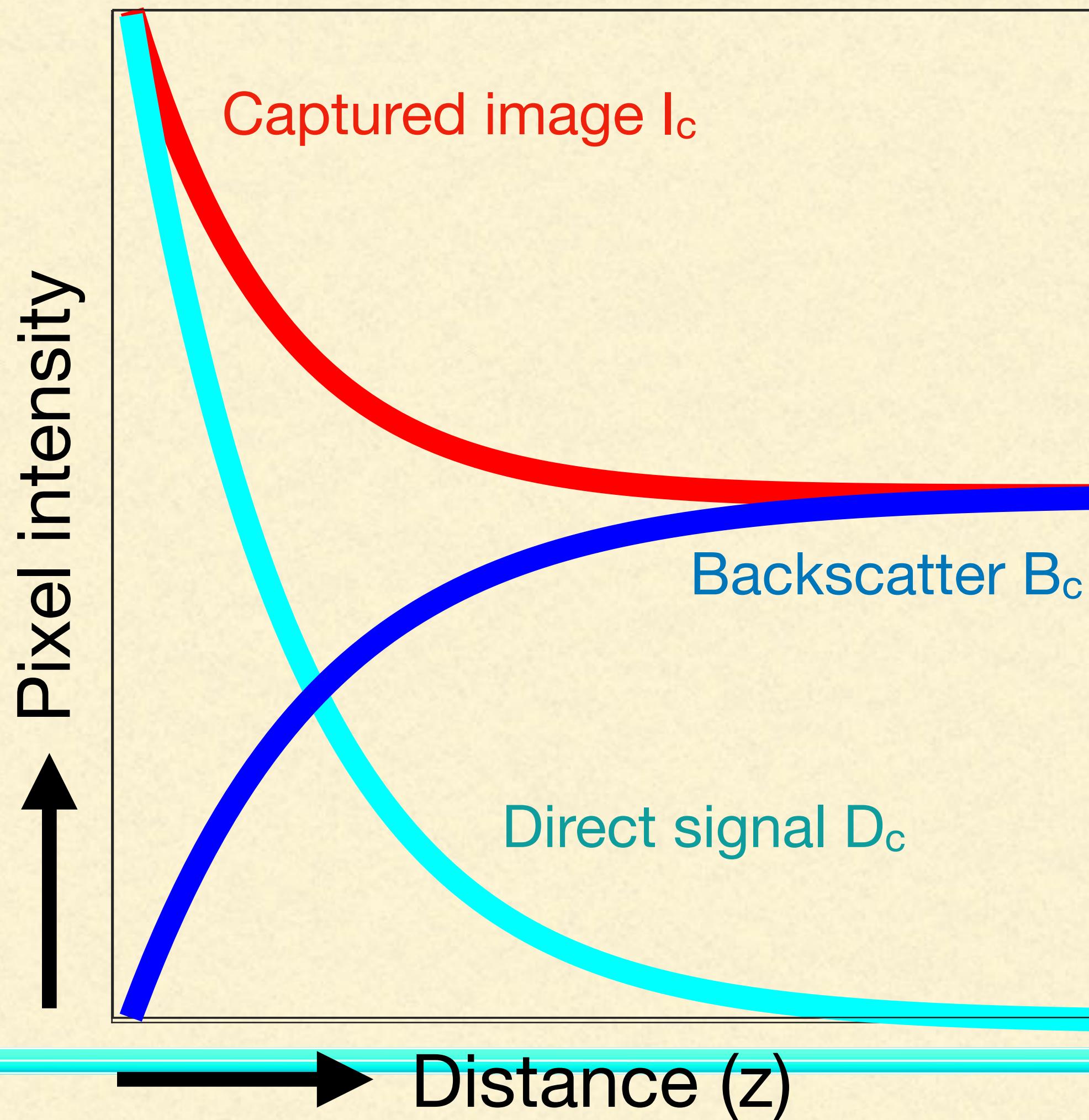


Actual data

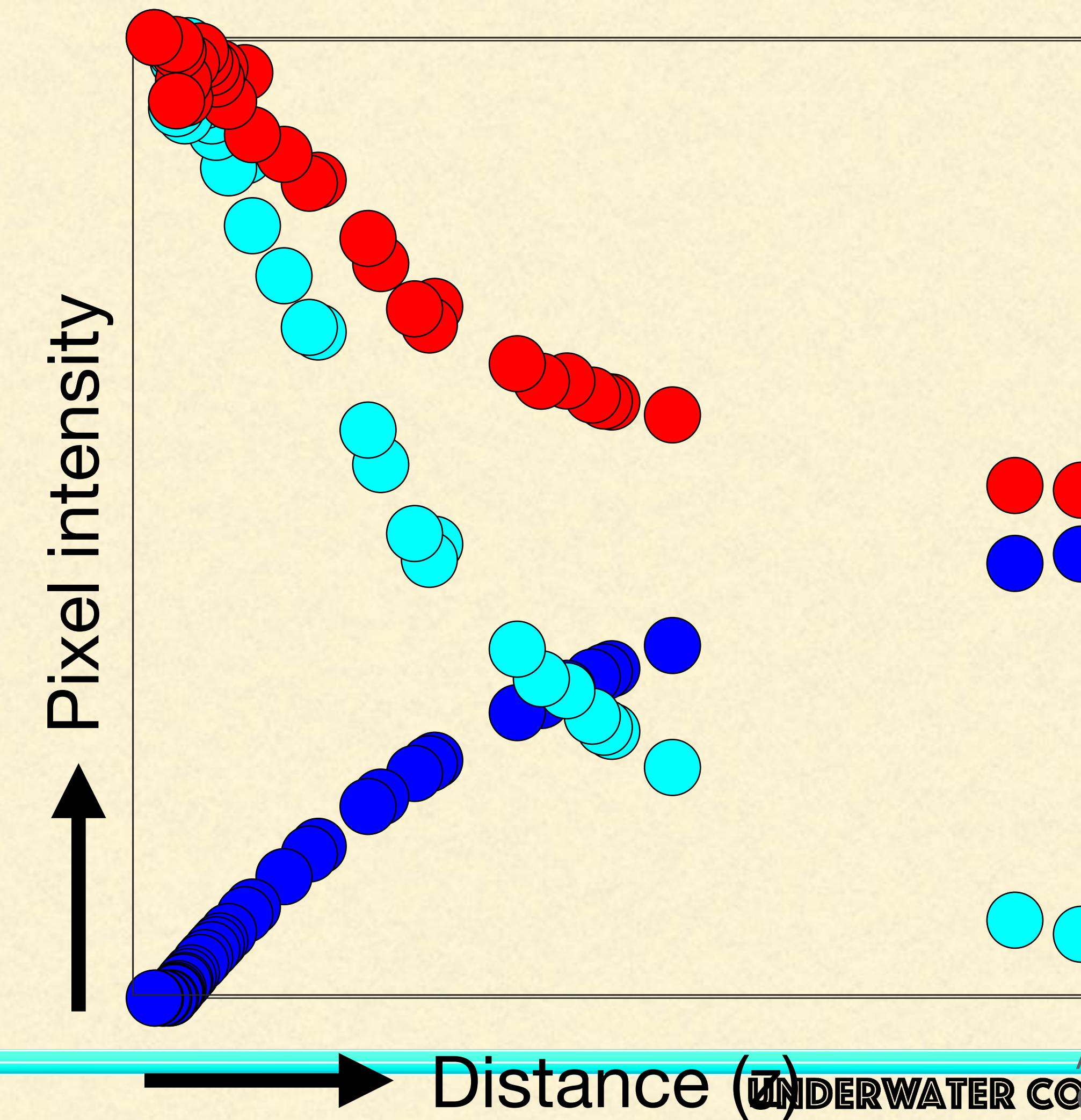


# Image Formation

Predicted by Akkaynak & Treibitz Model

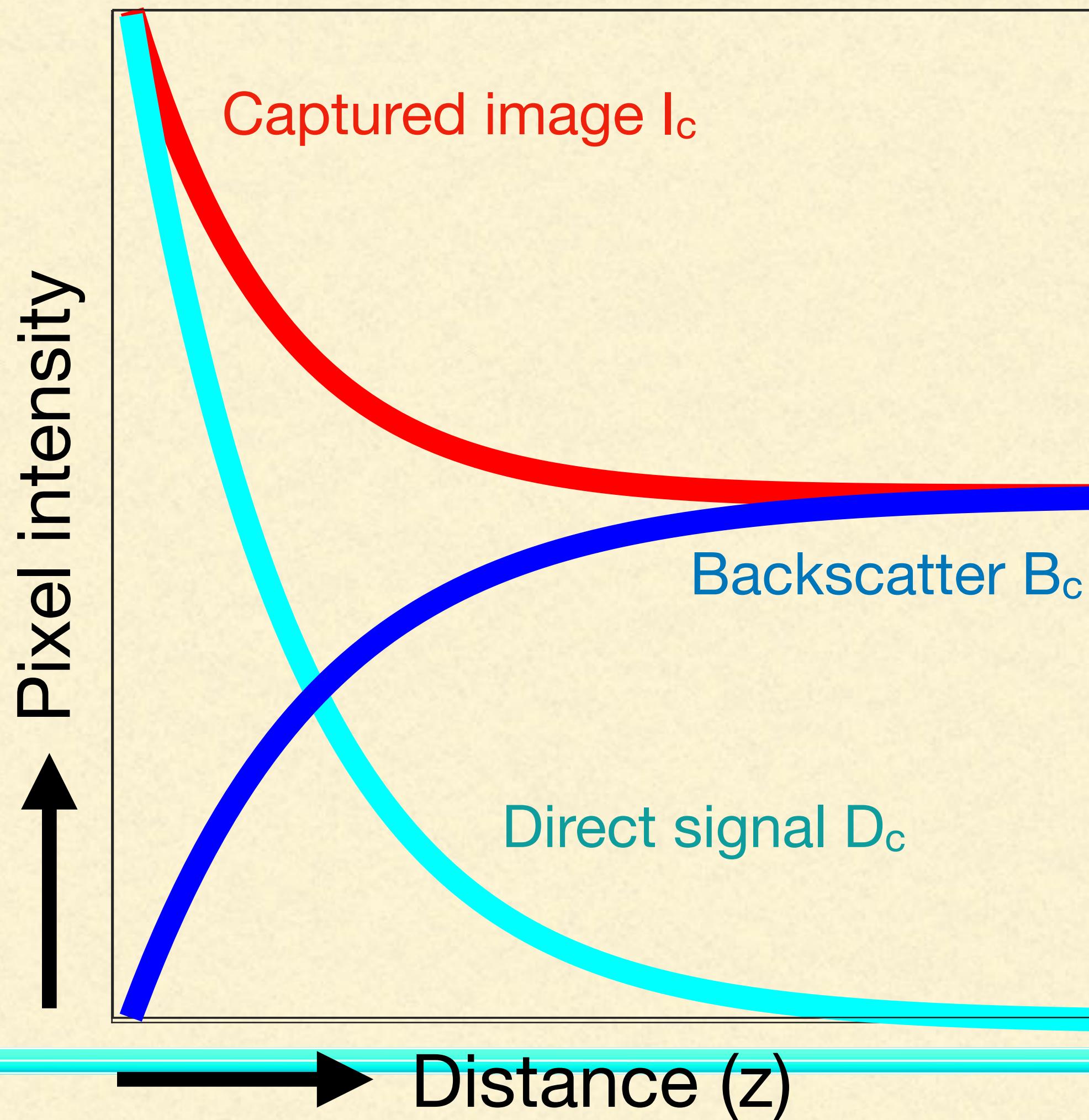


Actual data

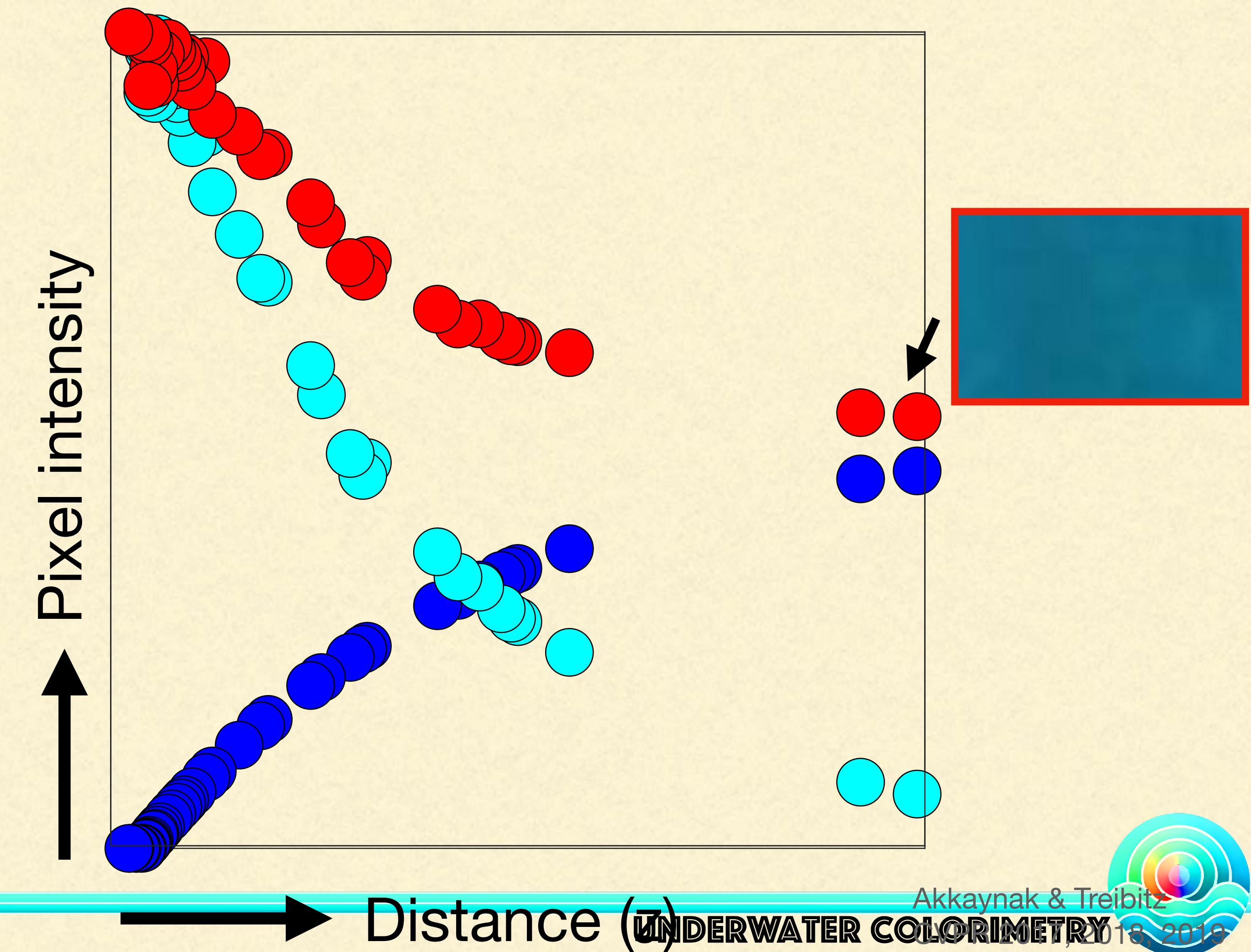


# Image Formation

Predicted by Akkaynak & Treibitz Model



Actual data



# Underwater Colorimetry

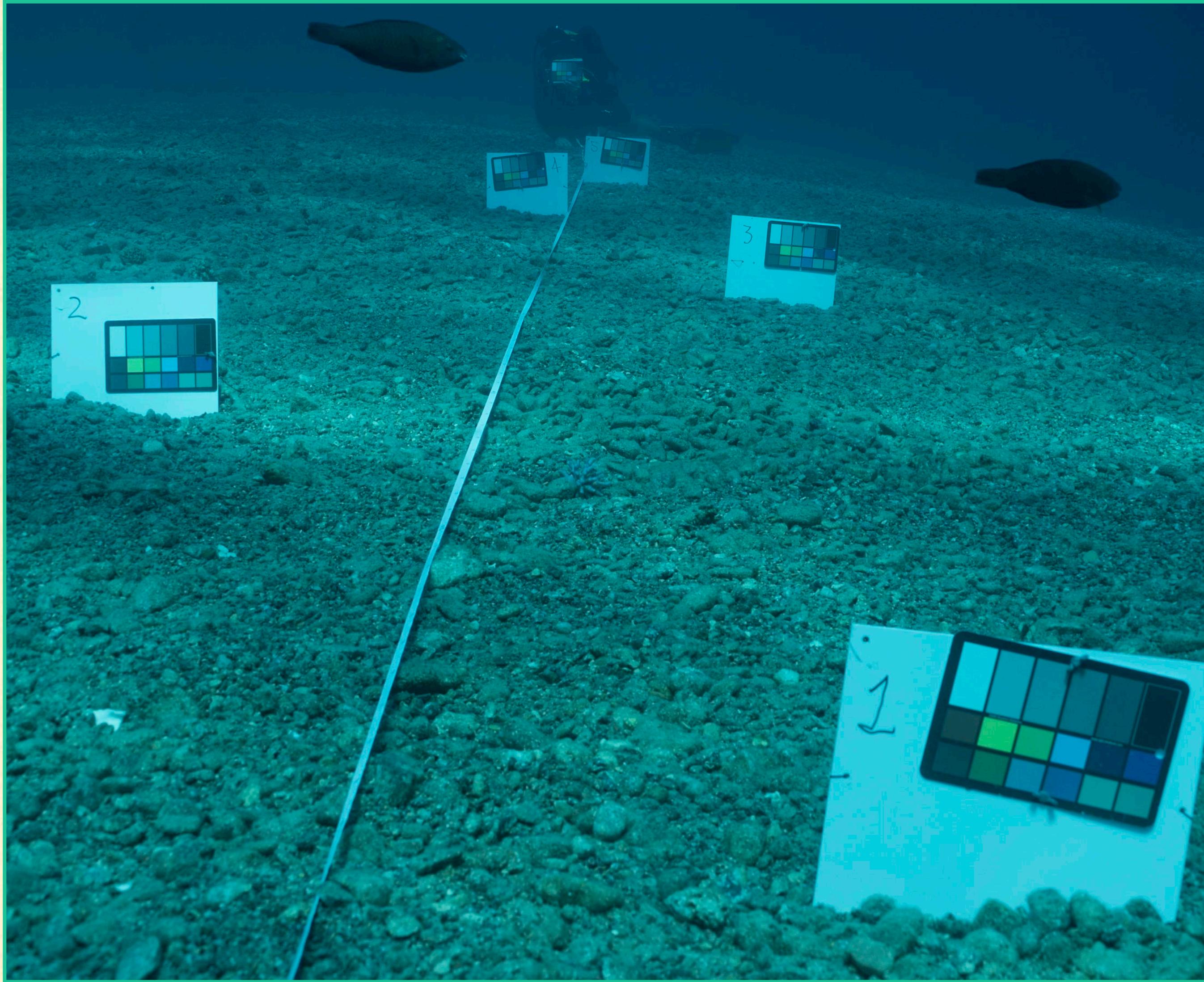
Given:



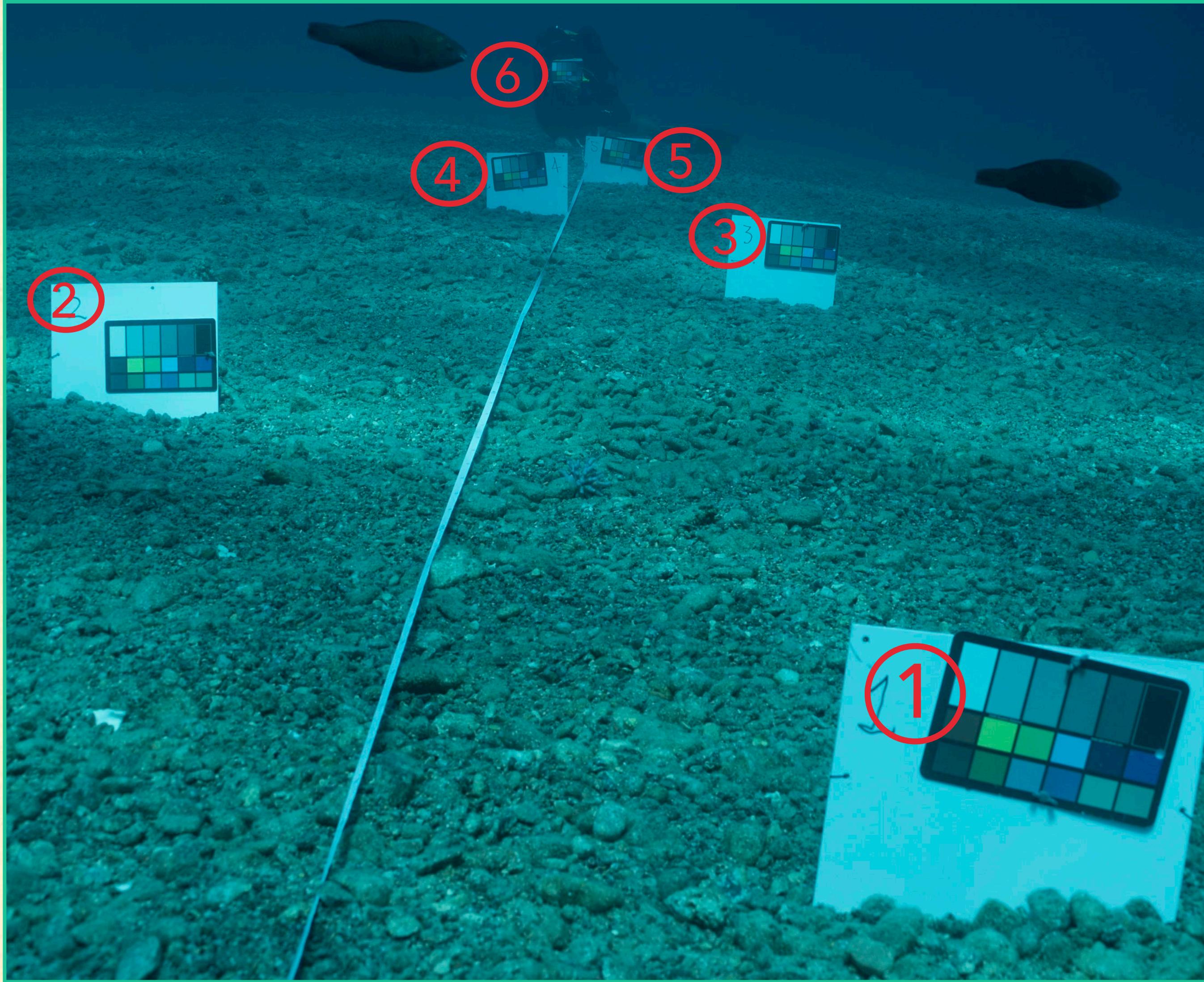
Can we get:



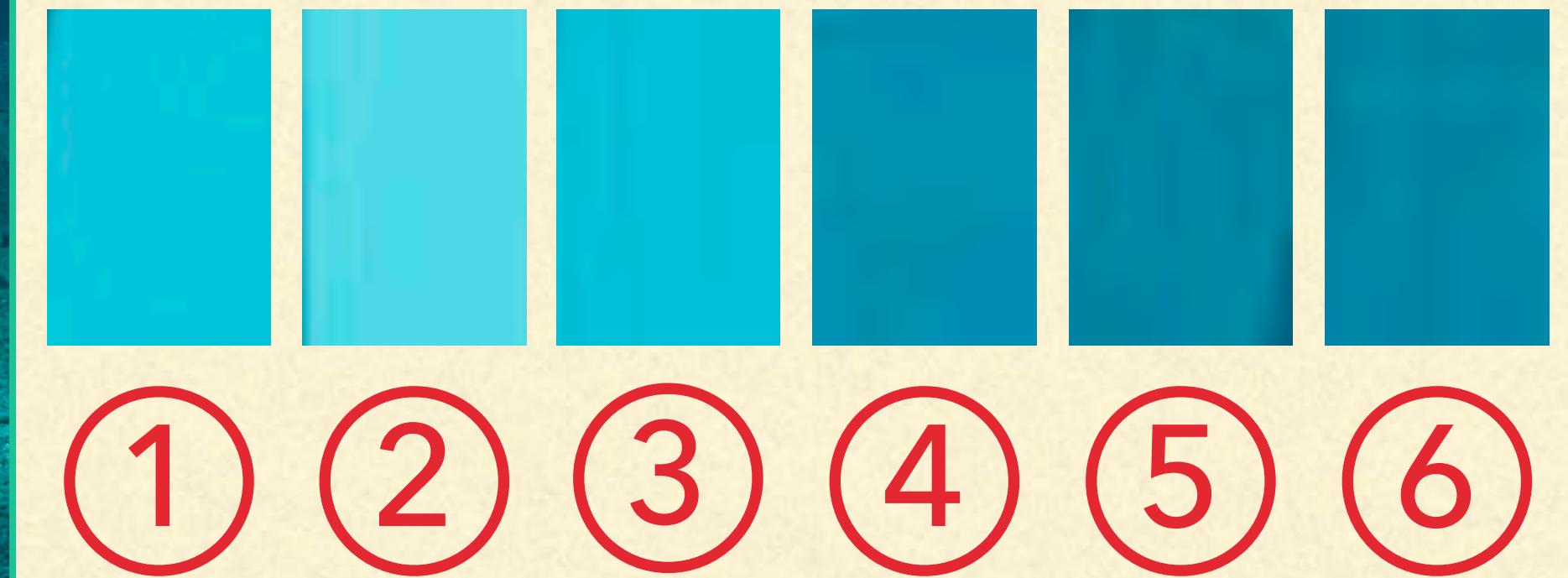
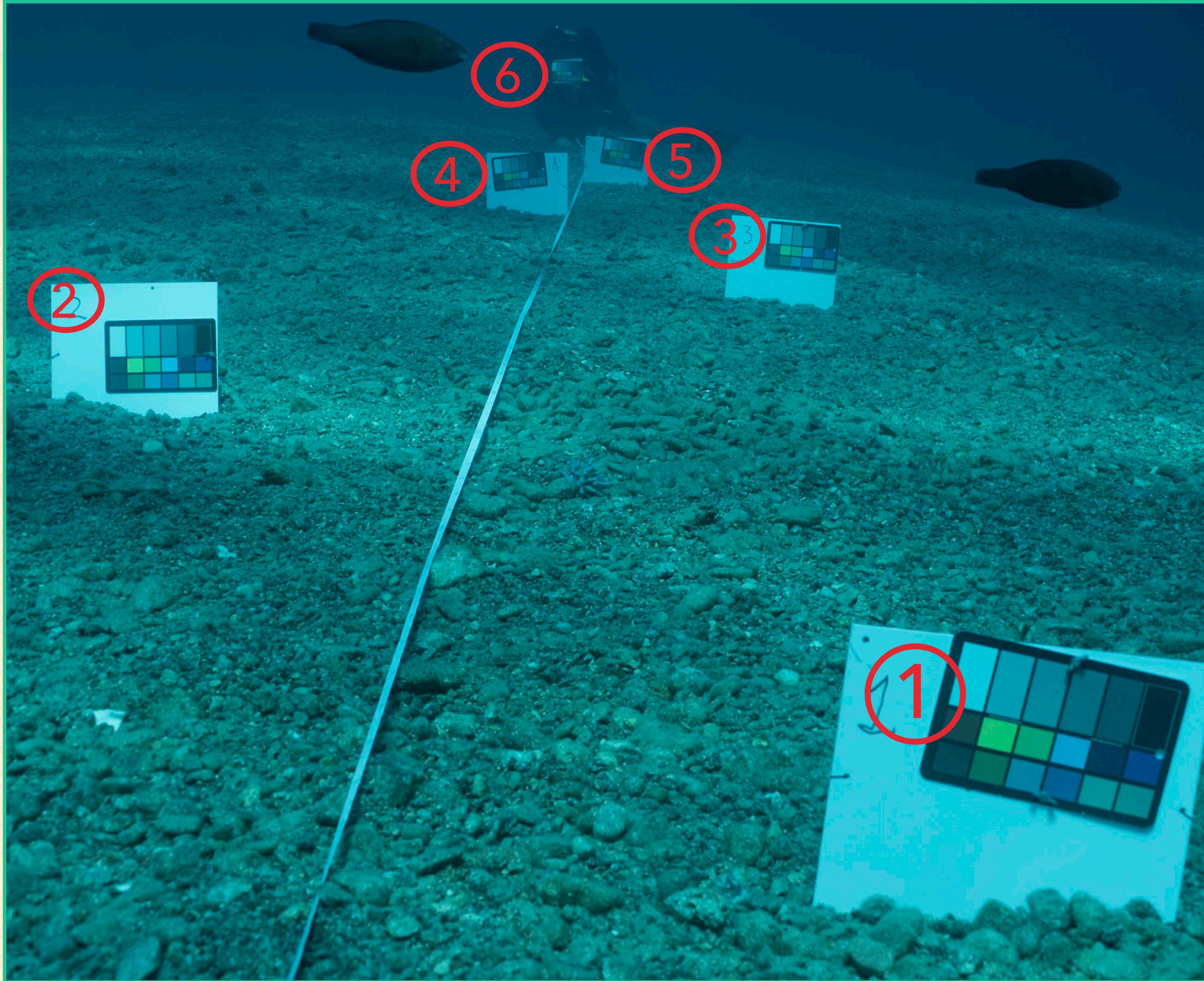
# Distance Dependency



# Distance Dependency



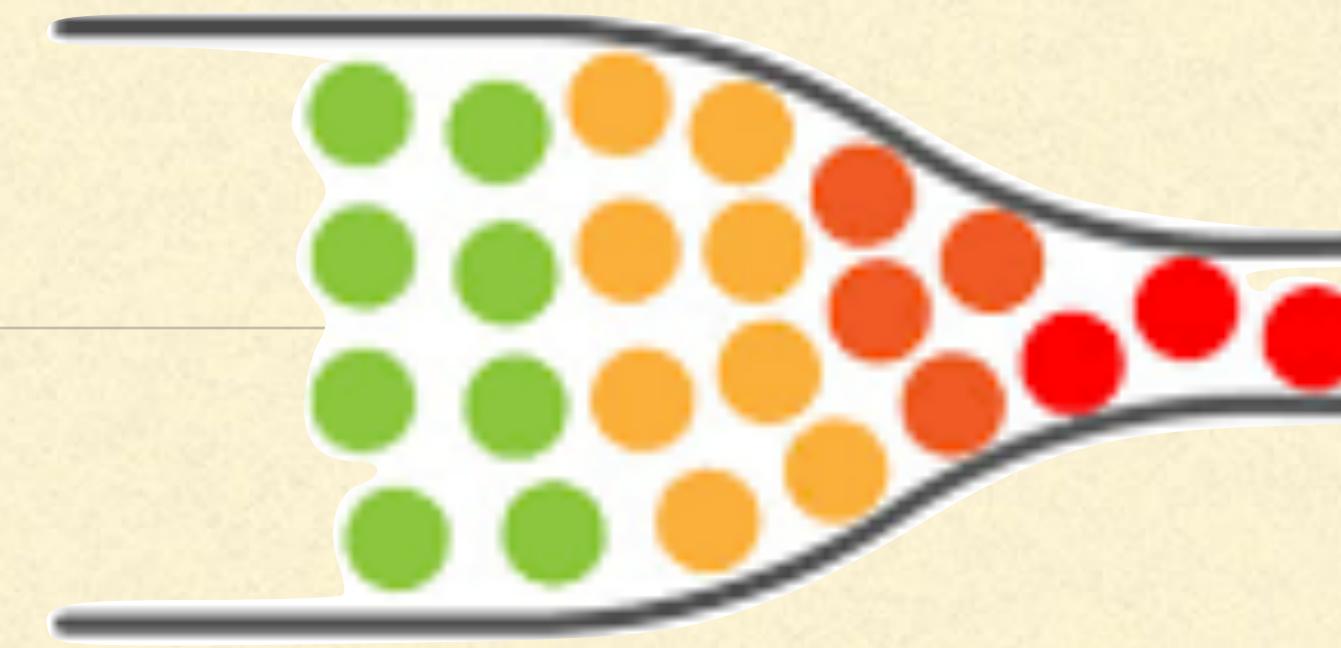
# Distance Dependency



"White" is different at every distance.

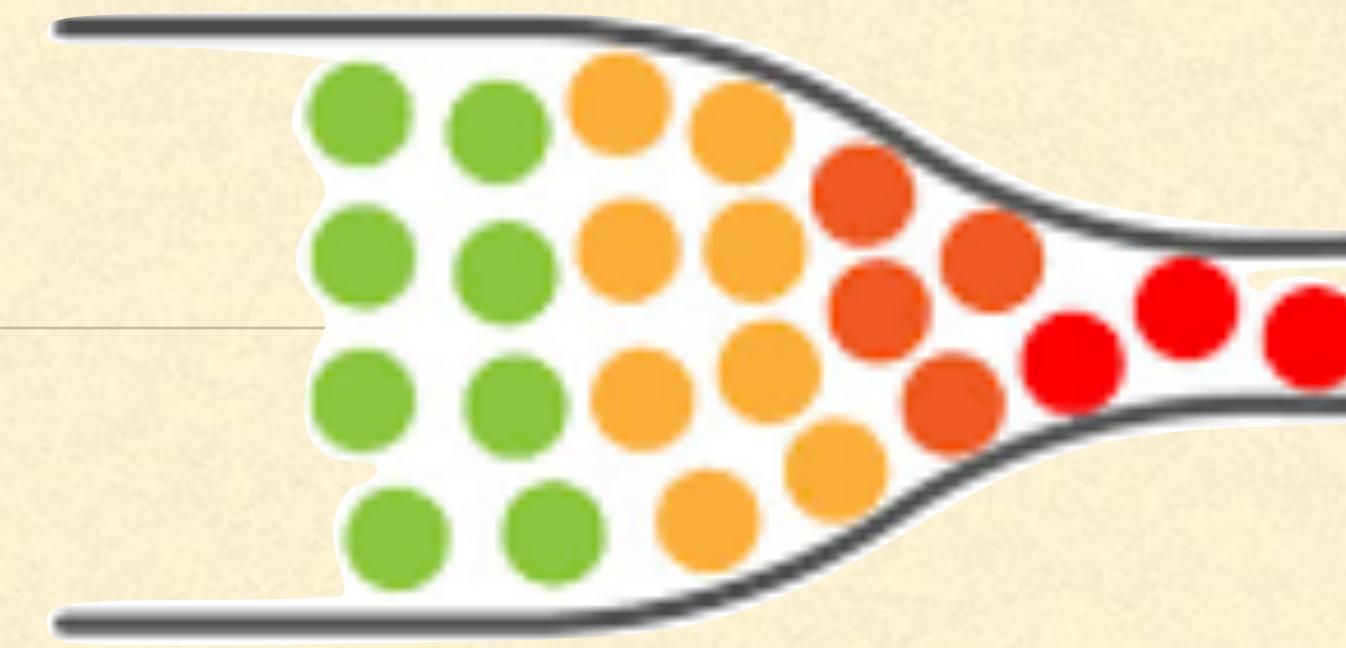


# A Technology Bottleneck



We are unable to estimate distance  
underwater in real-time

# A Technology Bottleneck



We are unable to estimate distance  
underwater in real-time

How can we estimate distance underwater?

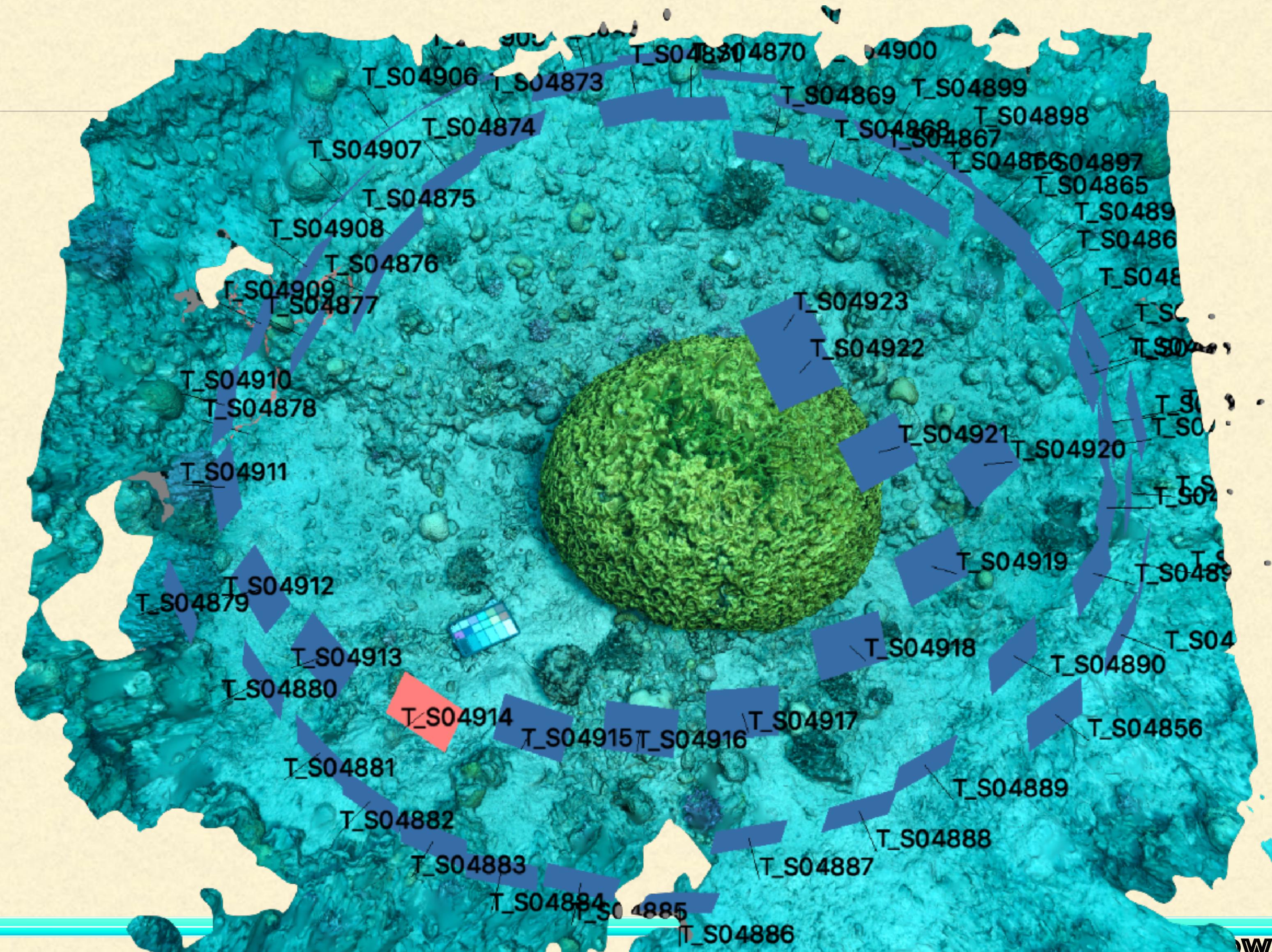


# Distance Estimation

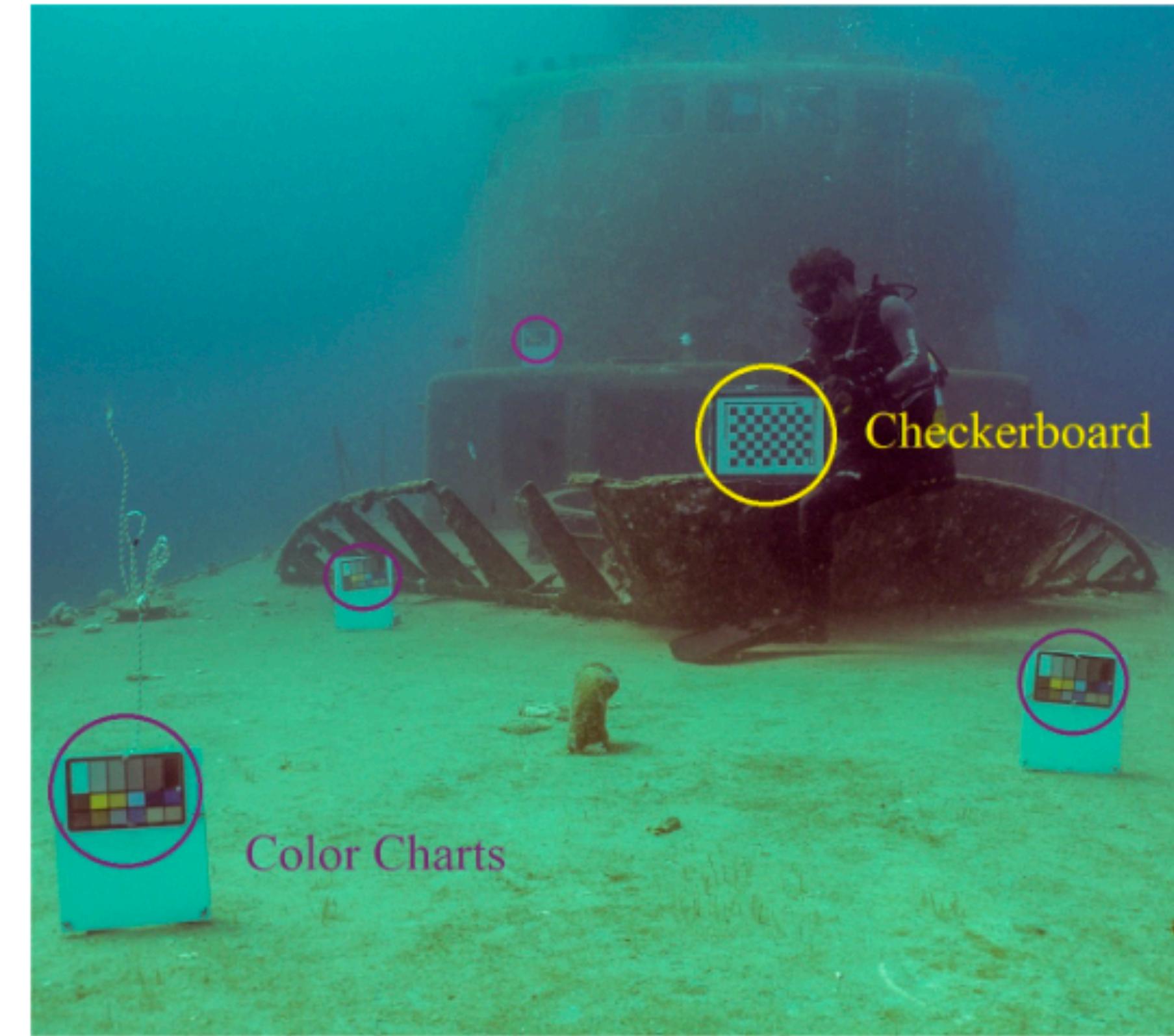
“Distance image”, “Depth map”, “Range map”



# Structure-From-Motion (~Photogrammetry)

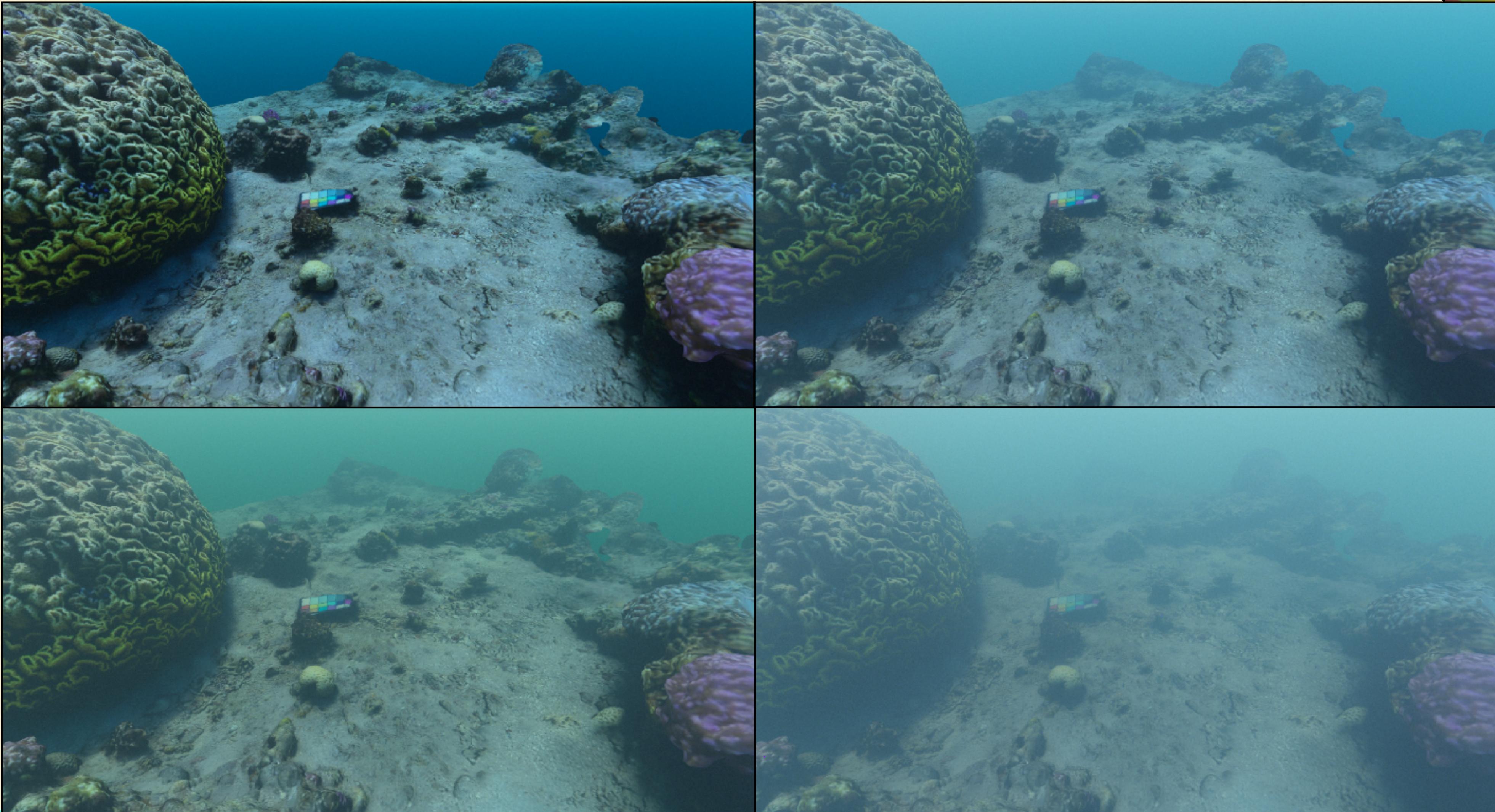
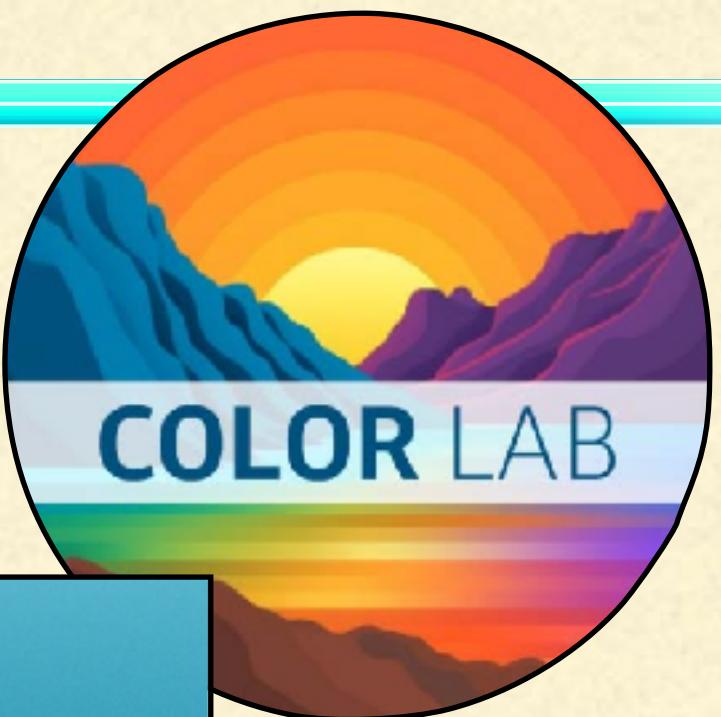


# I - Stereo/Multi-Camera

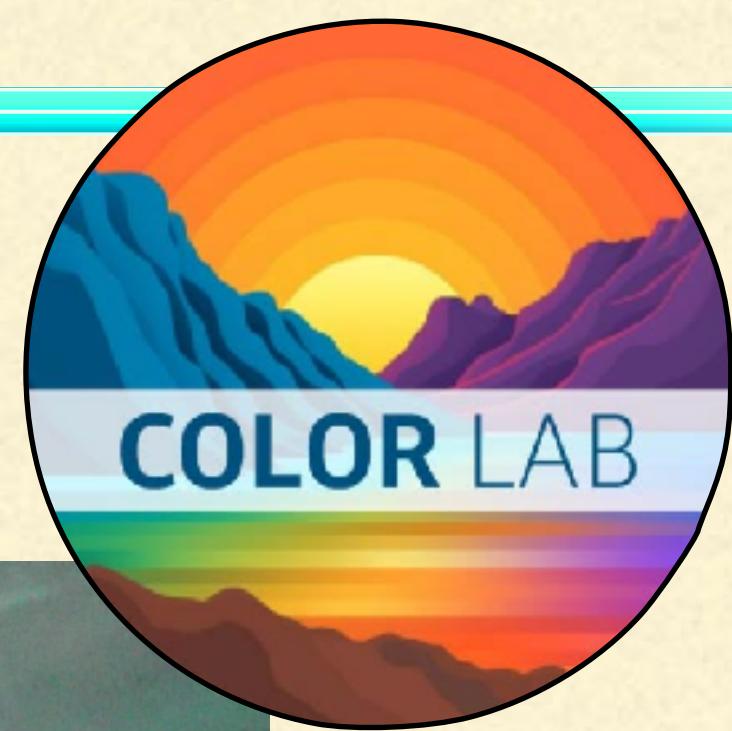


**Fig. 4. Creating the dataset.** The stereo rig is shown on the left, and the color charts and calibration checkerboard are visible on the right.

# Learning From Realistic Synthetic Data

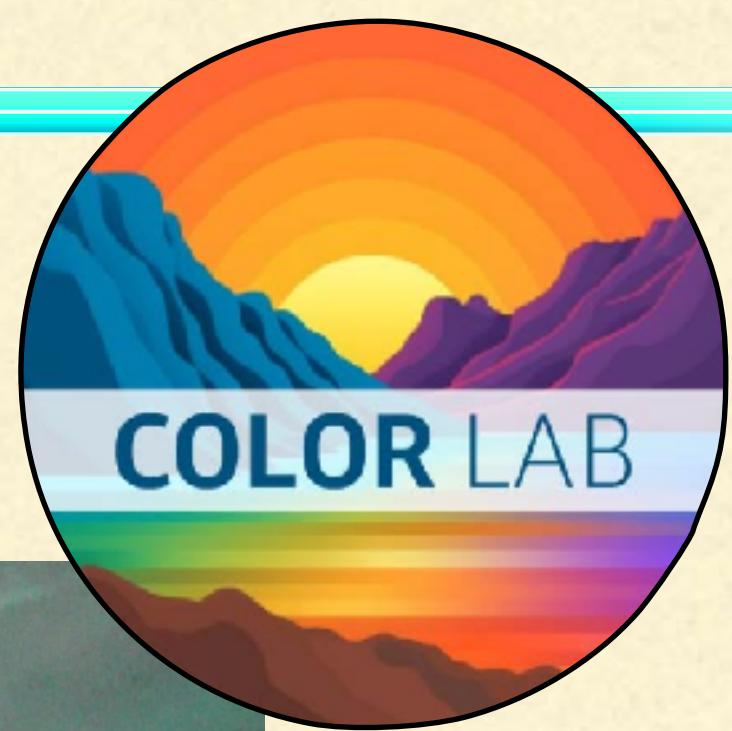


# Special Instruments - Lidar



METERY

# Special Instruments - Lidar



METERY

# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

## PROOF-OF-CONCEPT

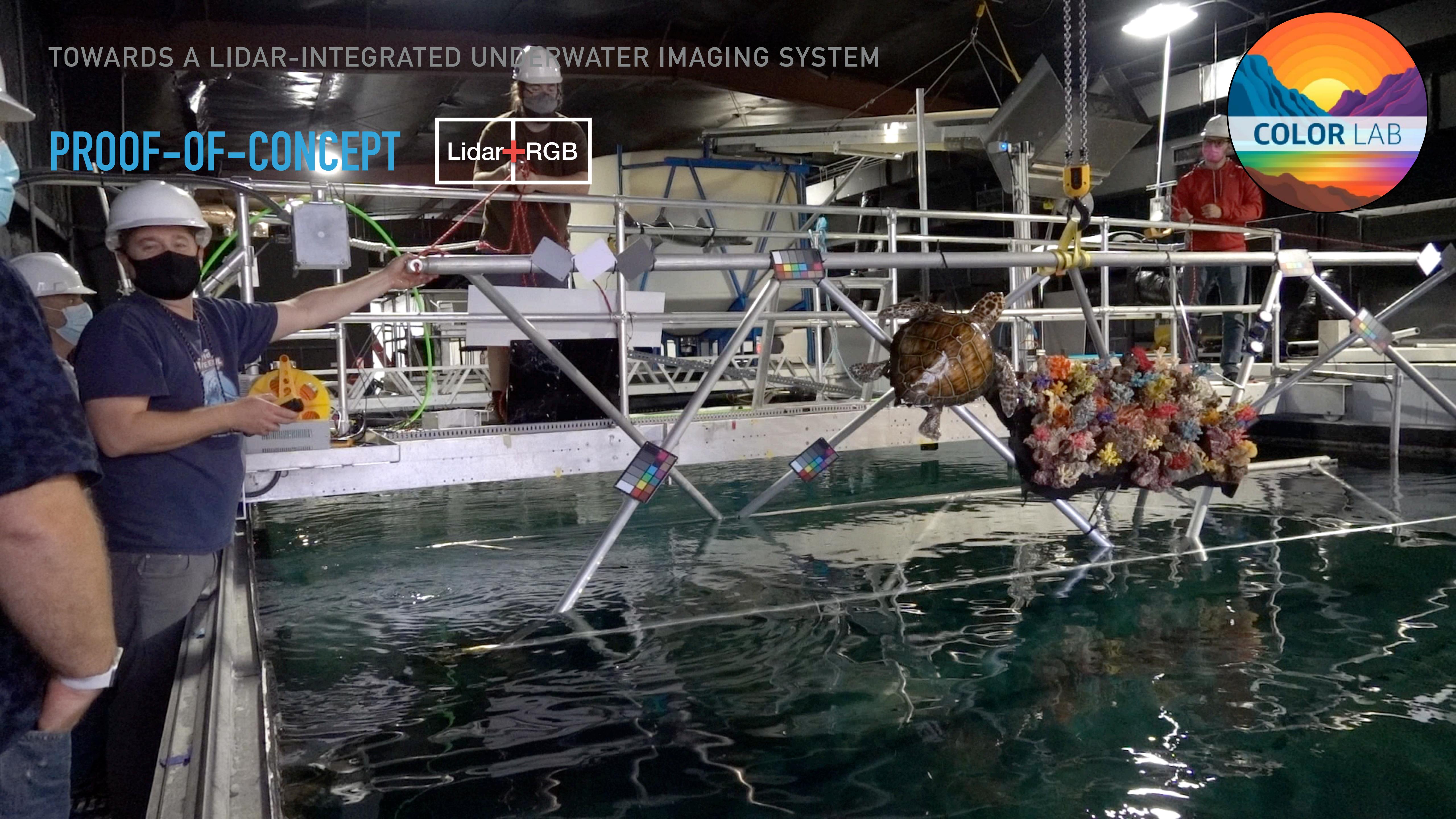
Lidar + RGB



Lidar  
camera  
Light

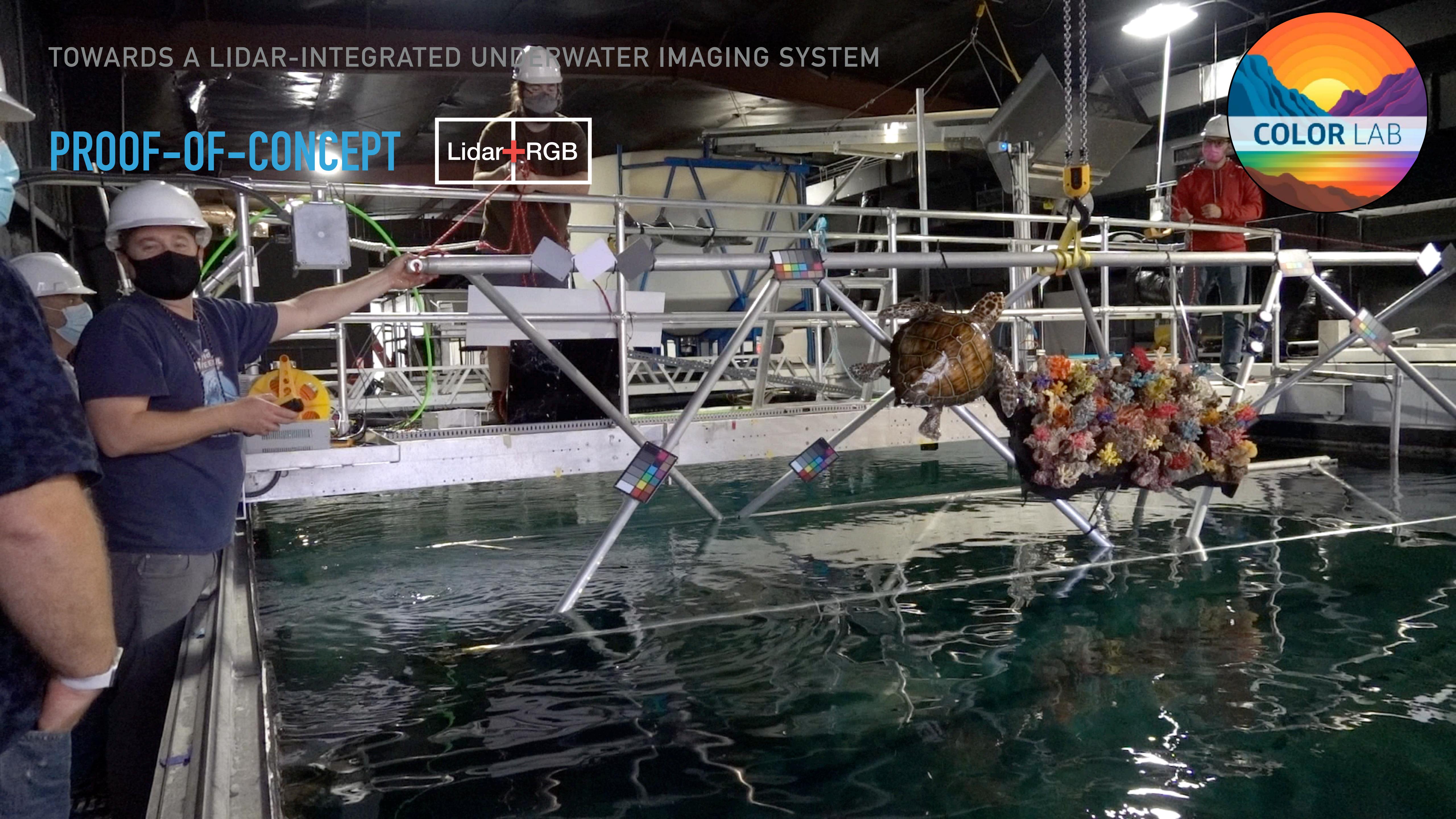
TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

# PROOF-OF-CONCEPT



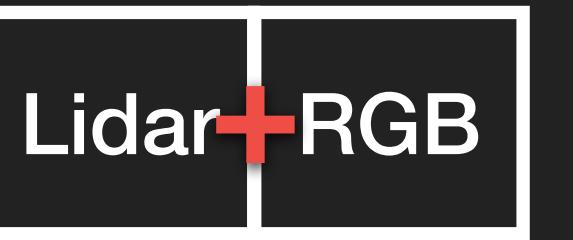
TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

# PROOF-OF-CONCEPT



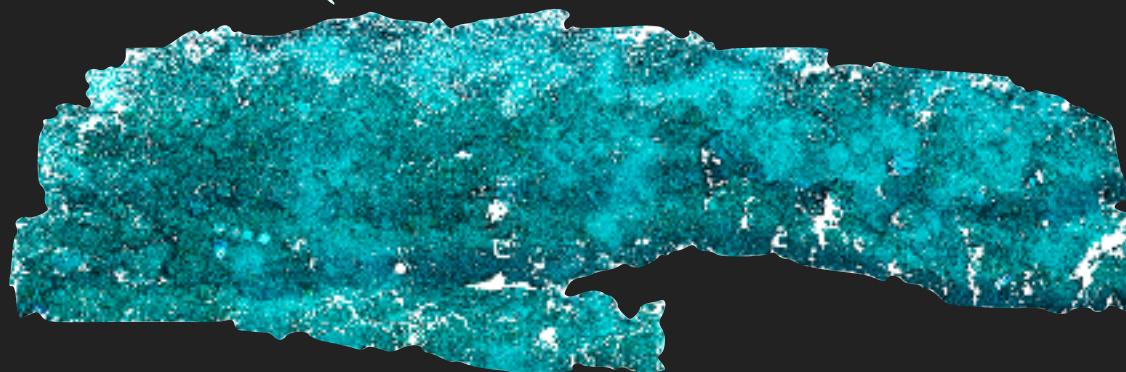


## PROOF-OF-CONCEPT



Lidar

3D point cloud



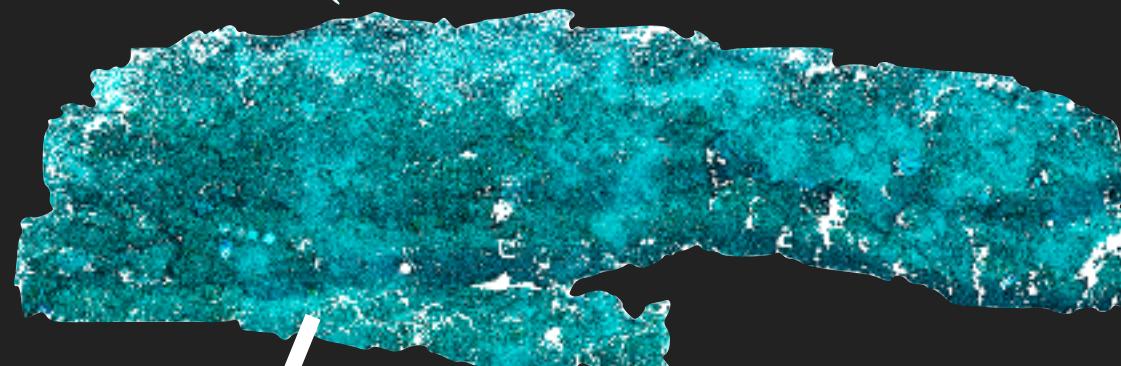


## PROOF-OF-CONCEPT



Lidar

3D point cloud



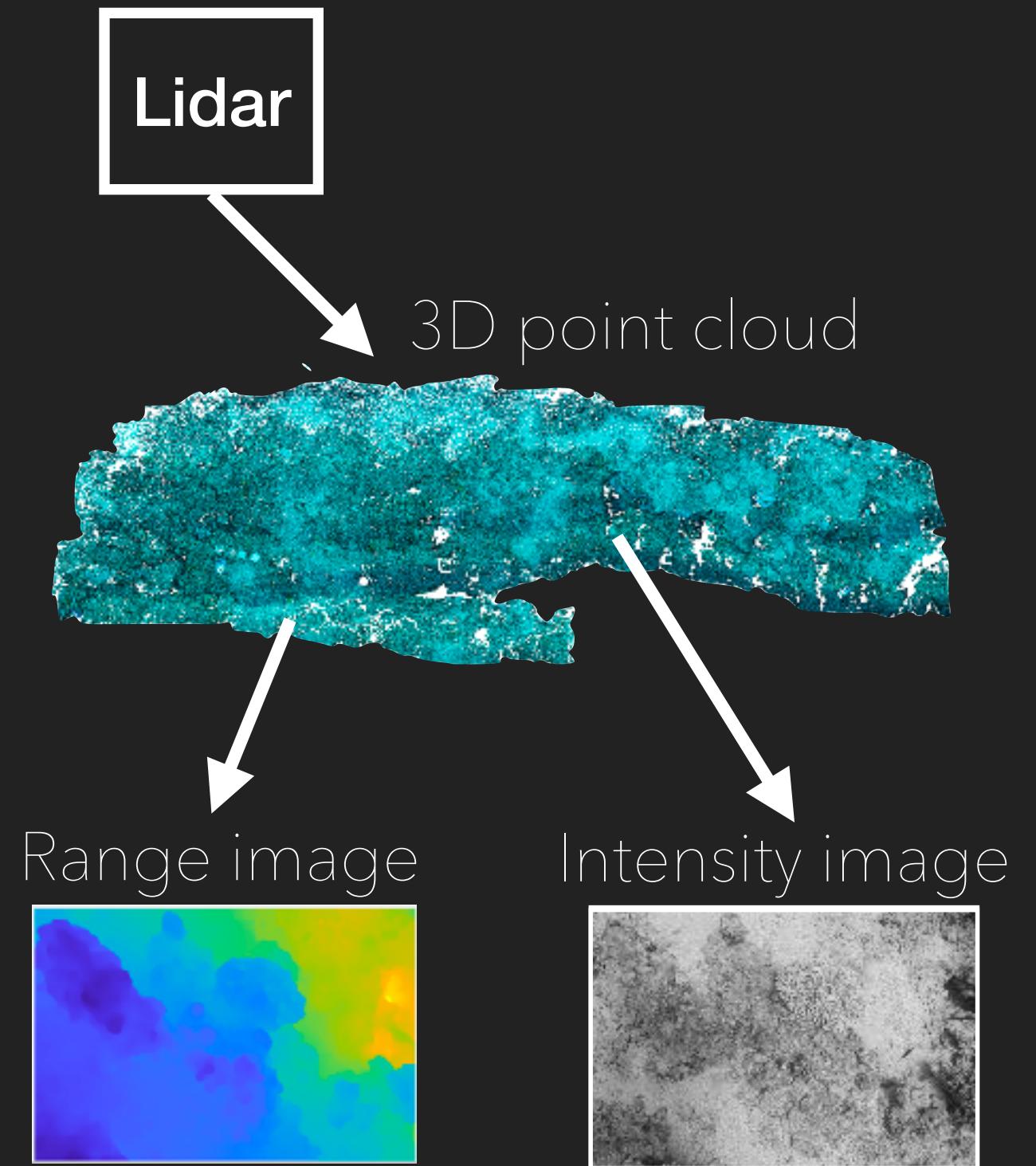
Range image





## PROOF-OF-CONCEPT

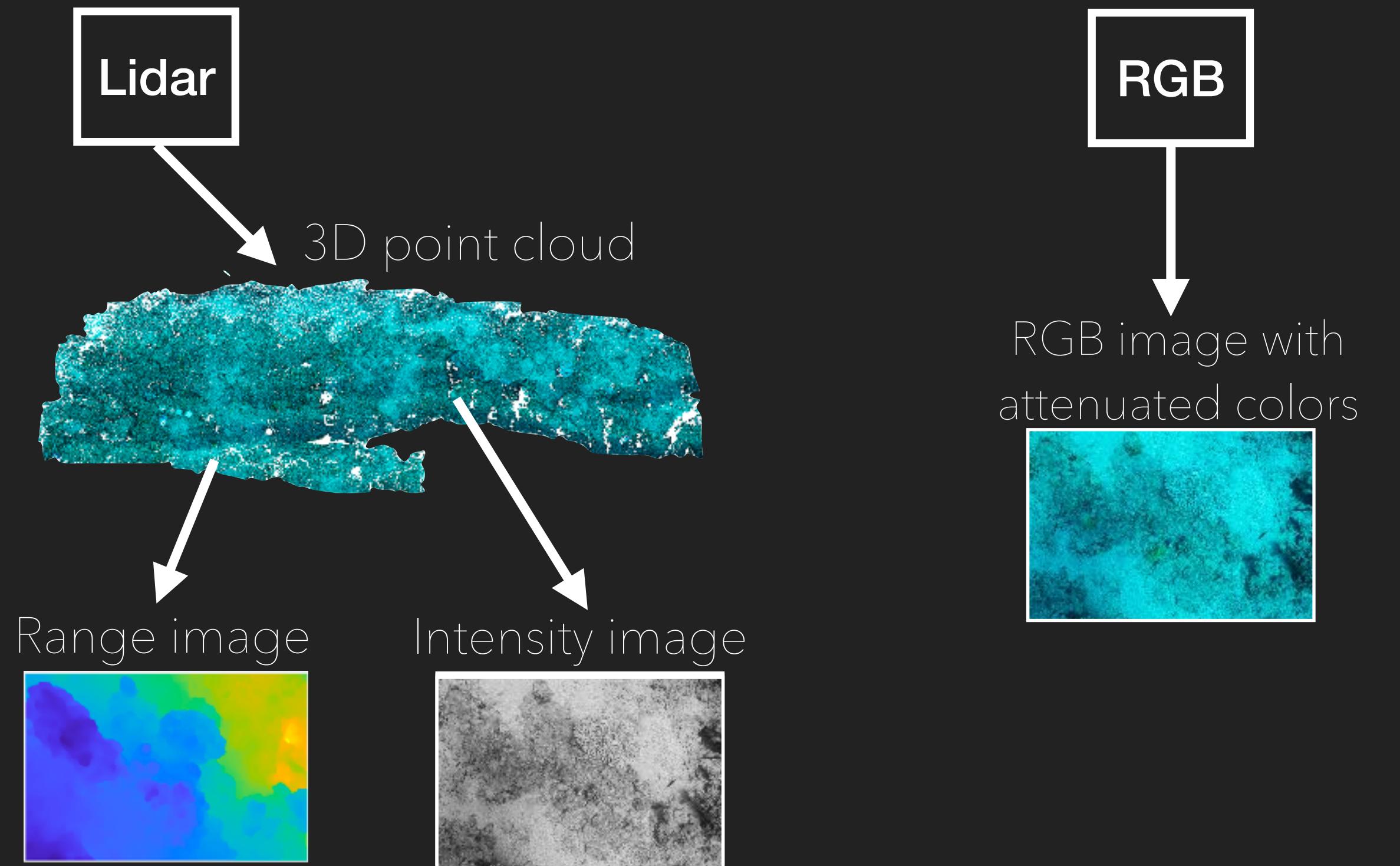
Lidar + RGB





## PROOF-OF-CONCEPT

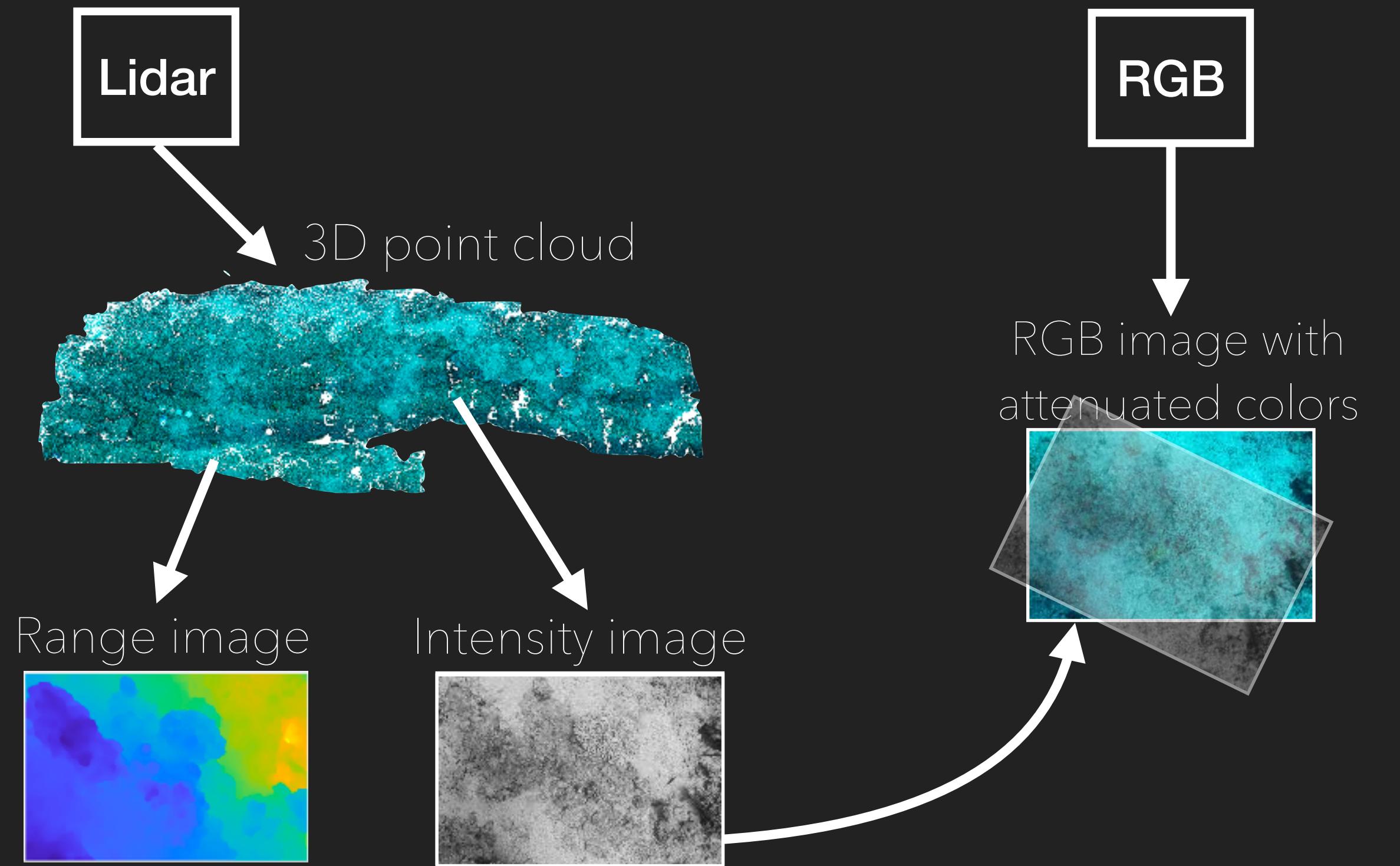
Lidar + RGB





## PROOF-OF-CONCEPT

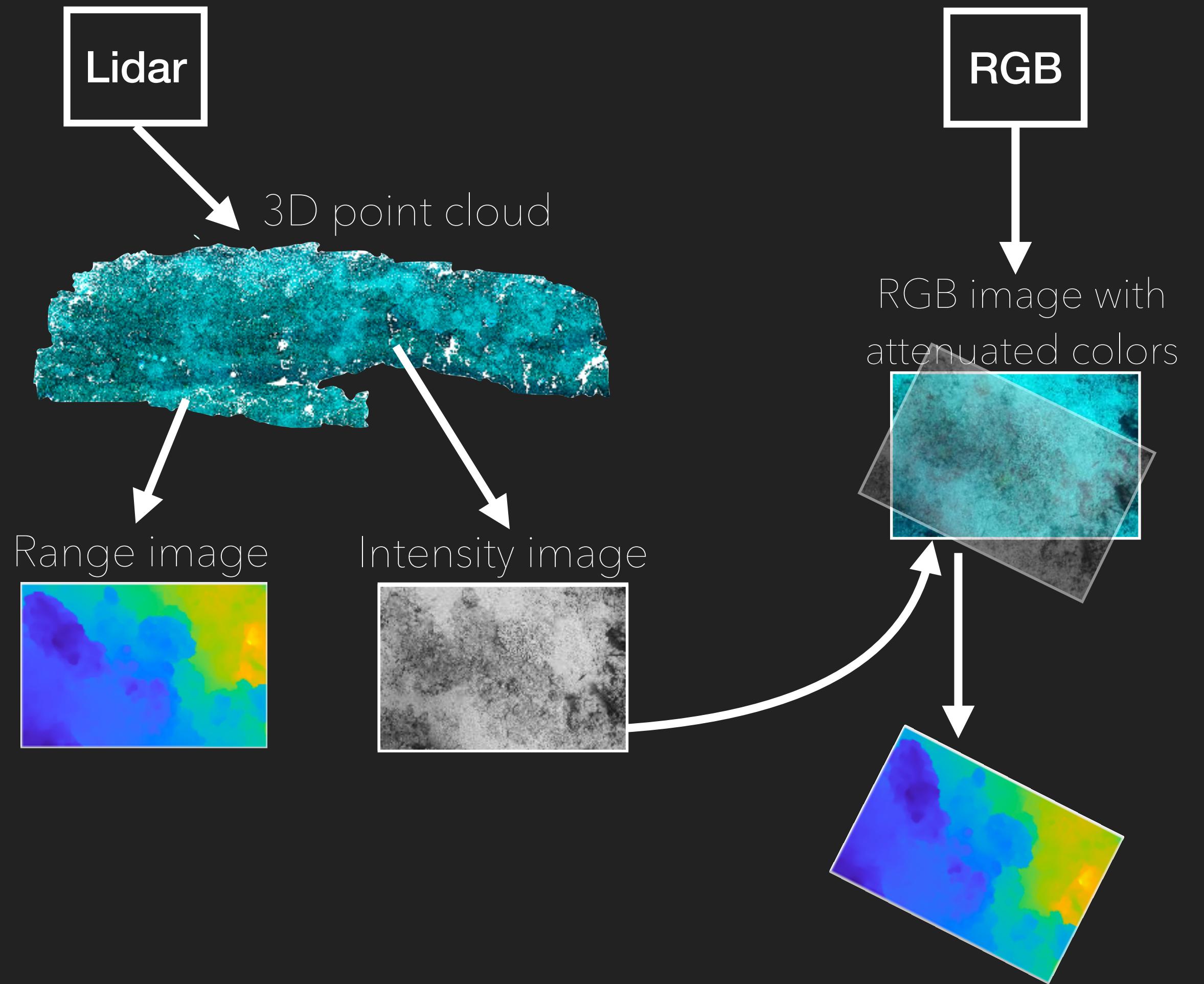
Lidar + RGB





## PROOF-OF-CONCEPT

Lidar + RGB

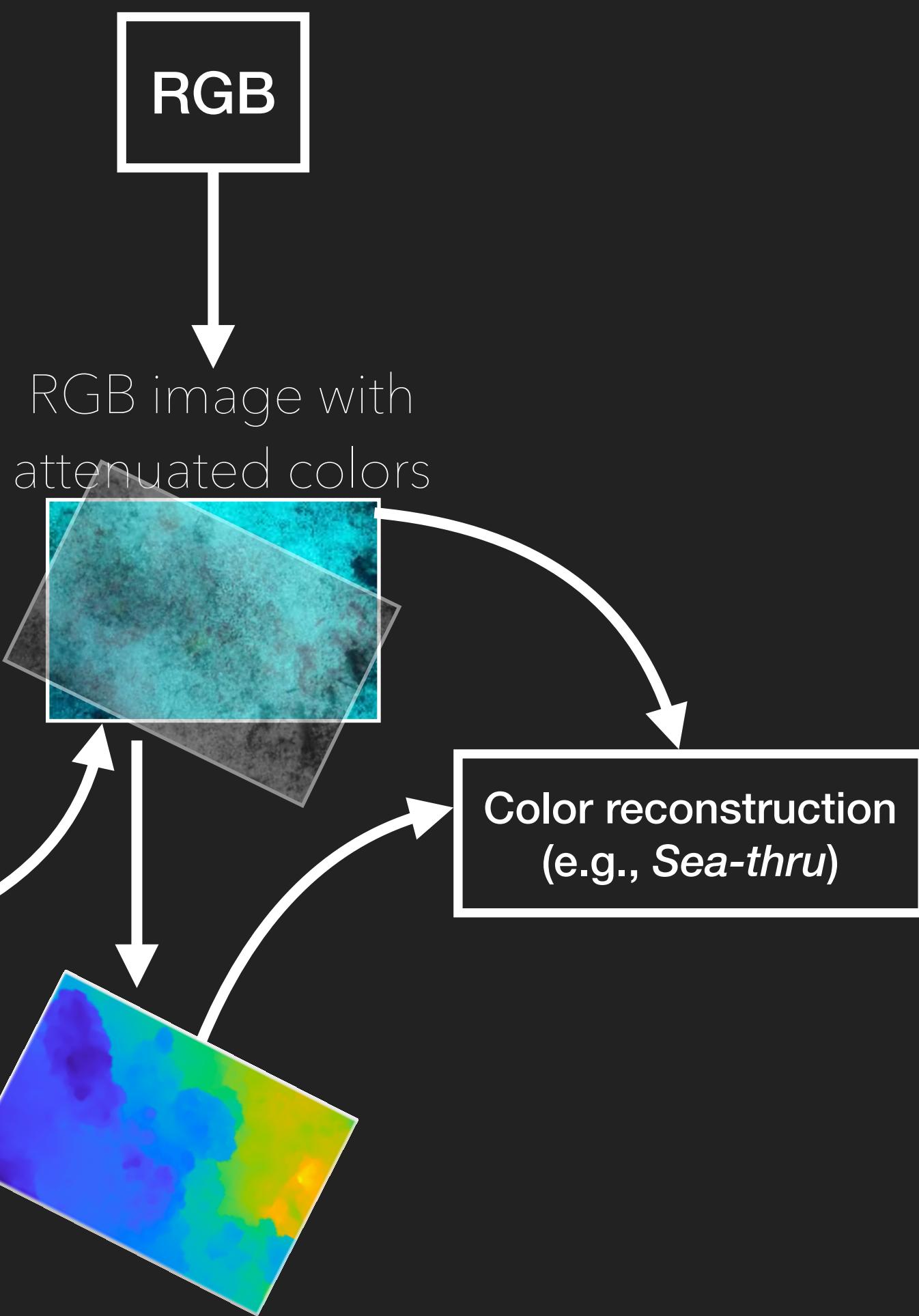
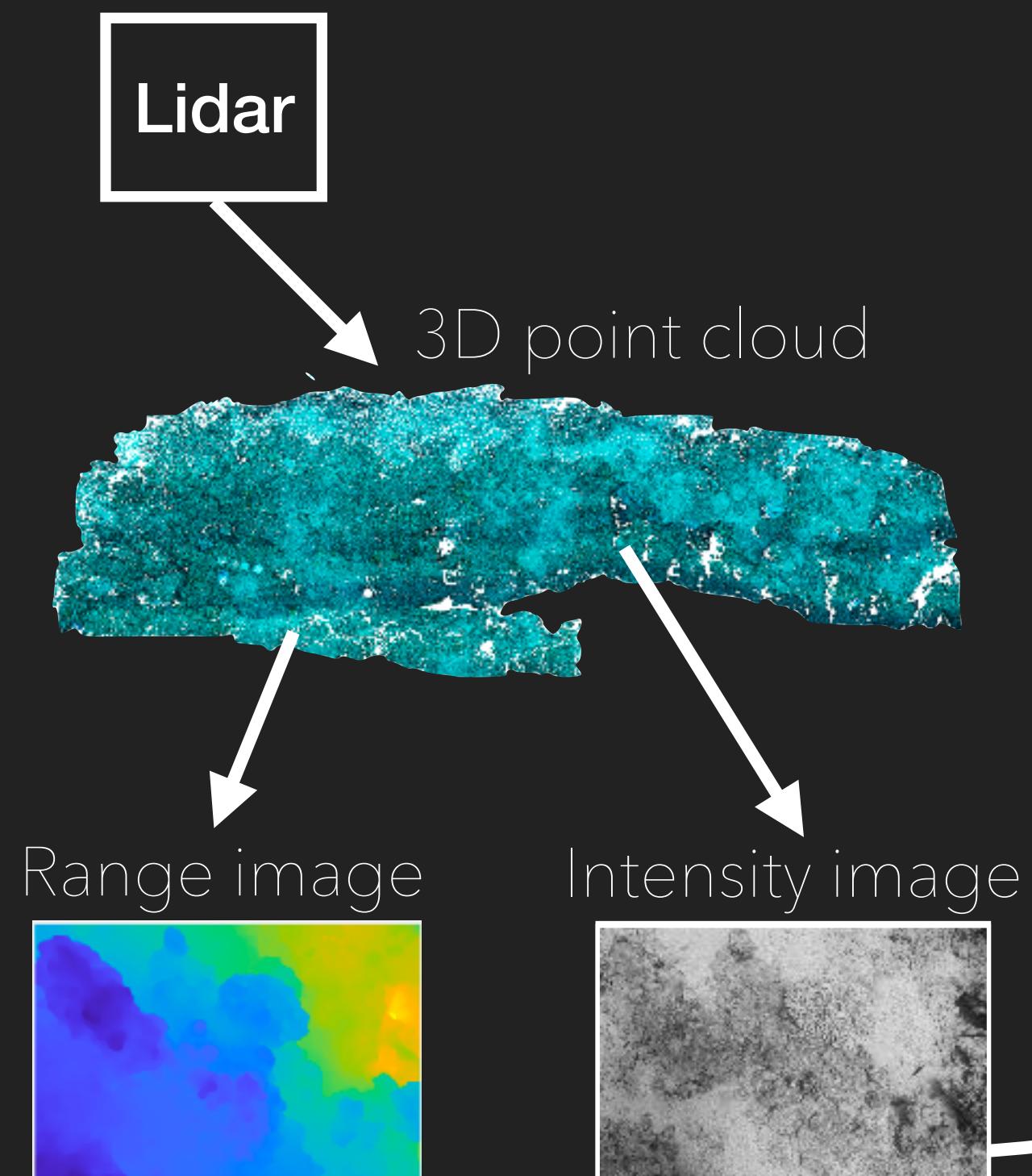


# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

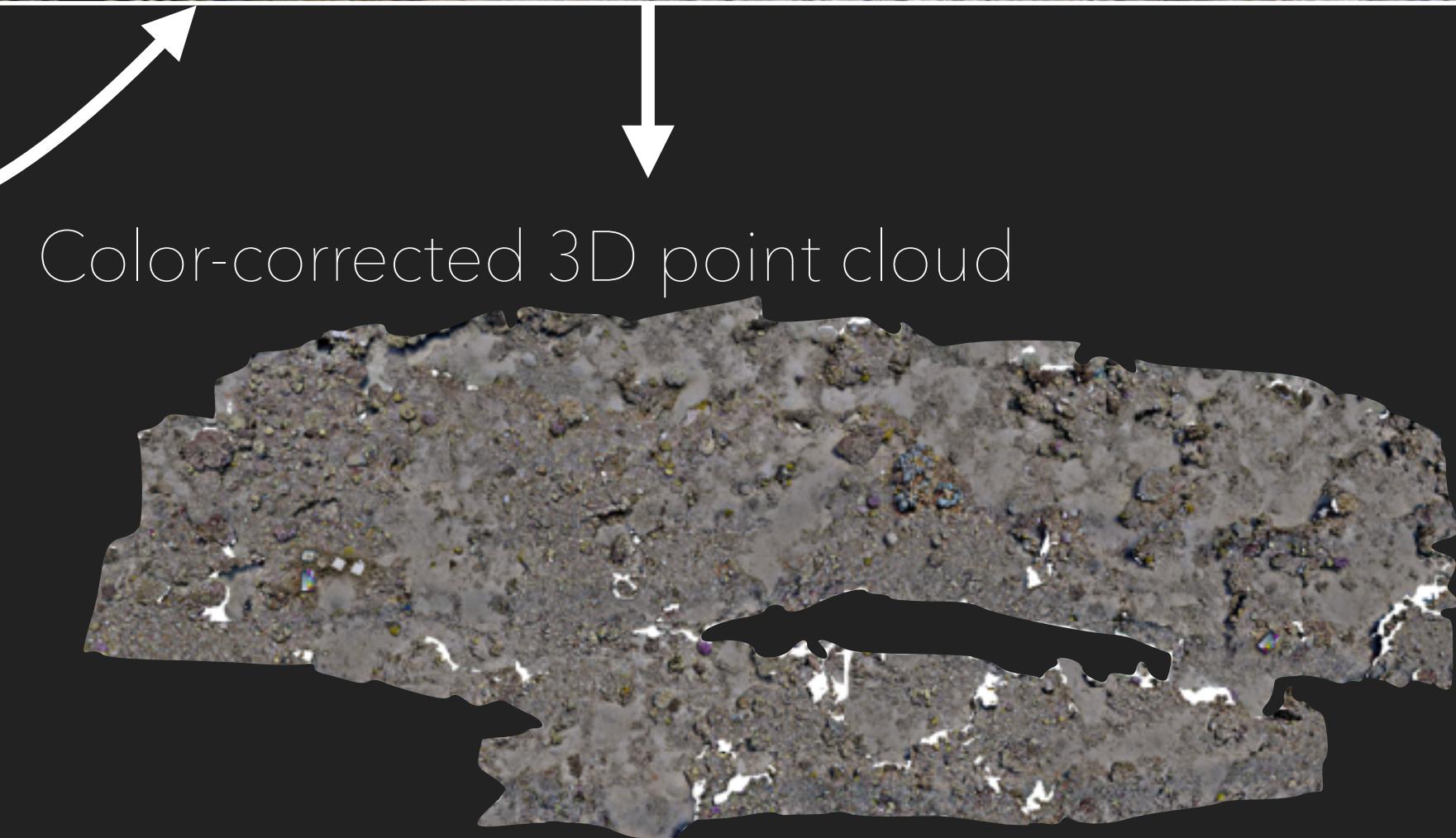


## PROOF-OF-CONCEPT

Lidar + RGB



RGB image with reconstructed colors

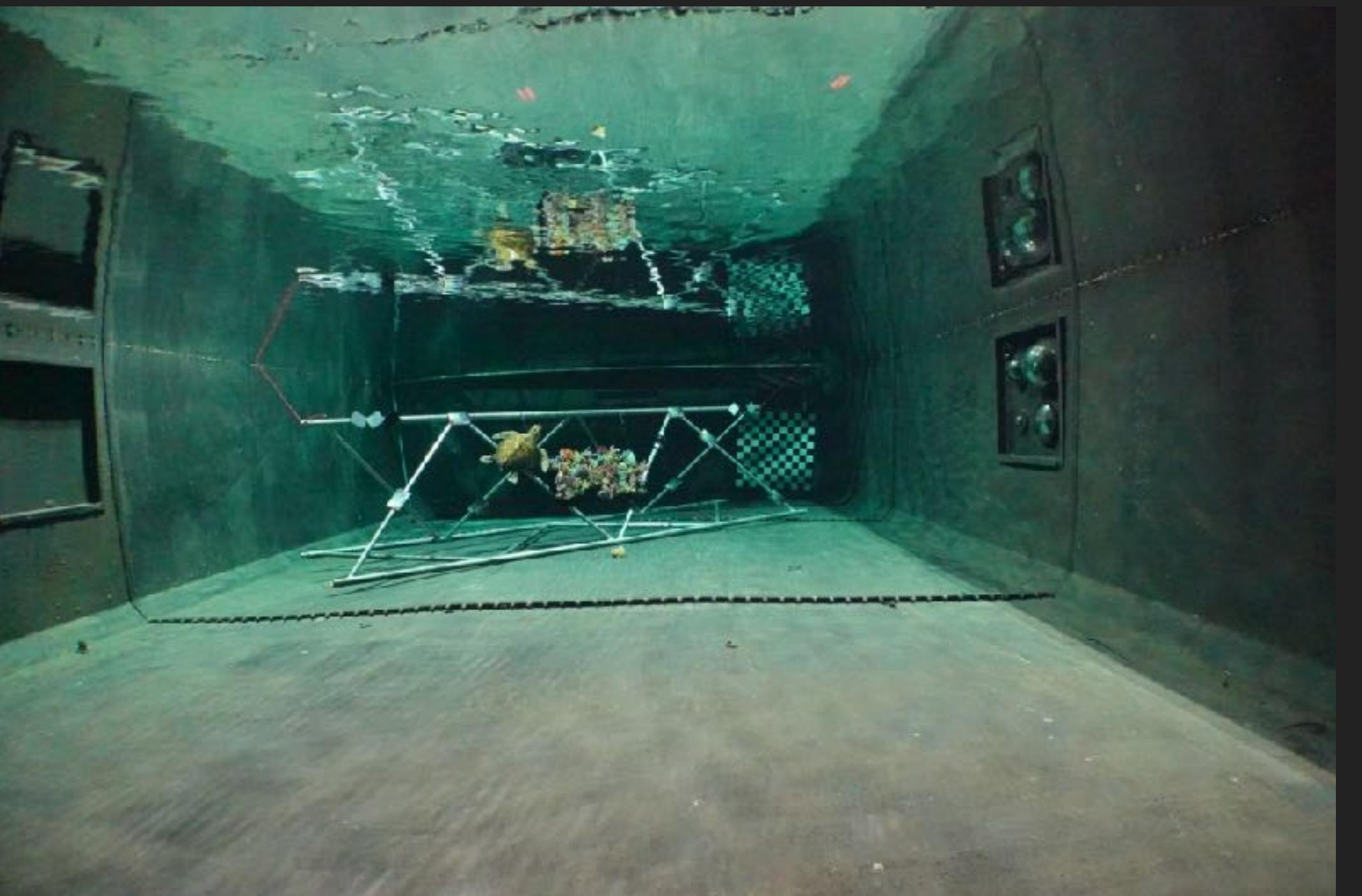


# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

## PROOF-OF-CONCEPT

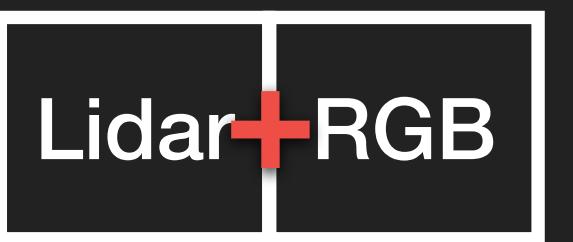


★Imaged from 5m

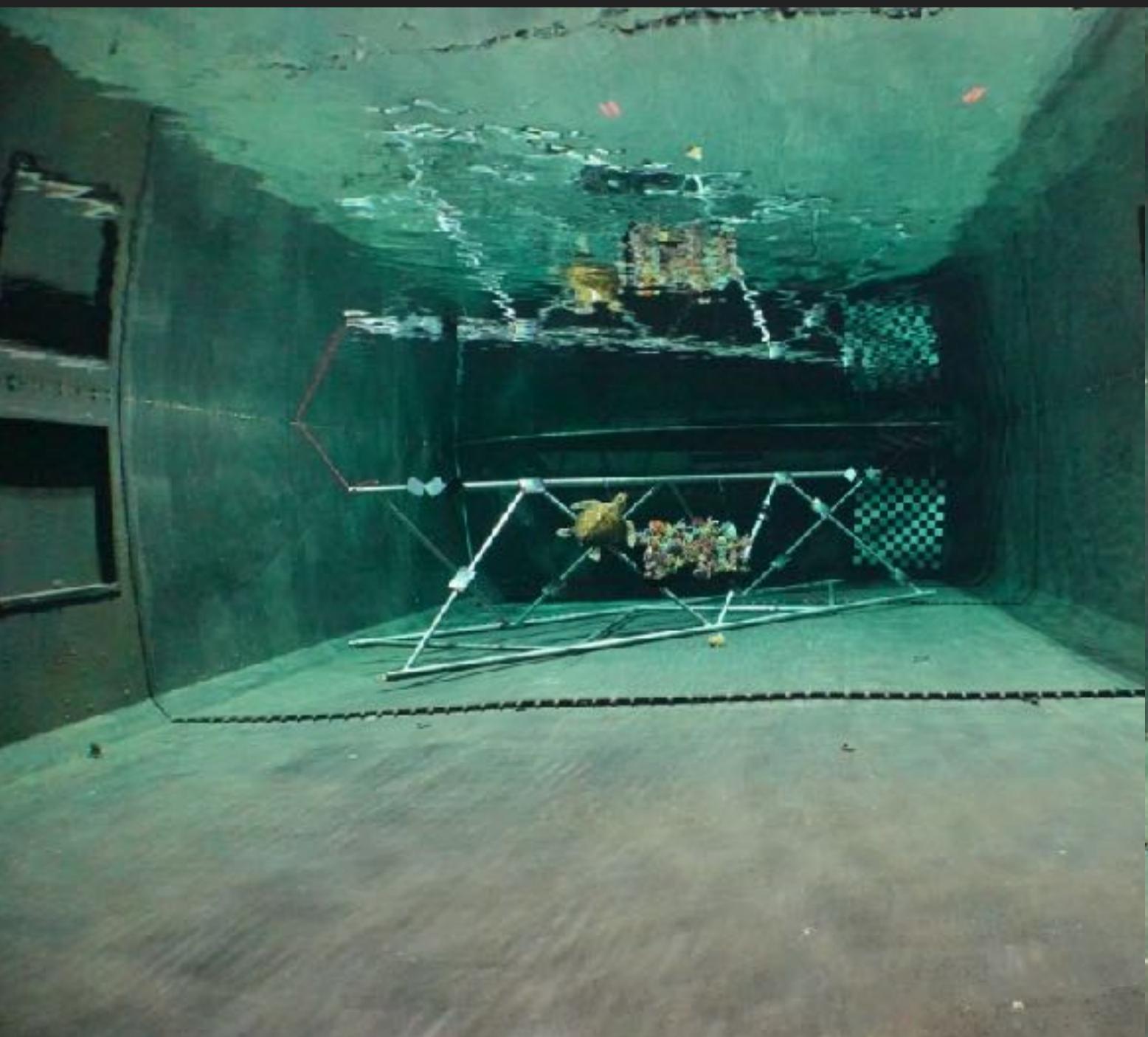




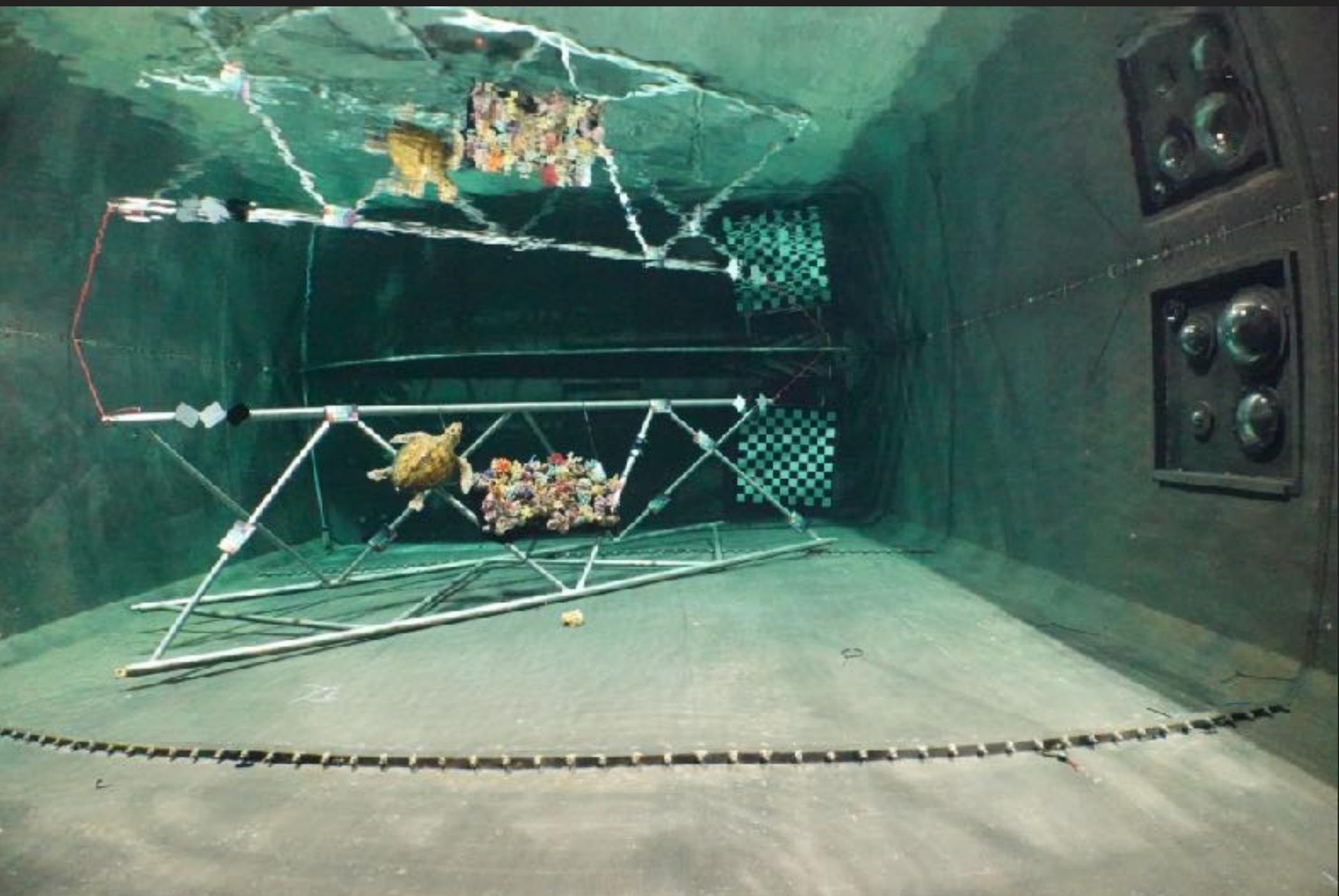
## PROOF-OF-CONCEPT



★Imaged from 5m

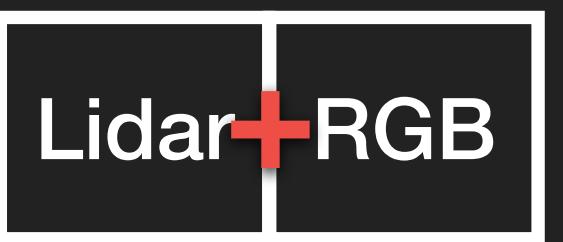


★Imaged from 3m

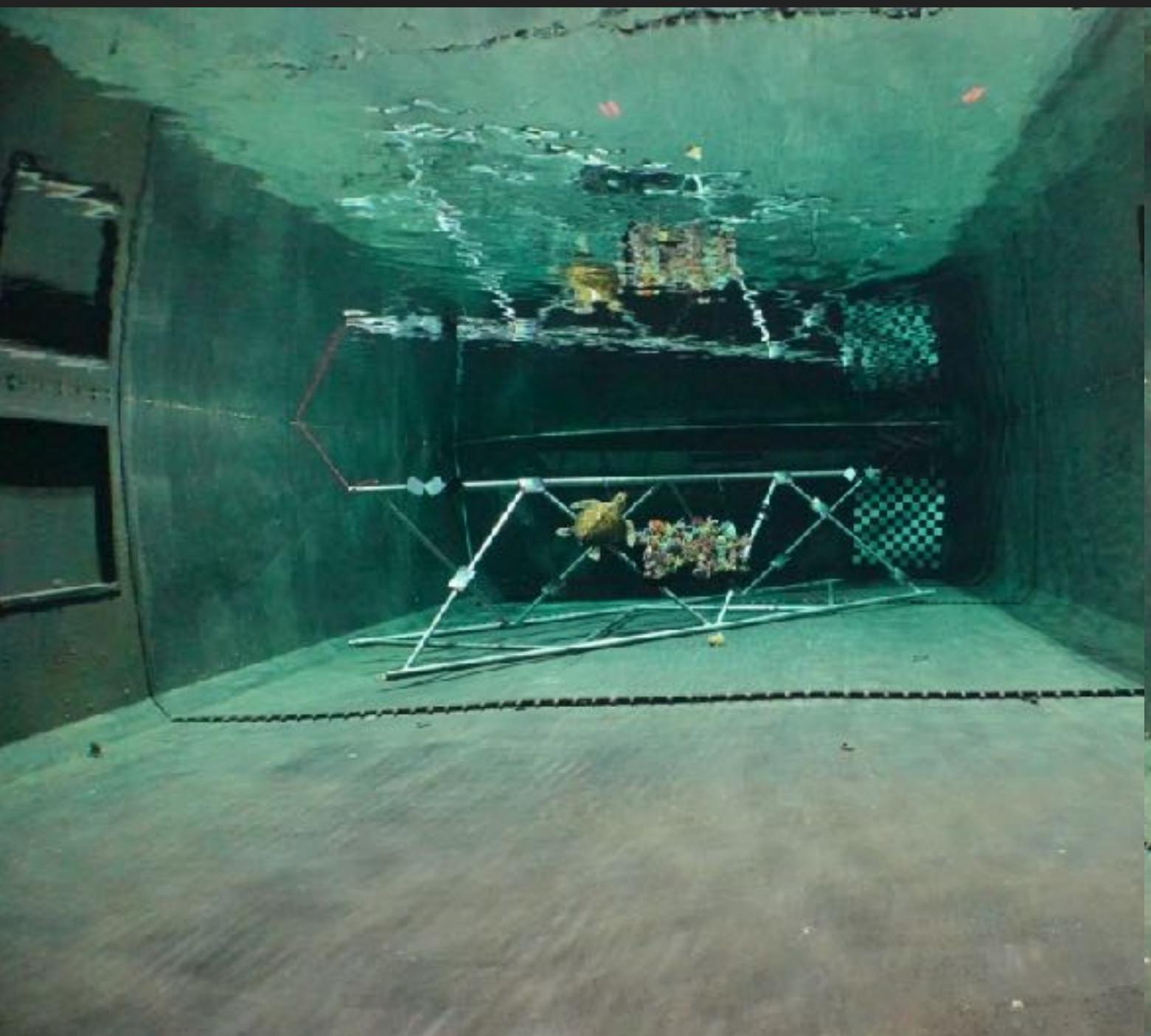


# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

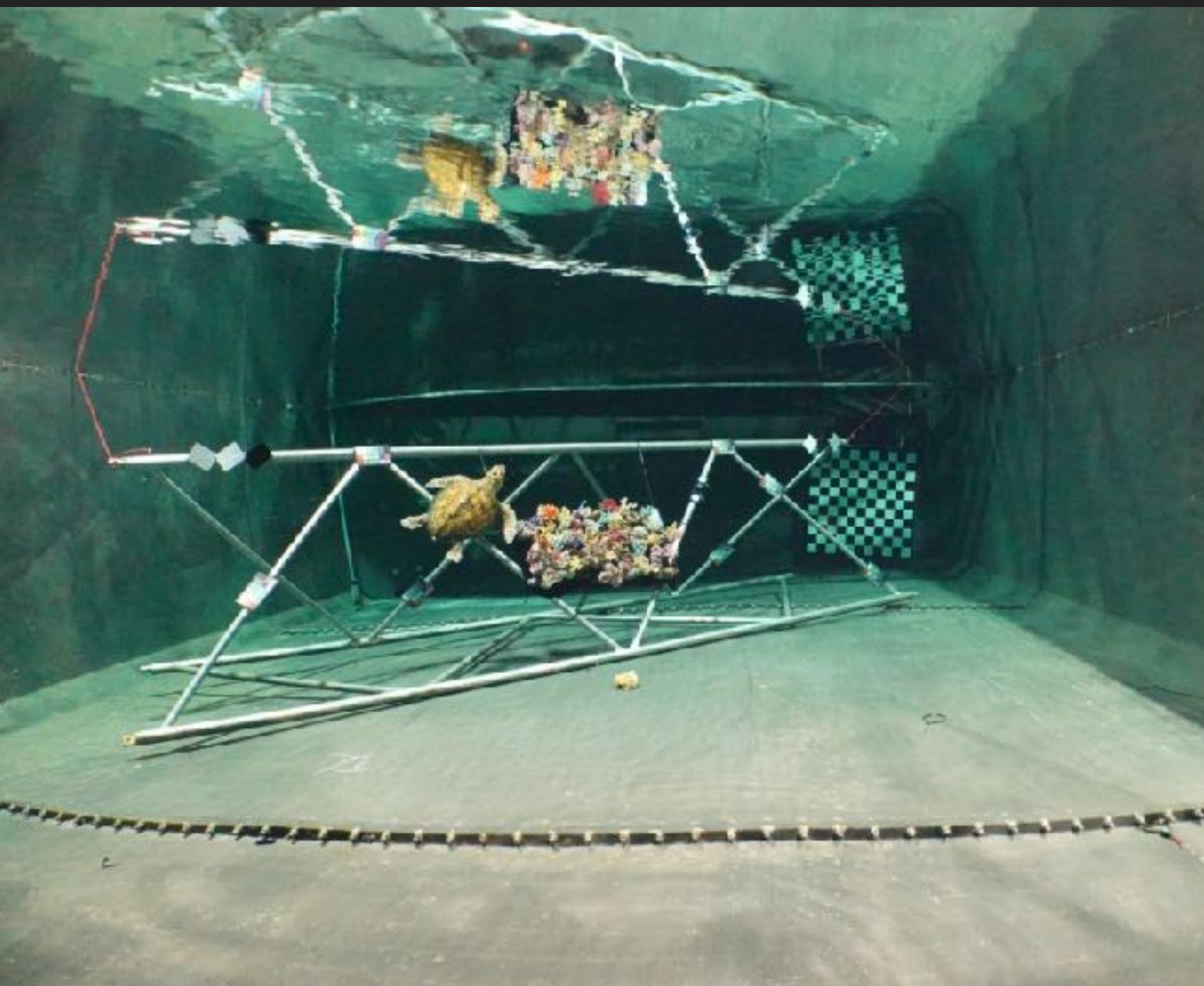
## PROOF-OF-CONCEPT



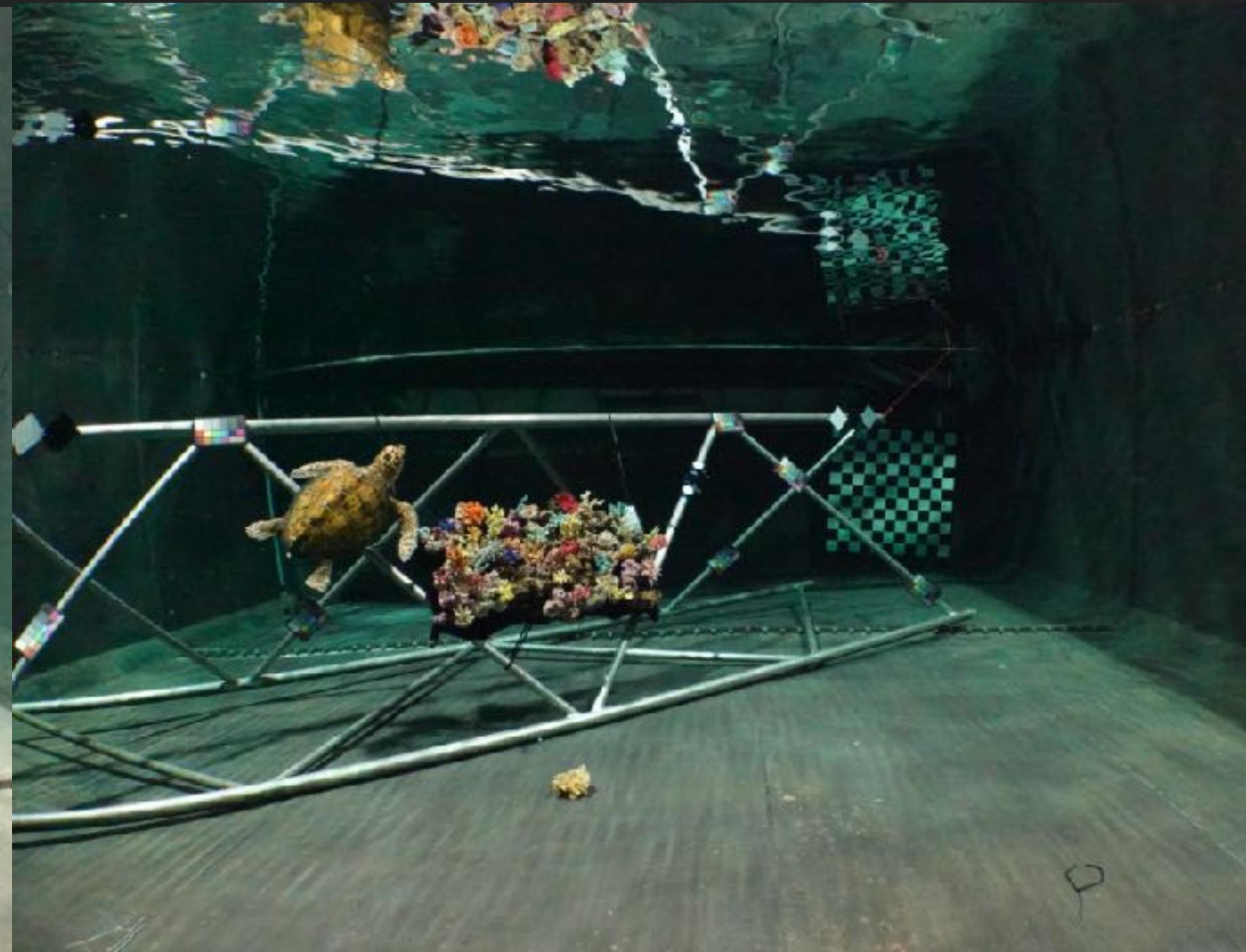
★Imaged from 5m



★Imaged from 3m



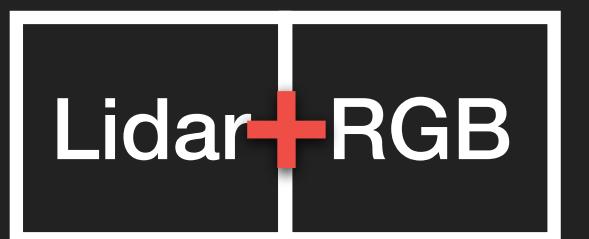
★Imaged from 1m



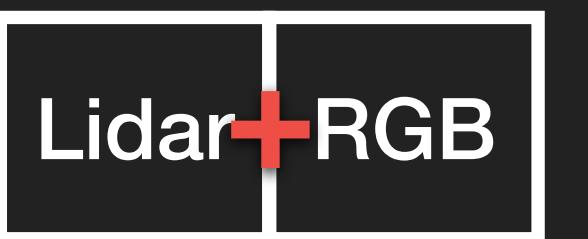
TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

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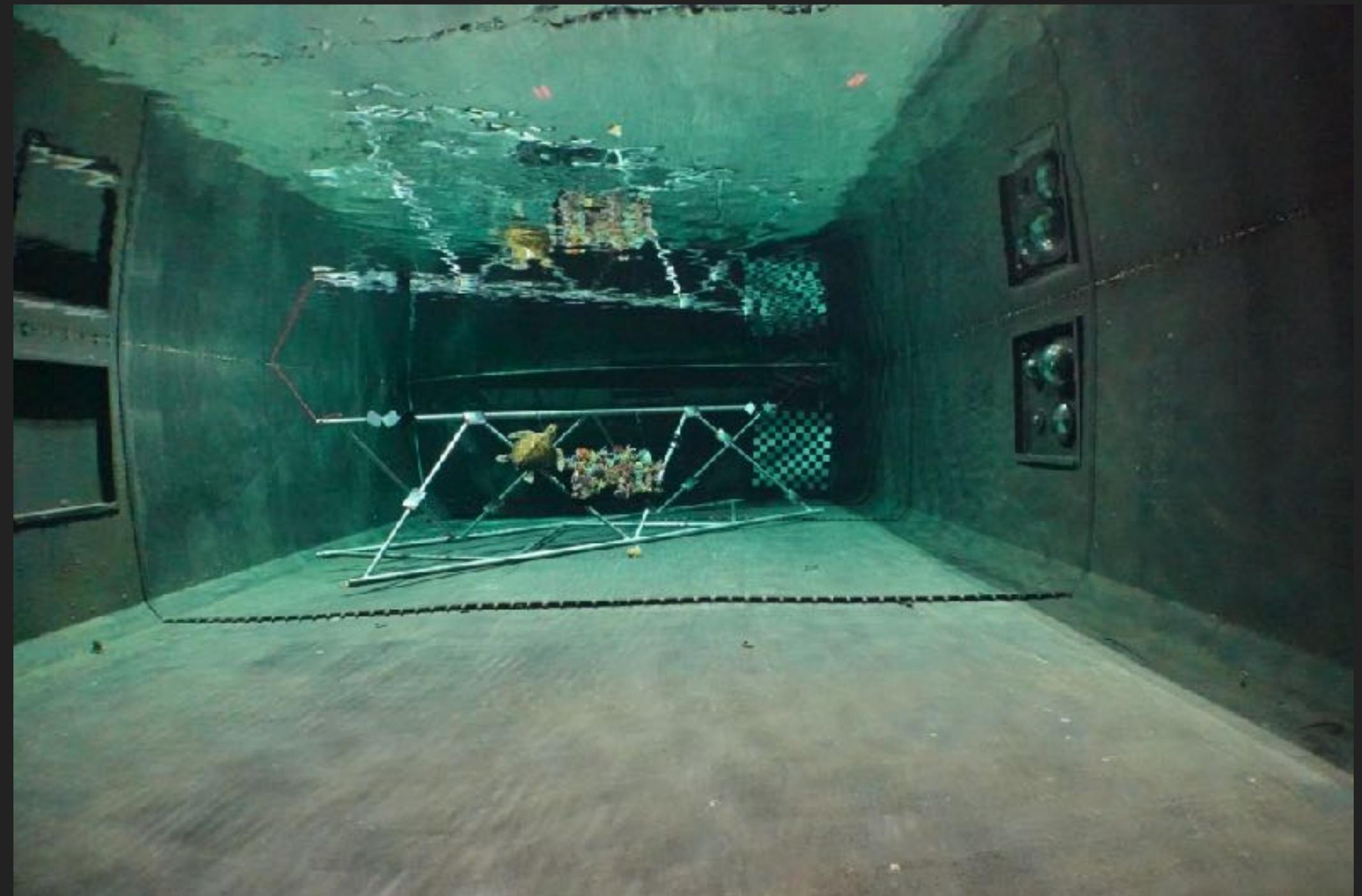
# PROOF-OF-CONCEPT



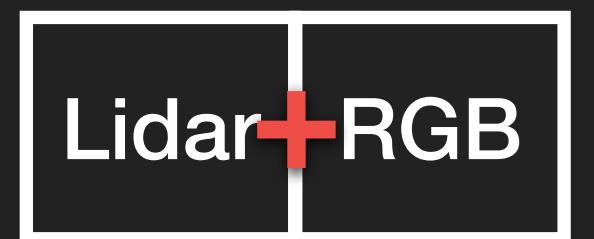
## PROOF-OF-CONCEPT



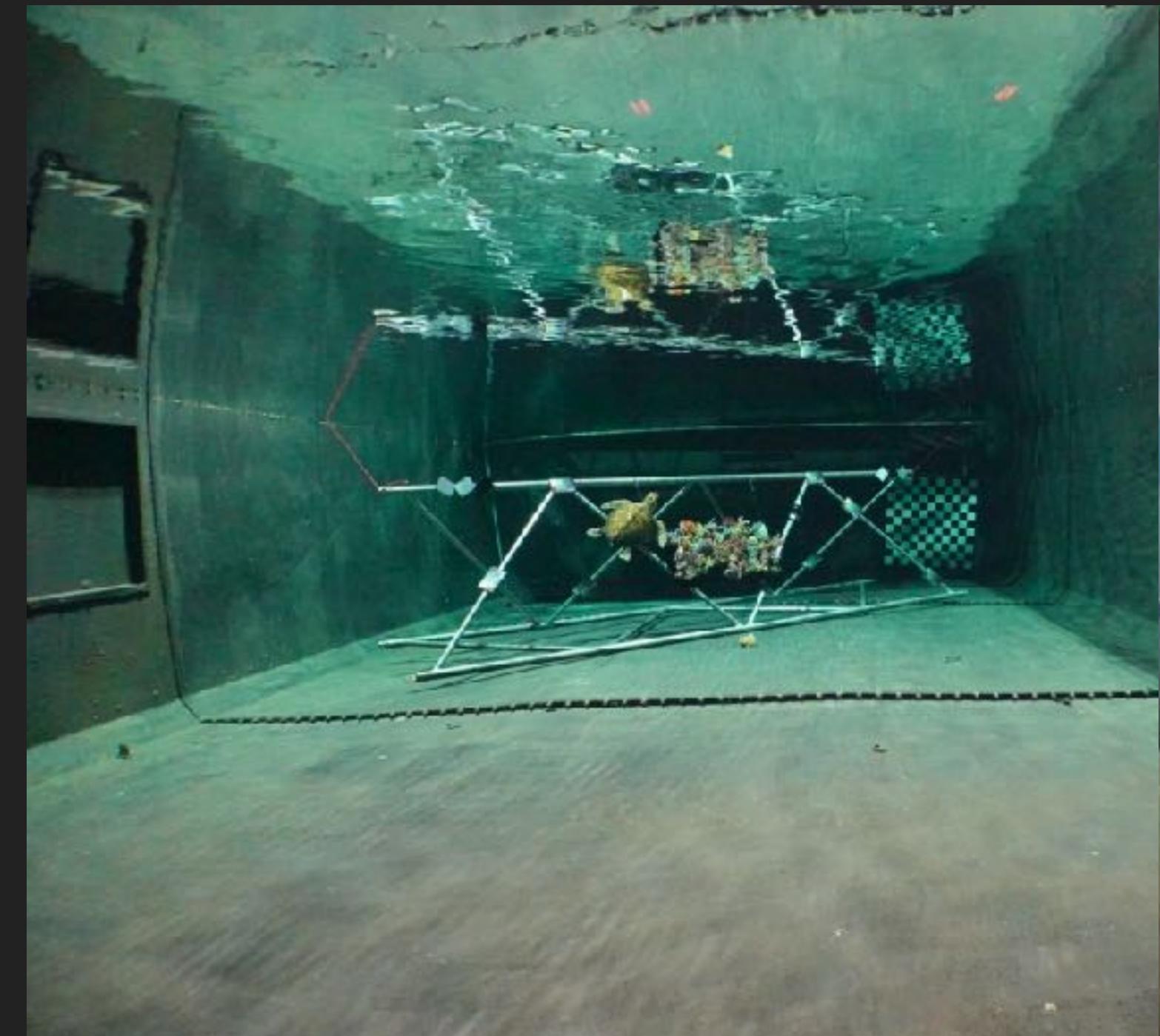
★Ambient light only



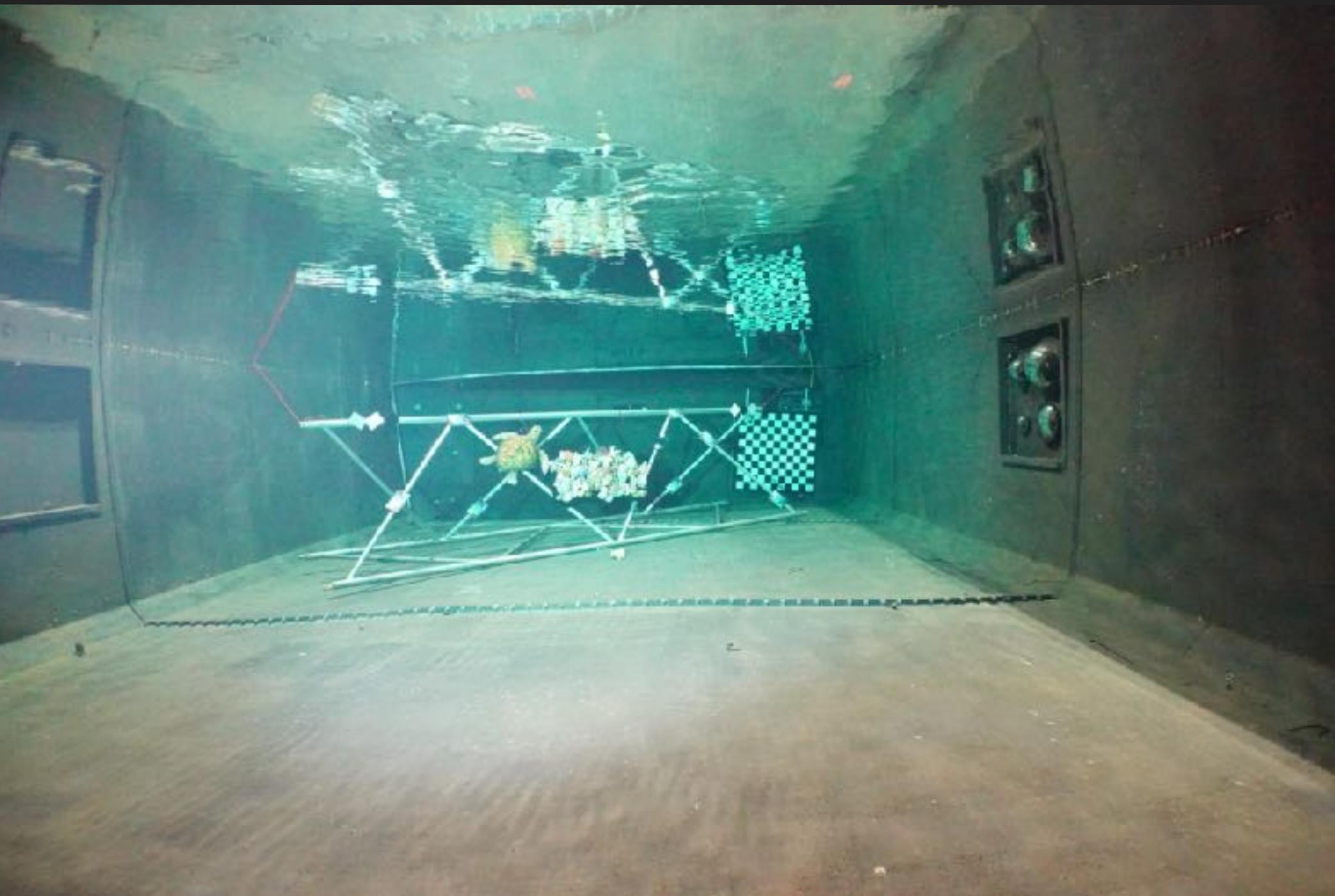
## PROOF-OF-CONCEPT



★Ambient light only



★Ambient light + strobe

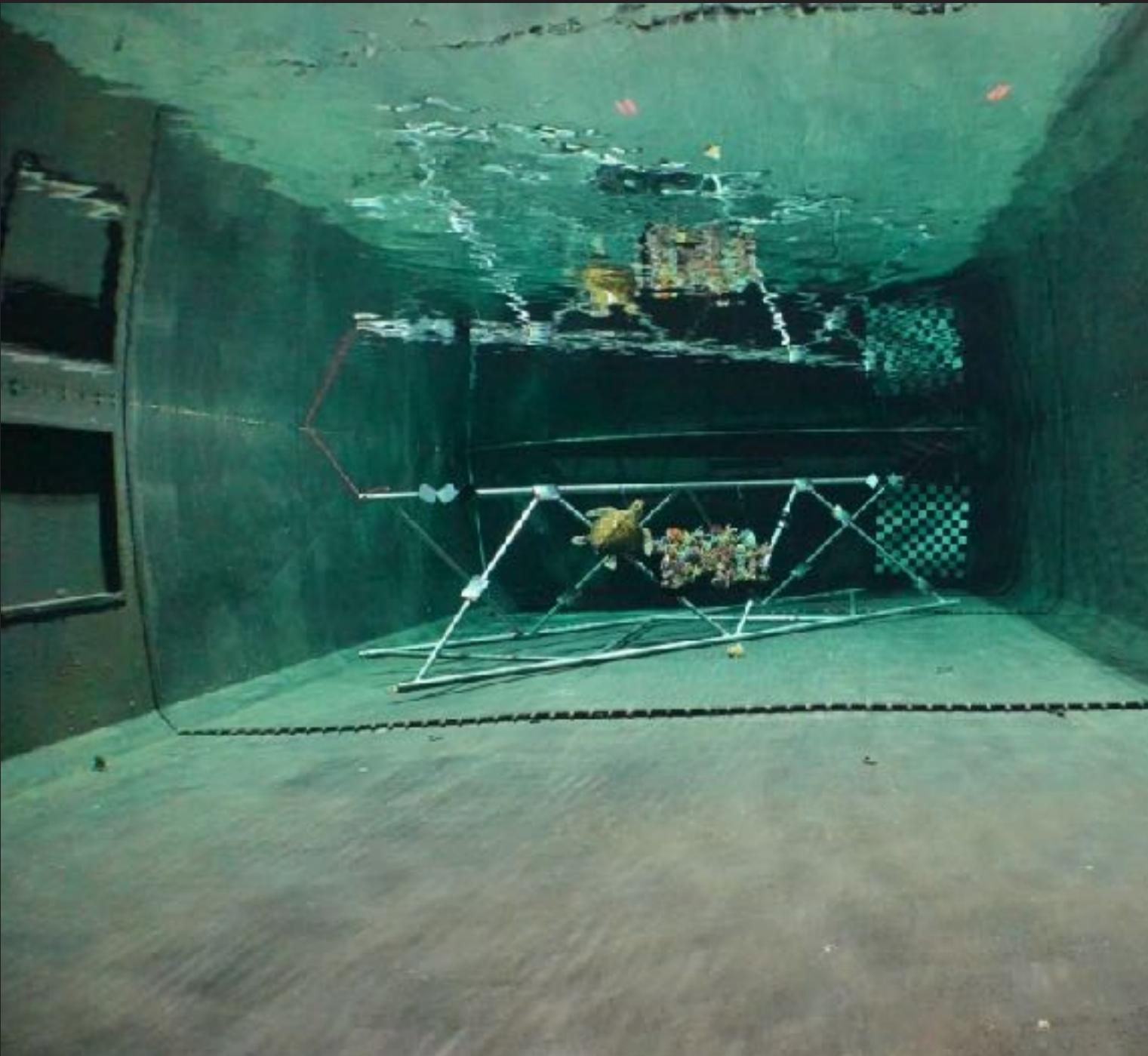


# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

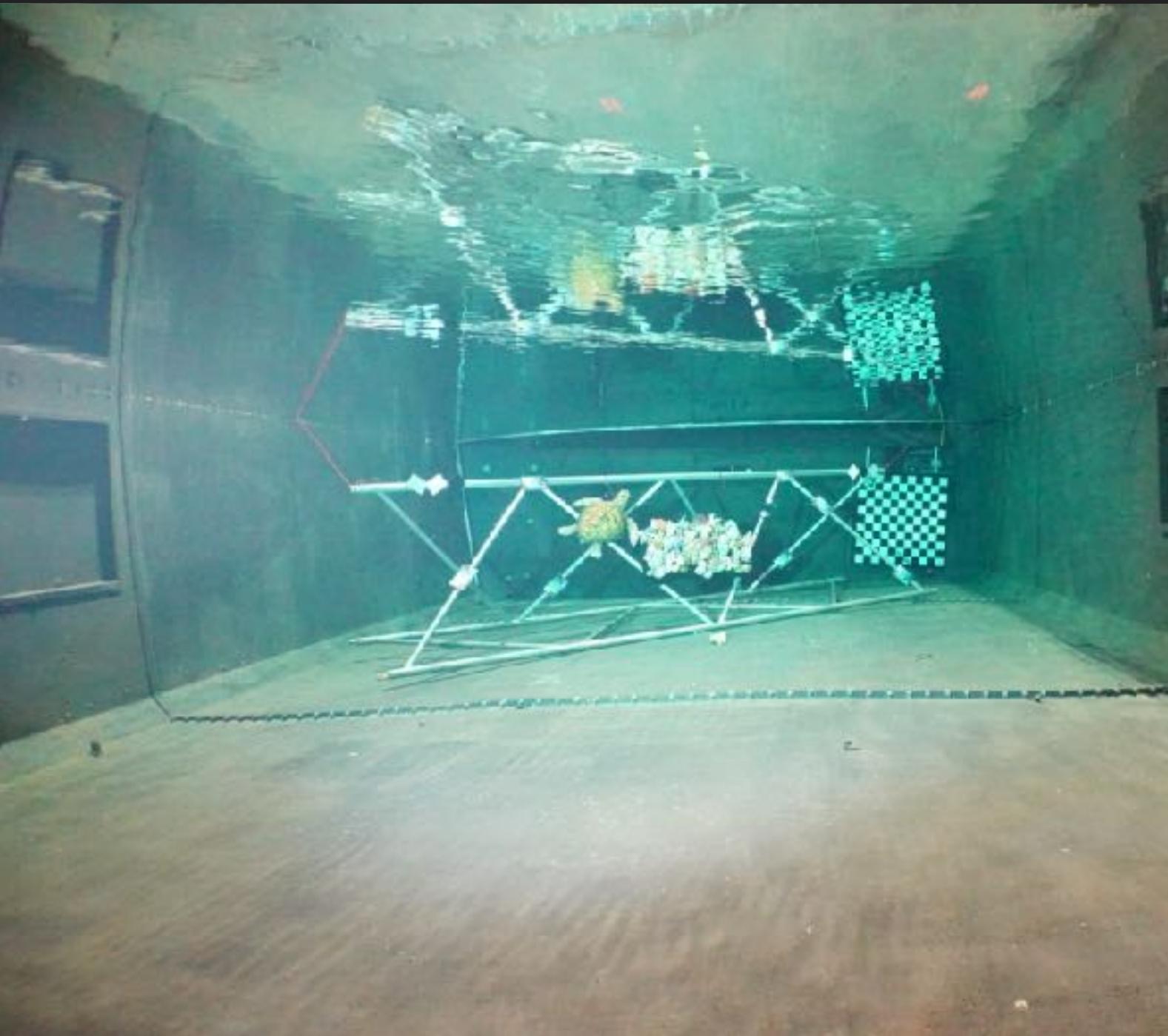
## PROOF-OF-CONCEPT



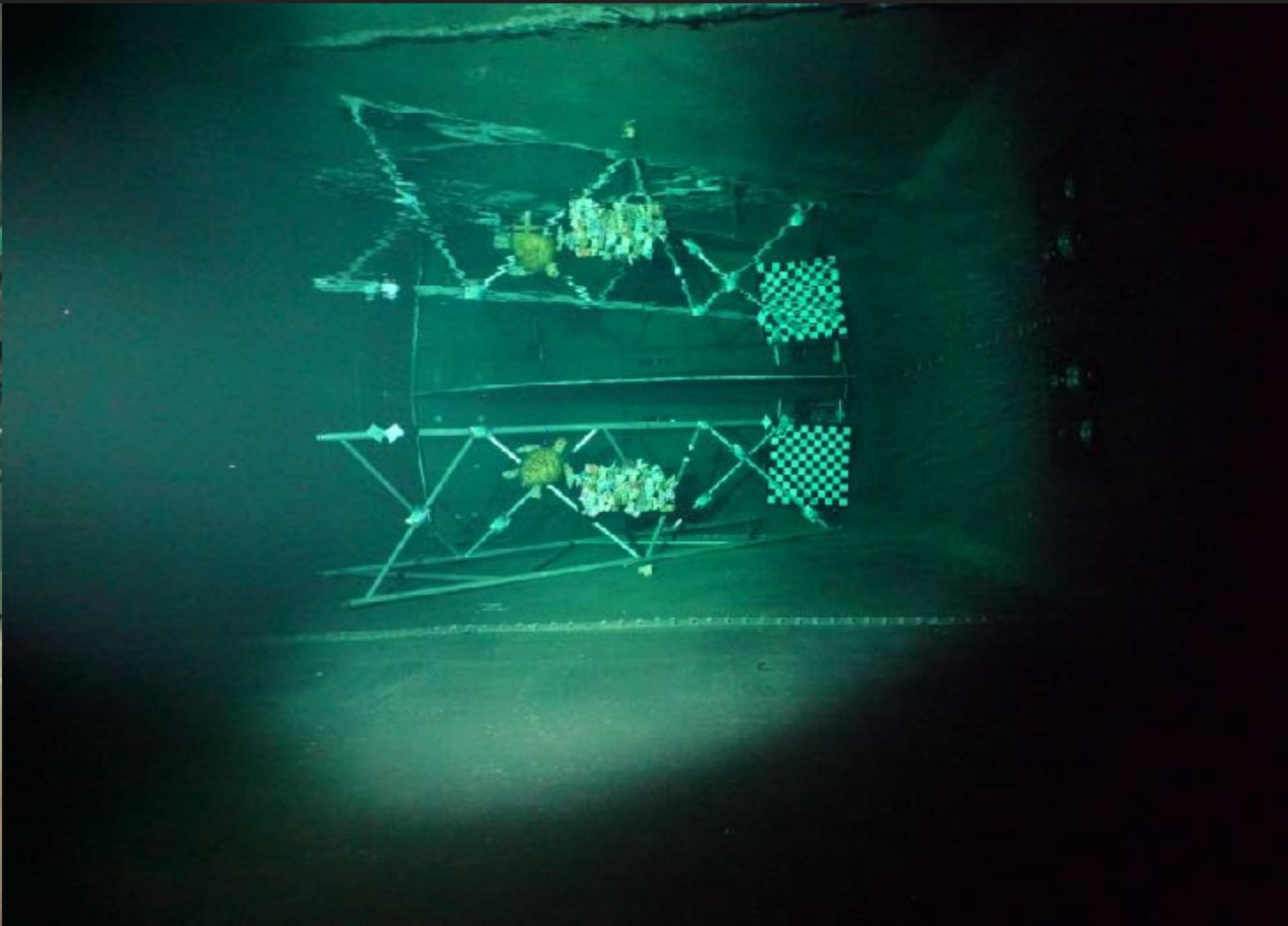
★Ambient light only



★Ambient light + strobe



★Strobe only

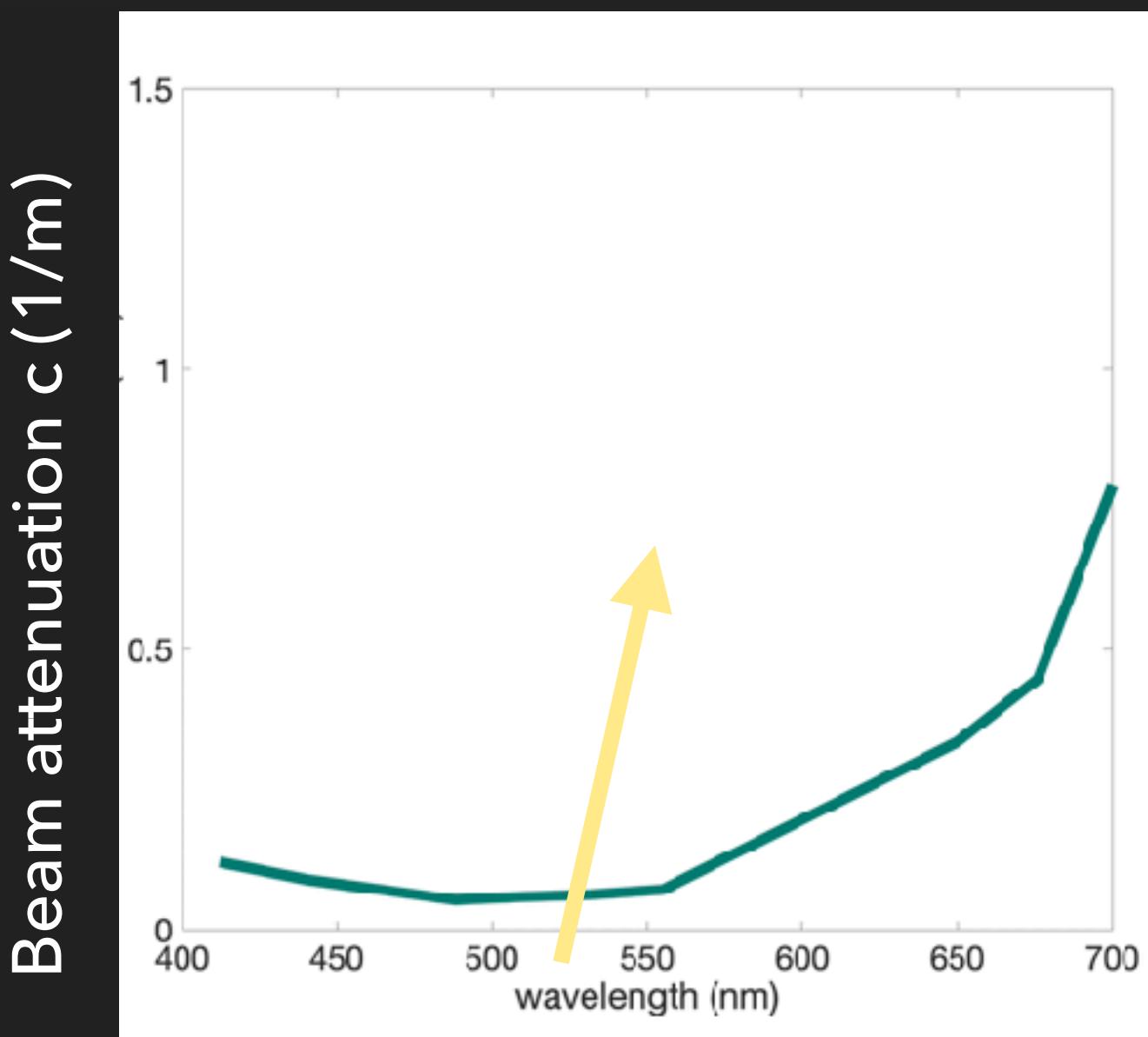




## PROOF-OF-CONCEPT

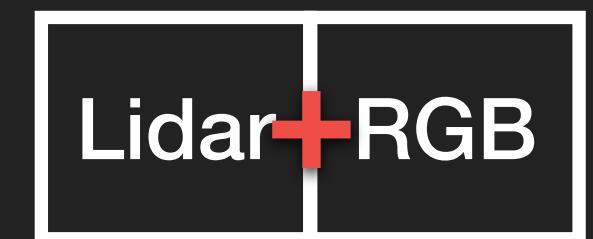
Lidar + RGB

★ Very clear water

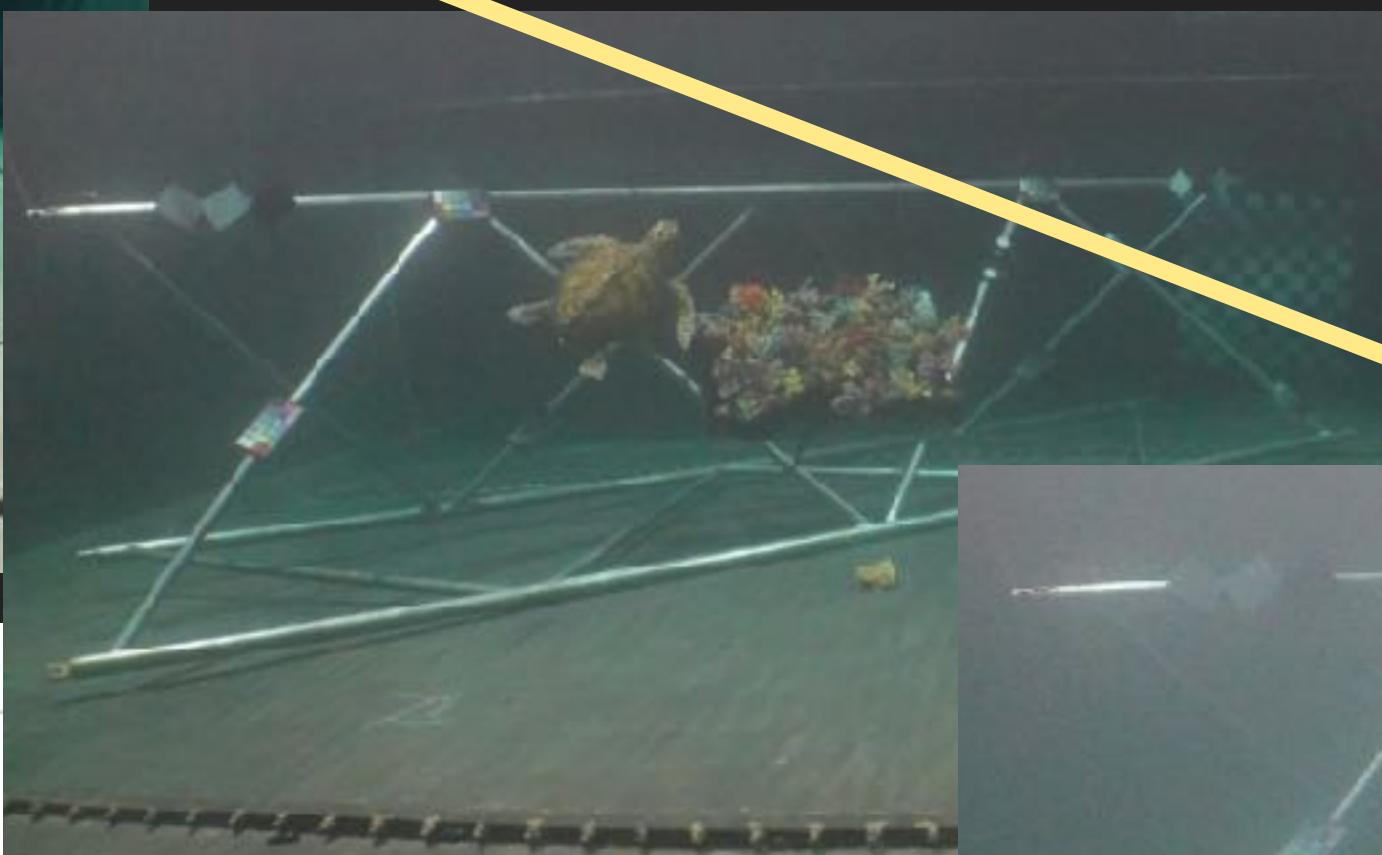


# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

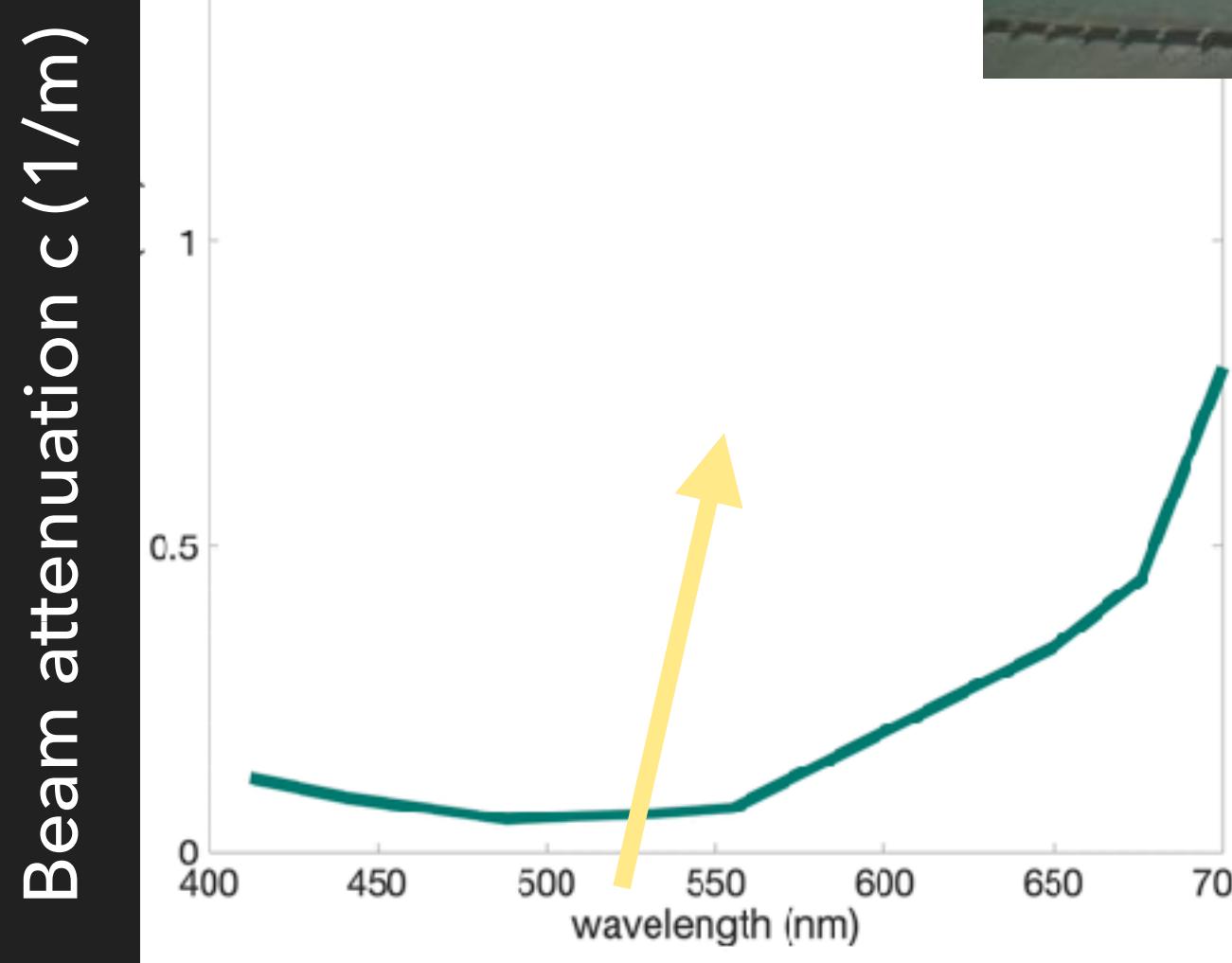
## PROOF-OF-CONCEPT



★Very clear water



★Moderately turbid water



# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

## PROOF-OF-CONCEPT

Lidar + RGB

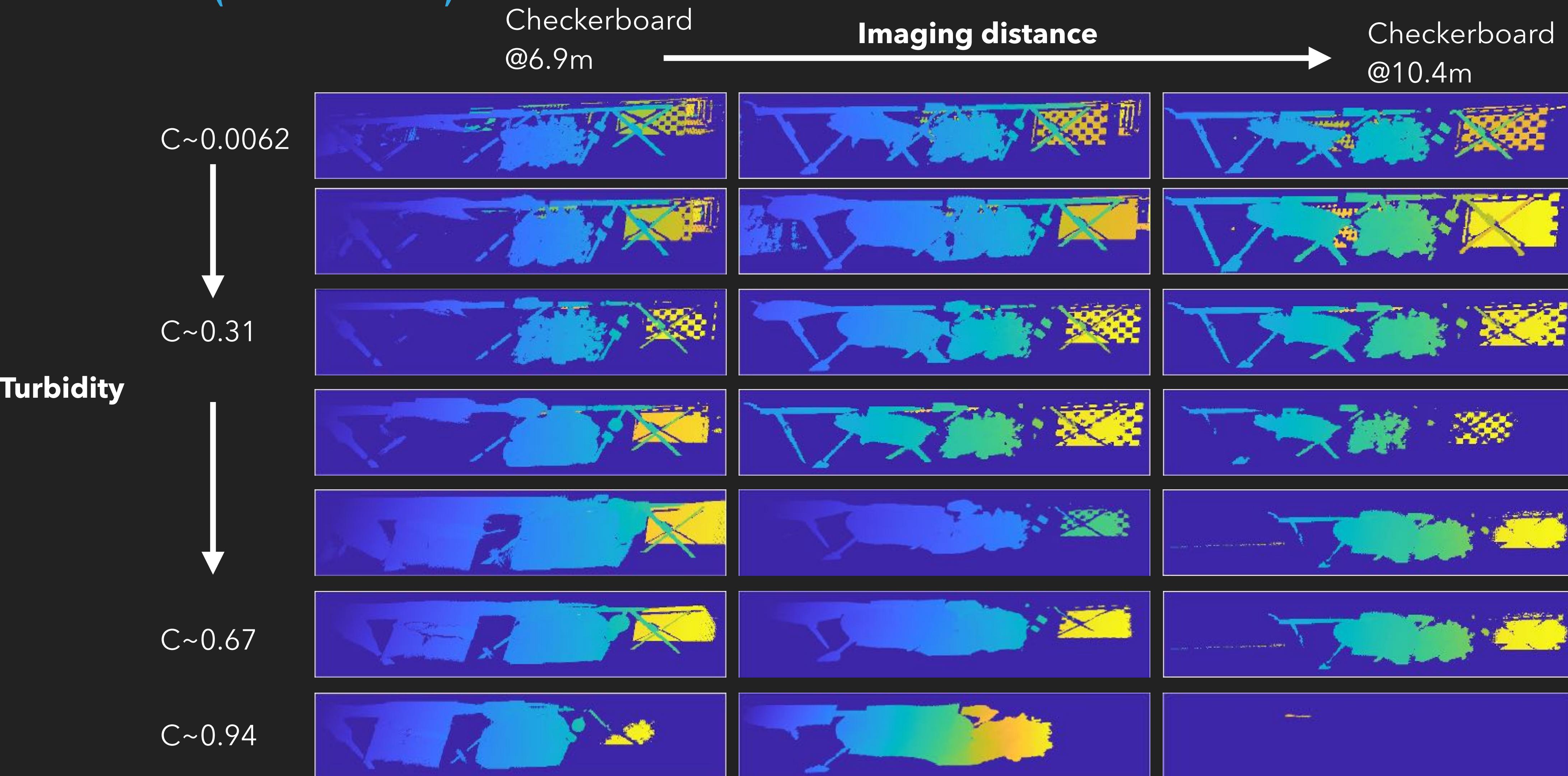


TOWARDS A LIDAR  
PROOF-OF-CONCEPT



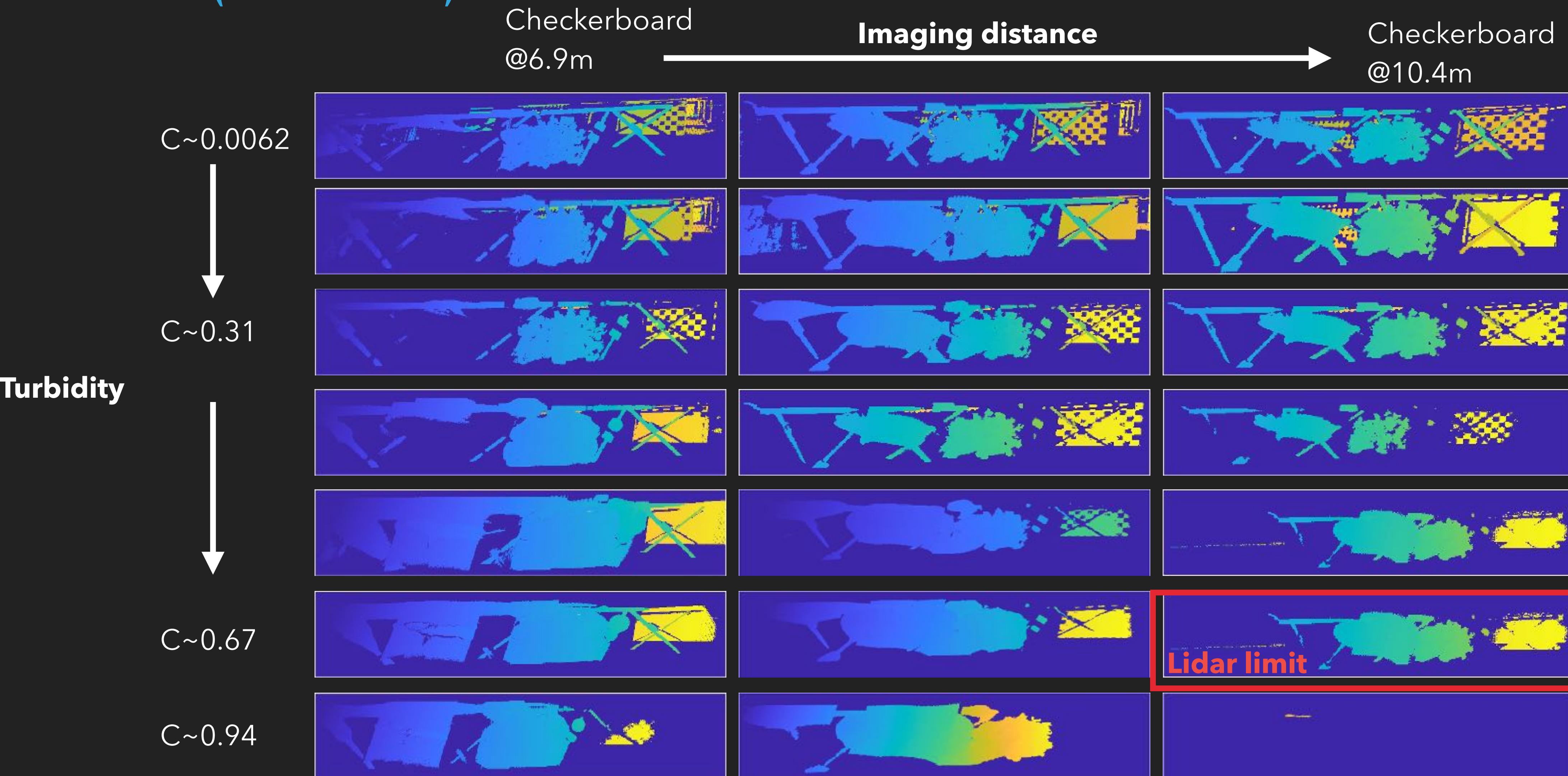


## RESULTS (TEST TANK)



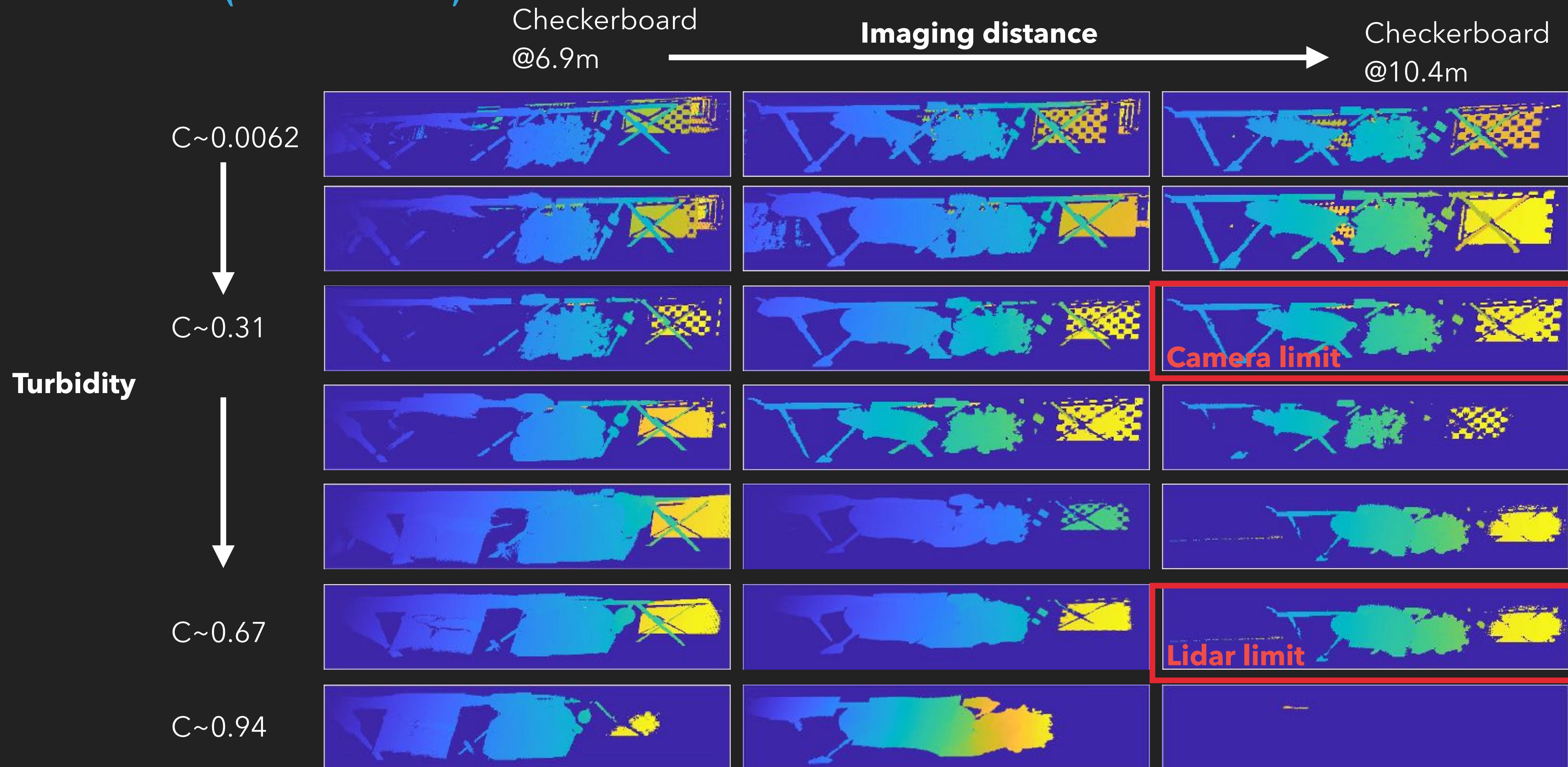


## RESULTS (TEST TANK)



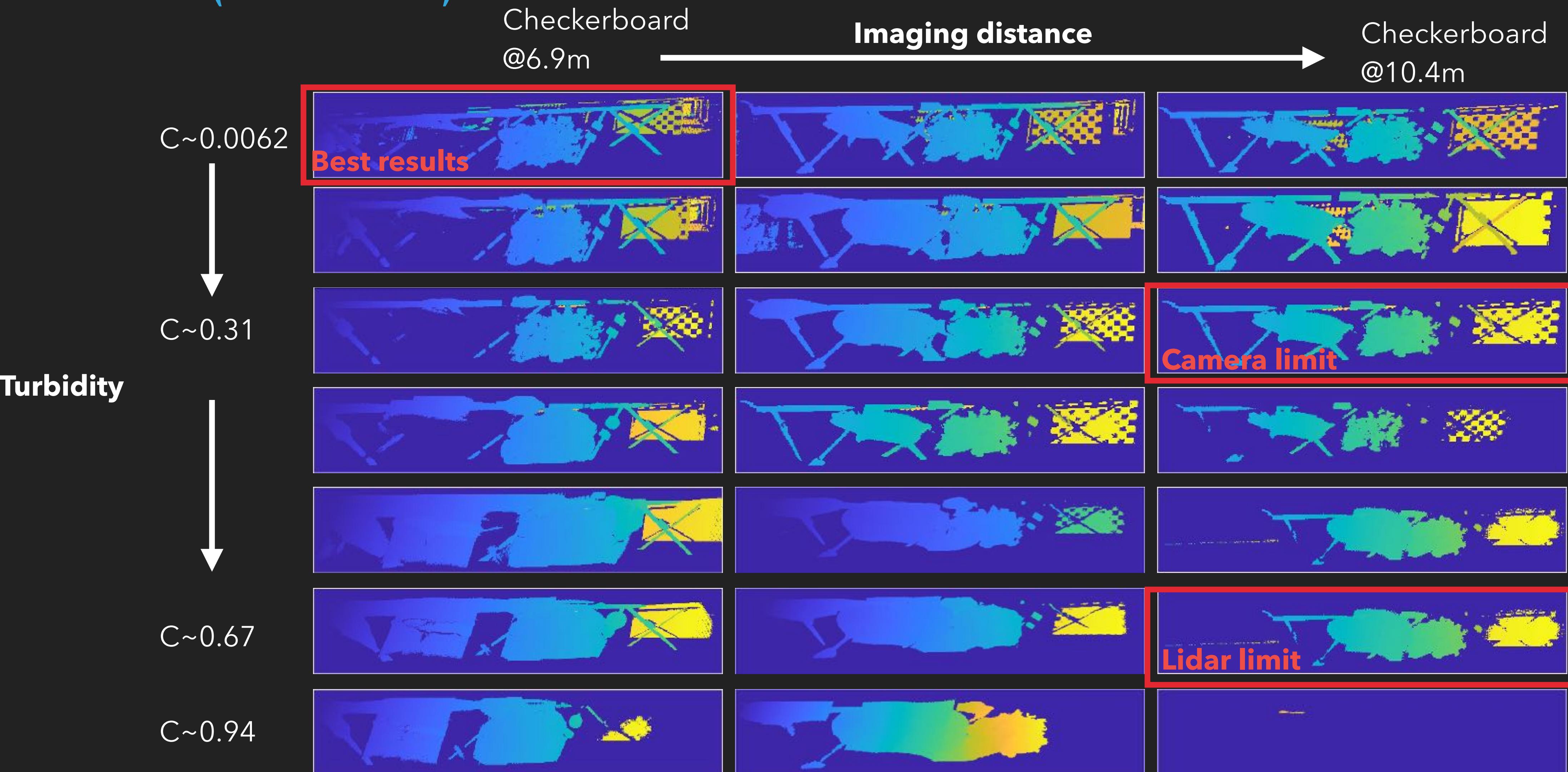


## RESULTS (TEST TANK)

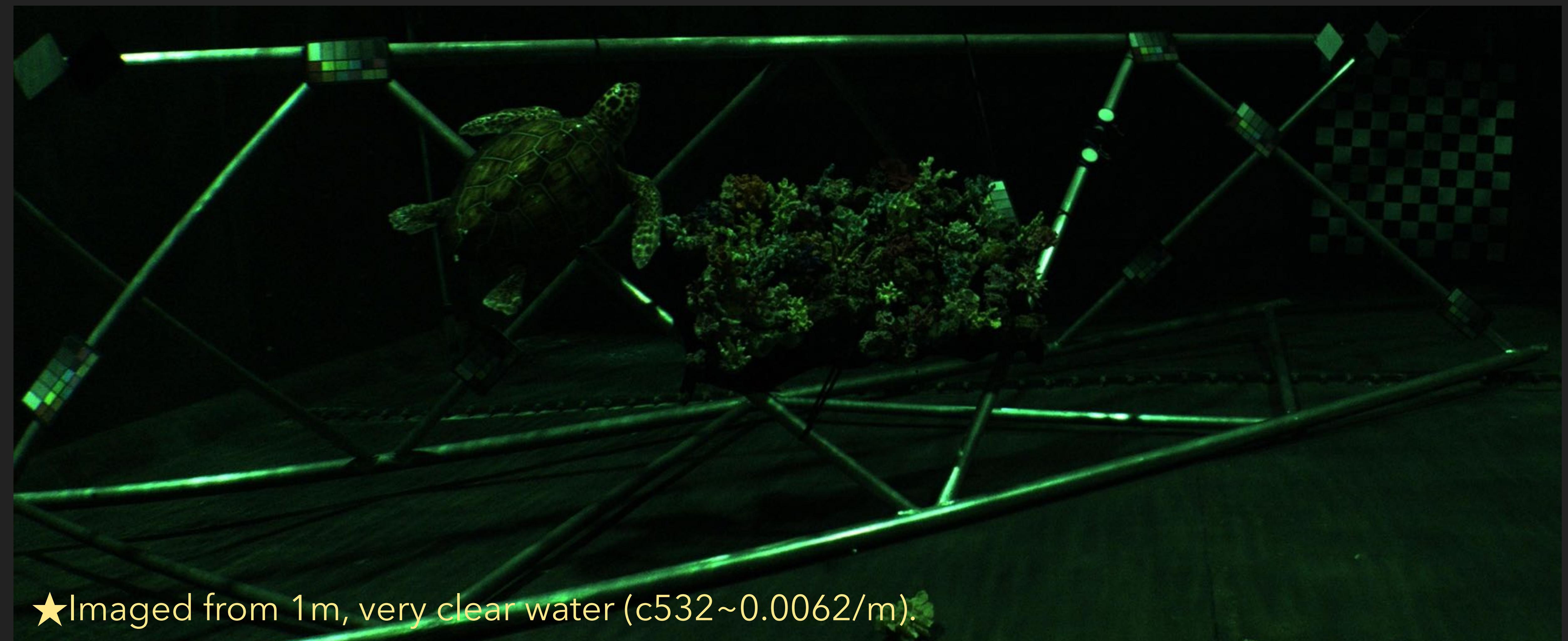
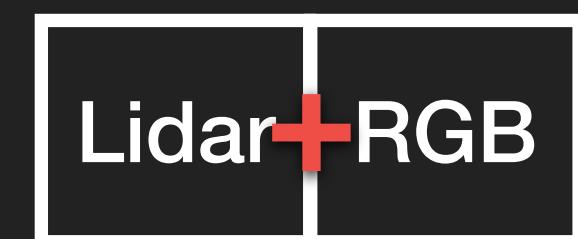




## RESULTS (TEST TANK)



## RESULTS (TEST TANK)



★Imaged from 1m, very clear water ( $c532 \sim 0.0062/m$ ).

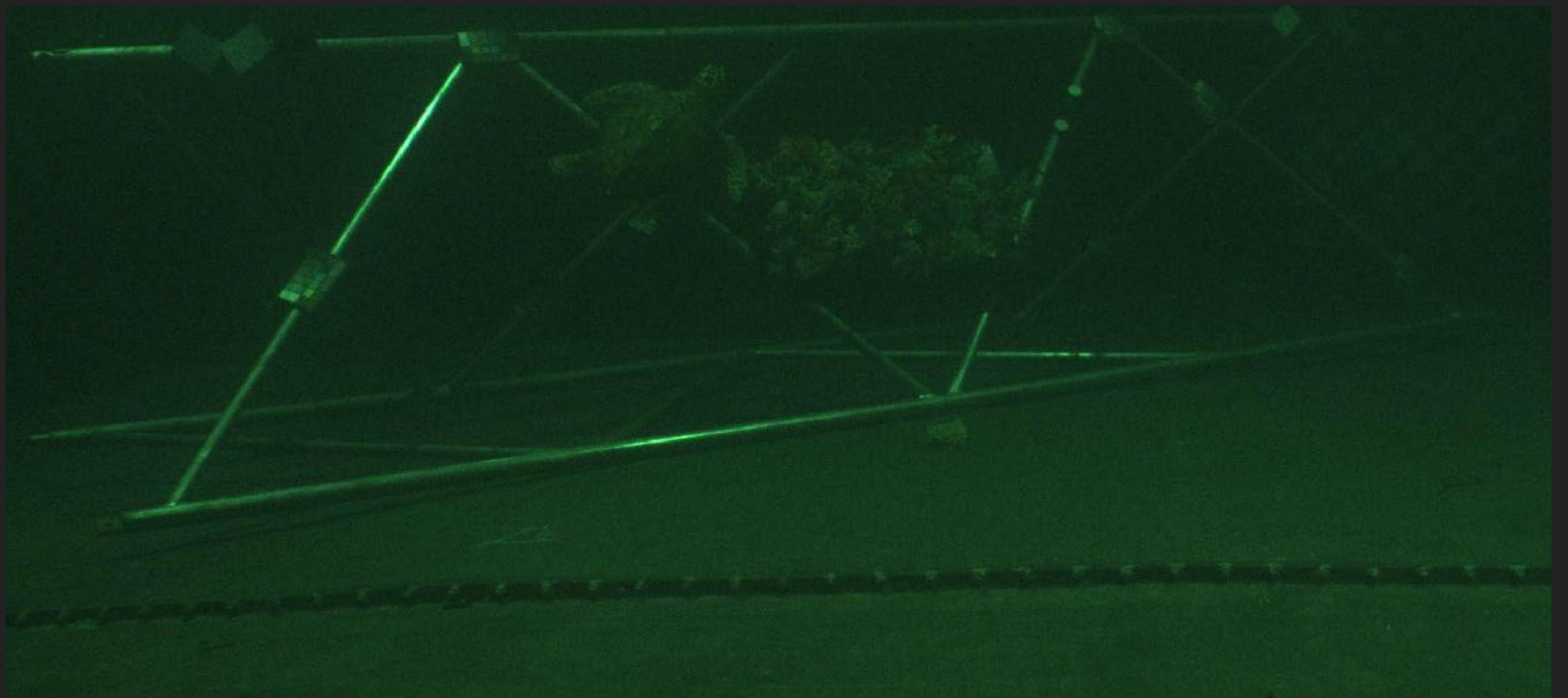
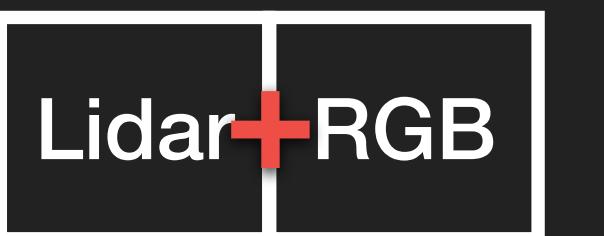
## RESULTS (TEST TANK)

Lidar + RGB



★Imaged from 1m, very clear water (c532~0.0062/m).

## RESULTS (TEST TANK)

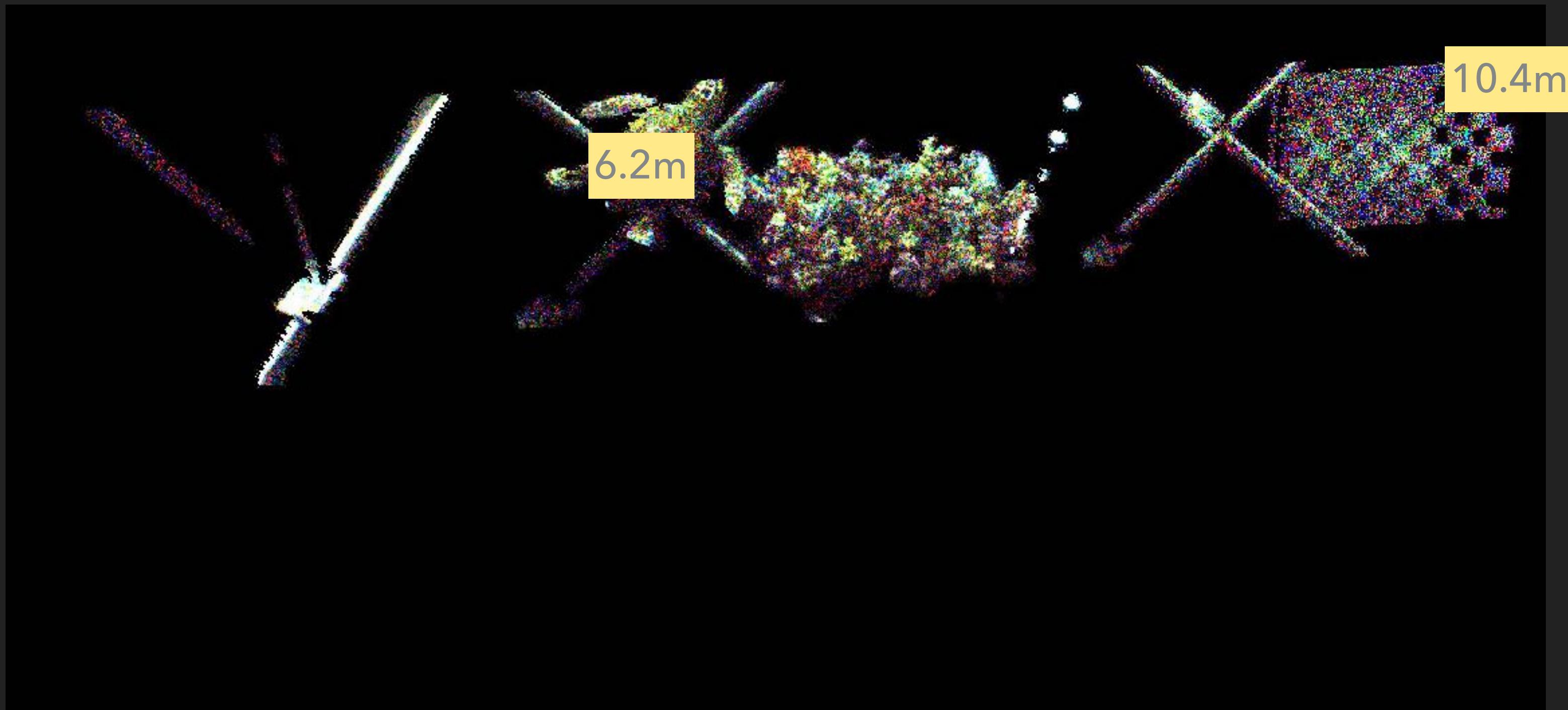


★Imaged from 5m, high turbidity (c532~0.31/m).



## RESULTS (TEST TANK)

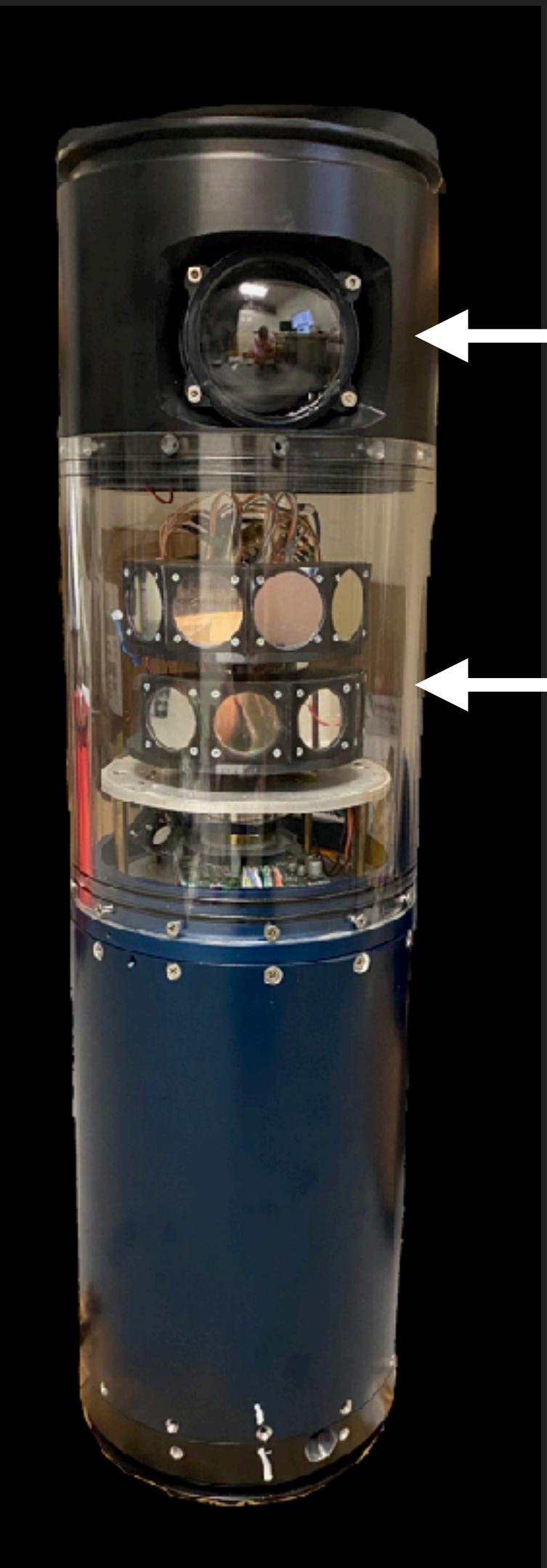
Lidar + RGB



★Imaged from 5m, high turbidity (c532~0.31/m).

# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

## SEA TRIALS

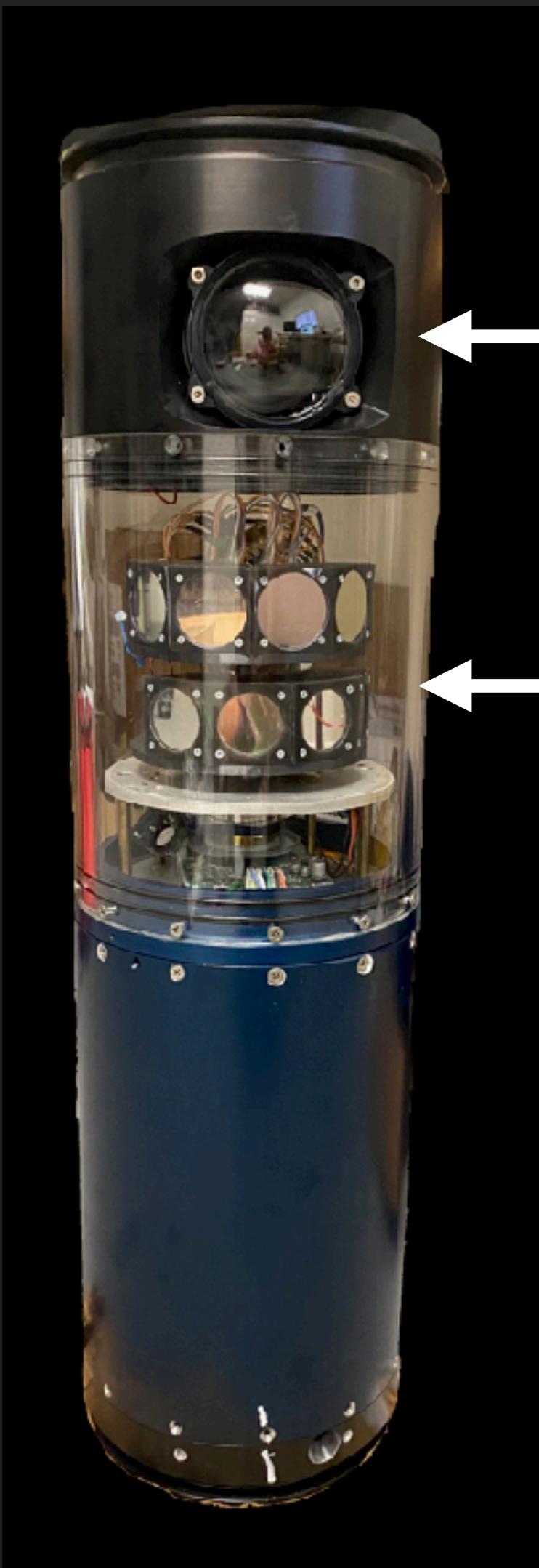


Lidar + RGB



# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

## SEA TRIALS

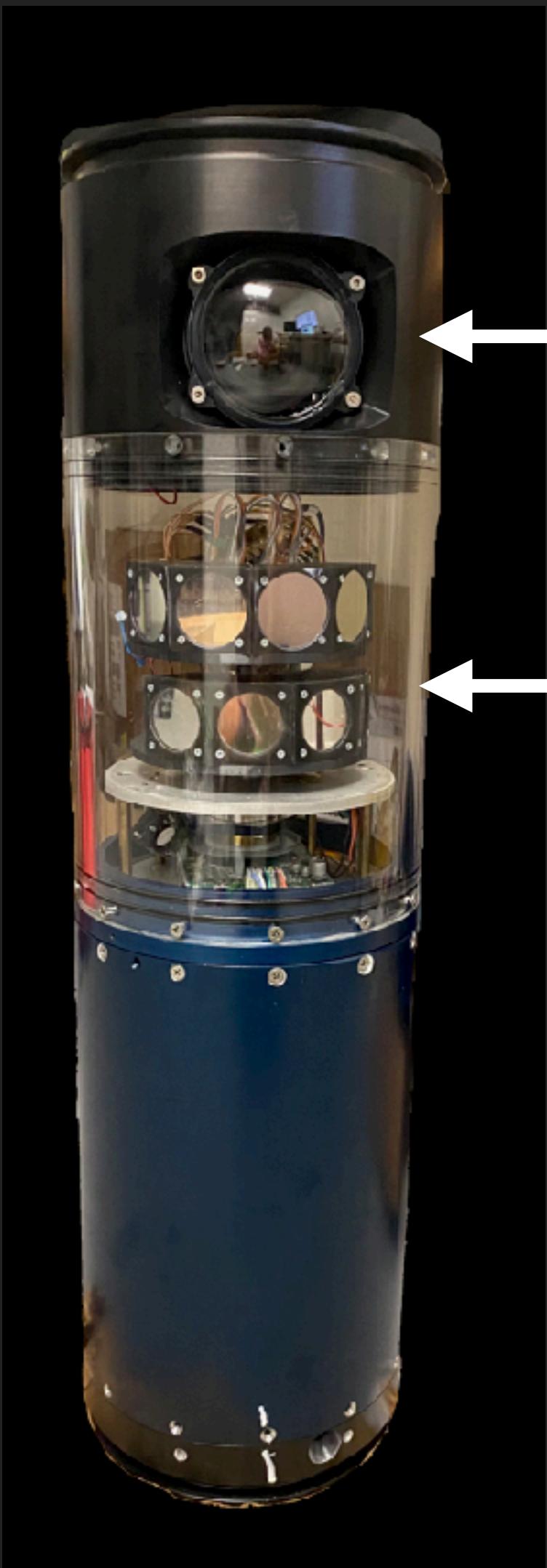


Lidar + RGB



# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

## SEA TRIALS



Lidar + RGB

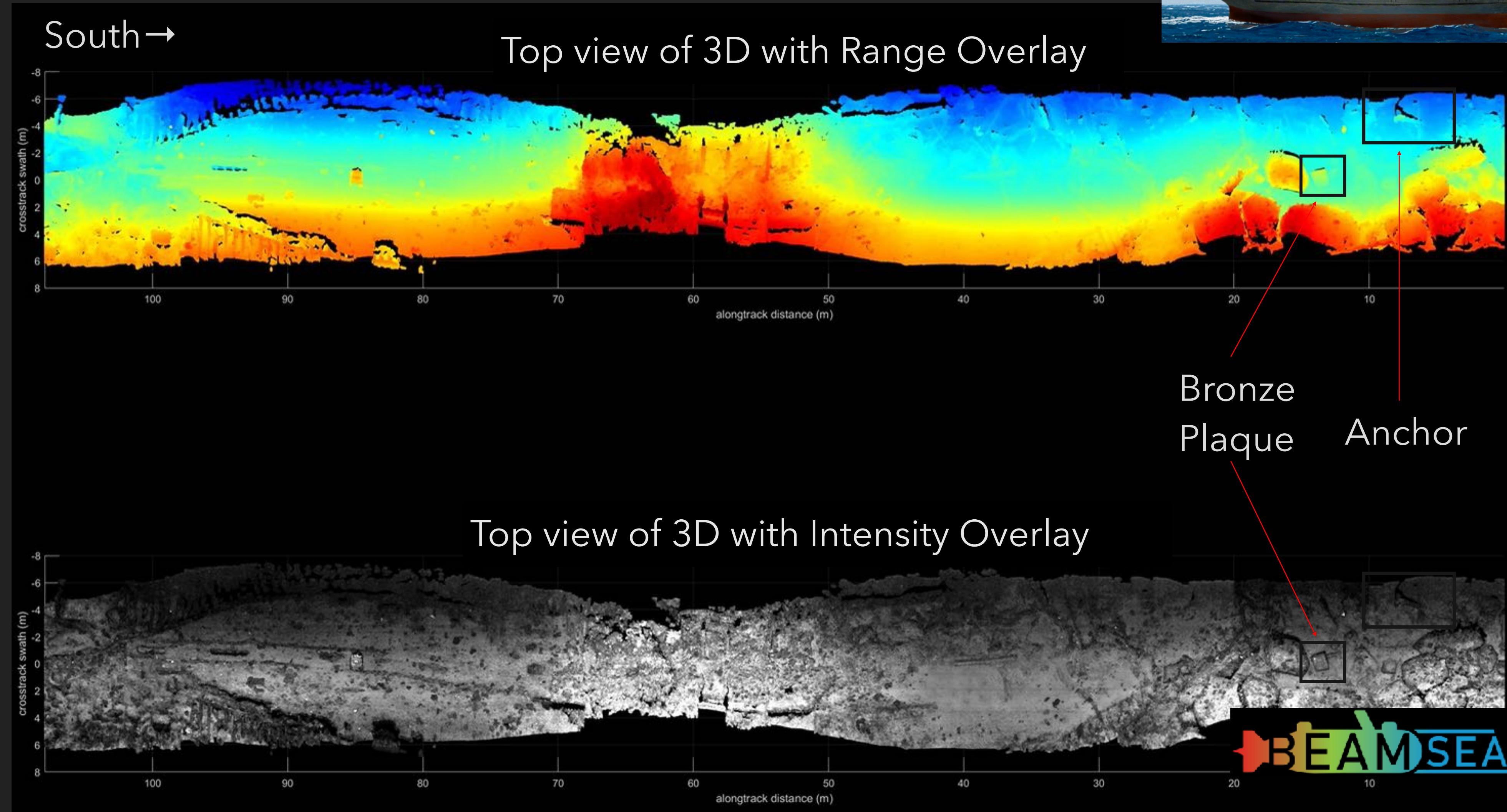


SS Copenhagen





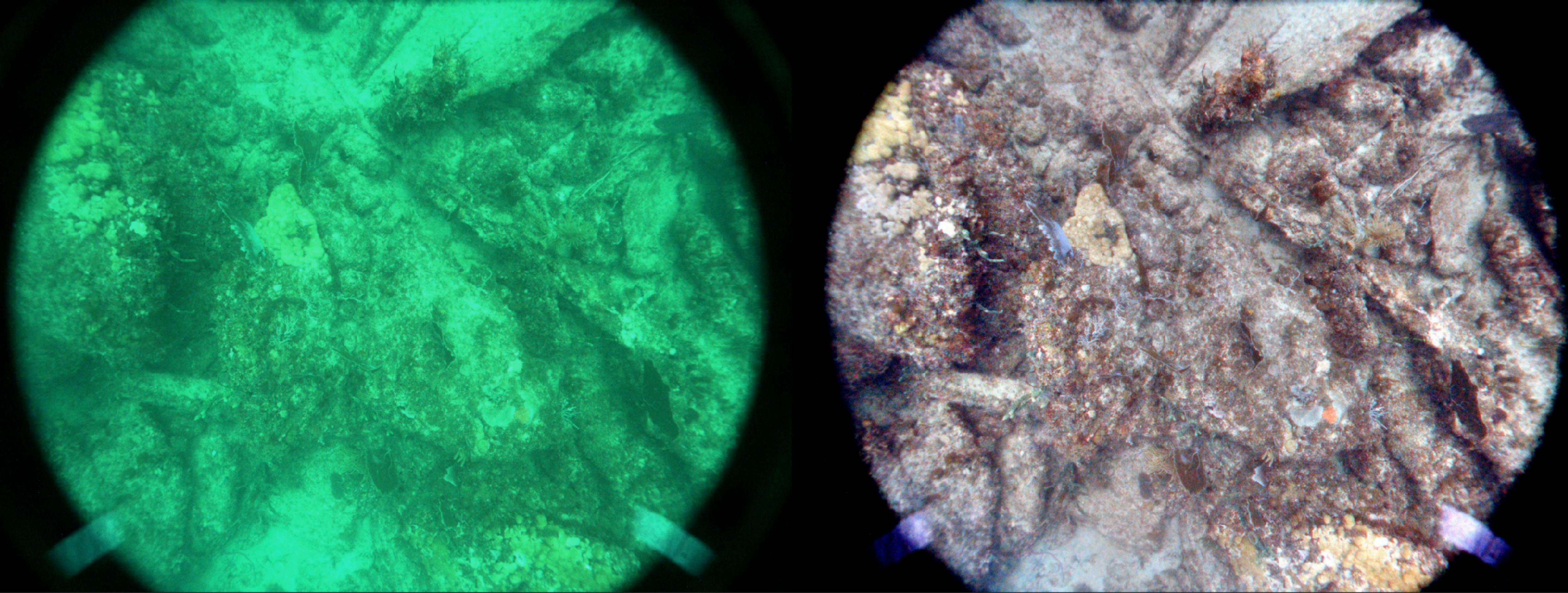
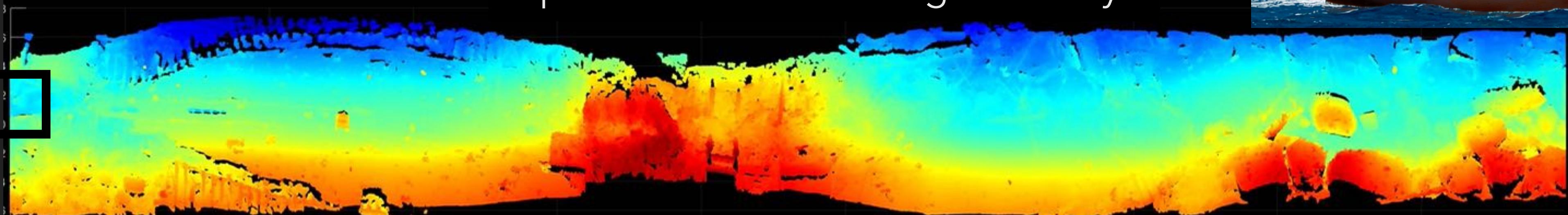
## SEA TRIALS



# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

SS Copenhagen

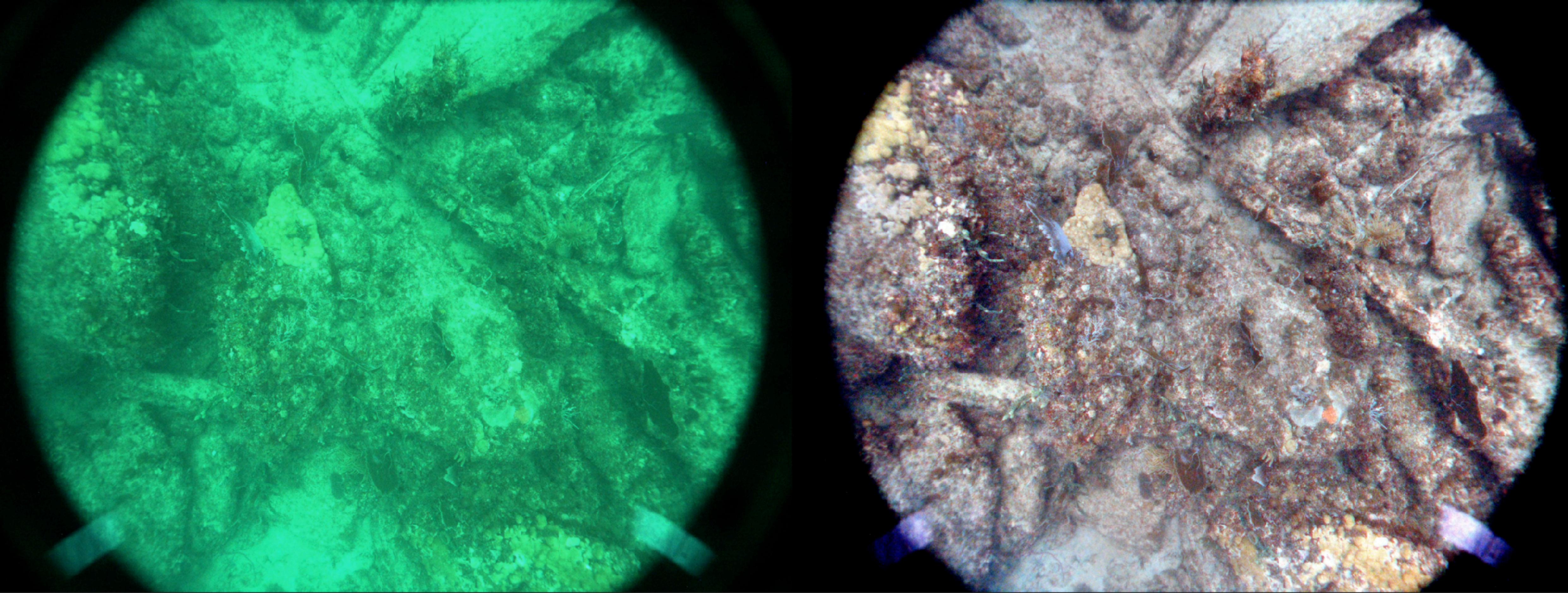
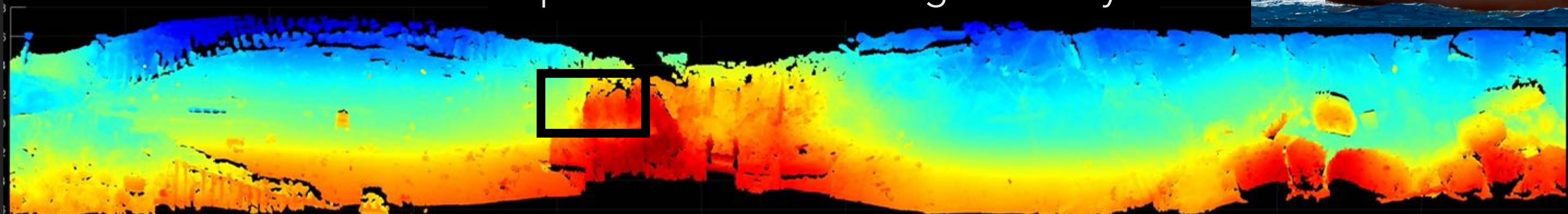
Top view of 3D with Range Overlay



# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM

SS Copenhagen

Top view of 3D with Range Overlay

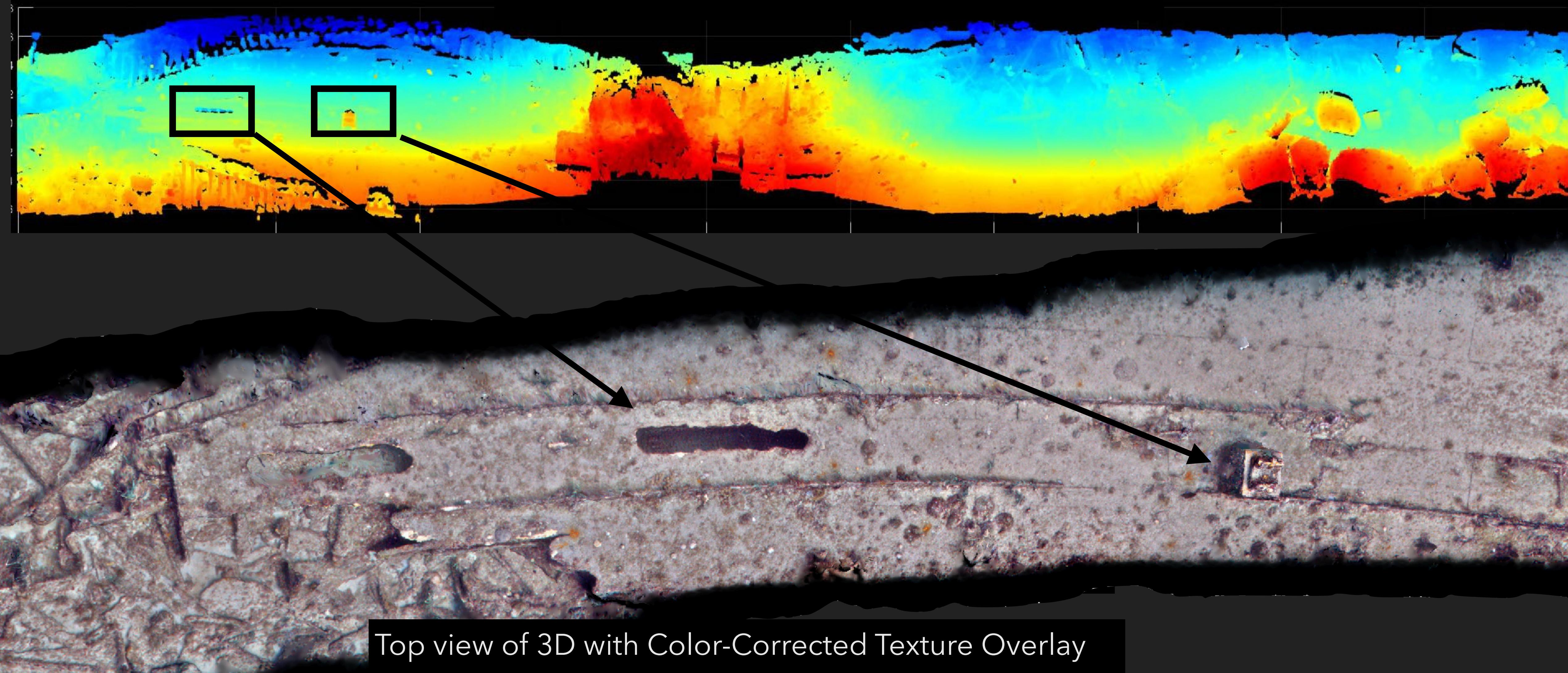


# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM



SS Copenhagen

Top view of 3D with Range Overlay



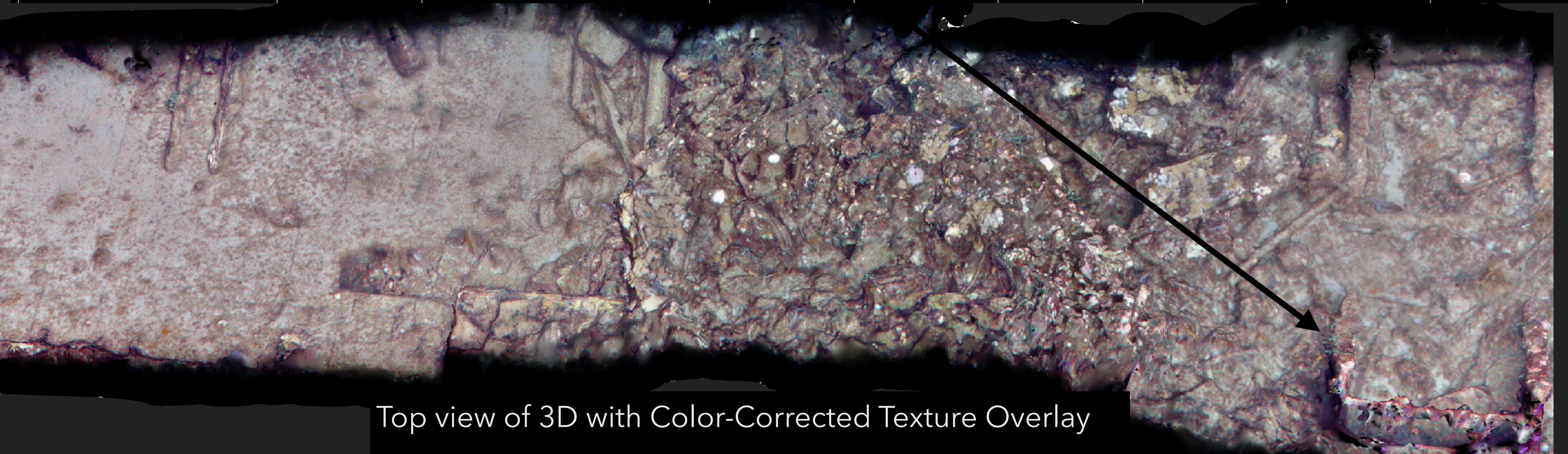
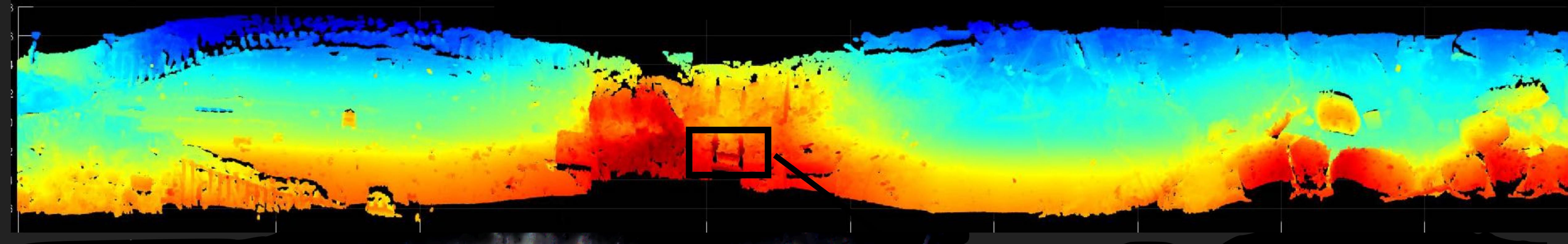
Top view of 3D with Color-Corrected Texture Overlay

# TOWARDS A LIDAR-INTEGRATED UNDERWATER IMAGING SYSTEM



SS Copenhagen

Top view of 3D with Range Overlay



Top view of 3D with Color-Corrected Texture Overlay

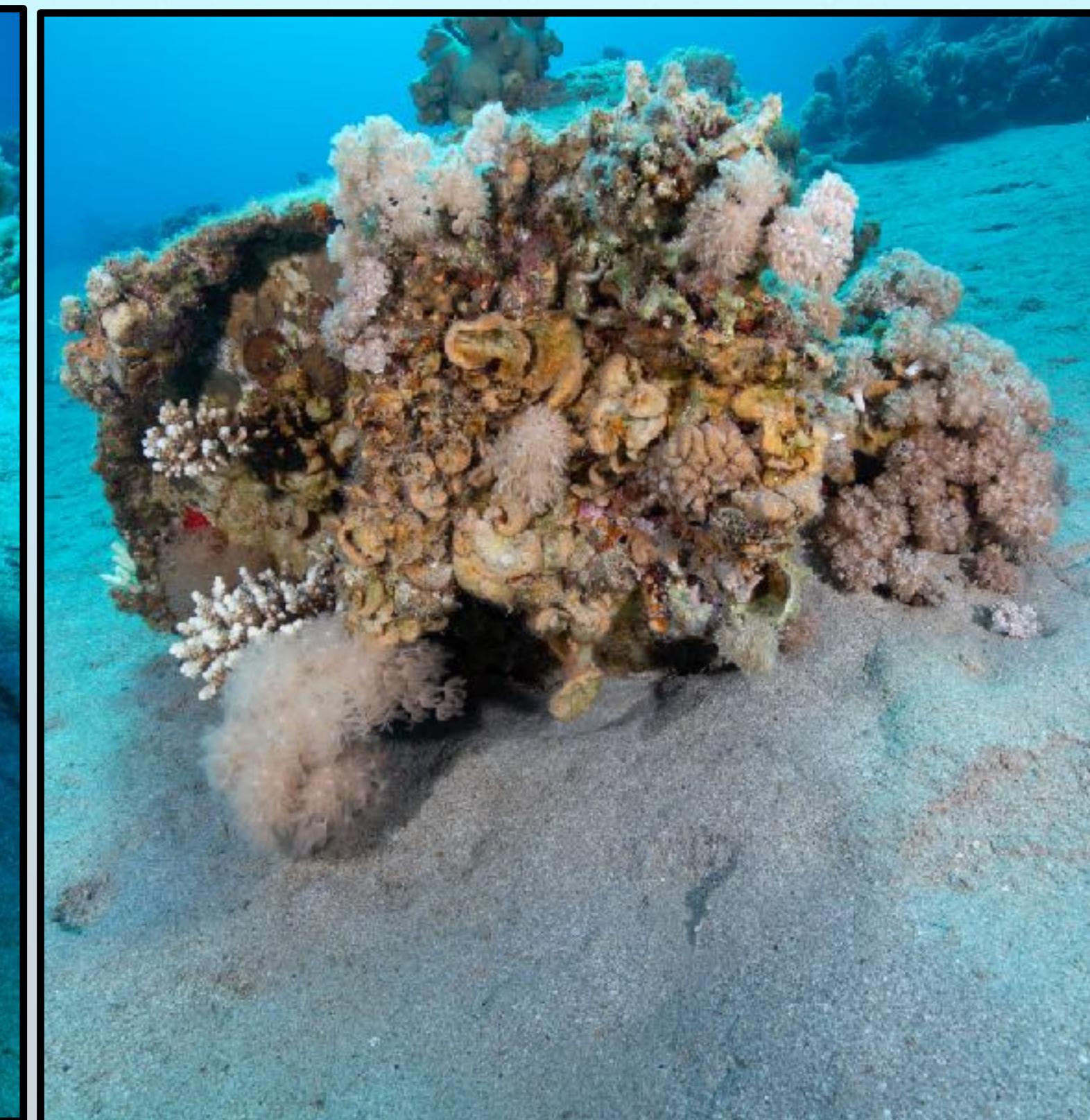
# Challenge #1

We only have an image formation model for imaging under natural light.

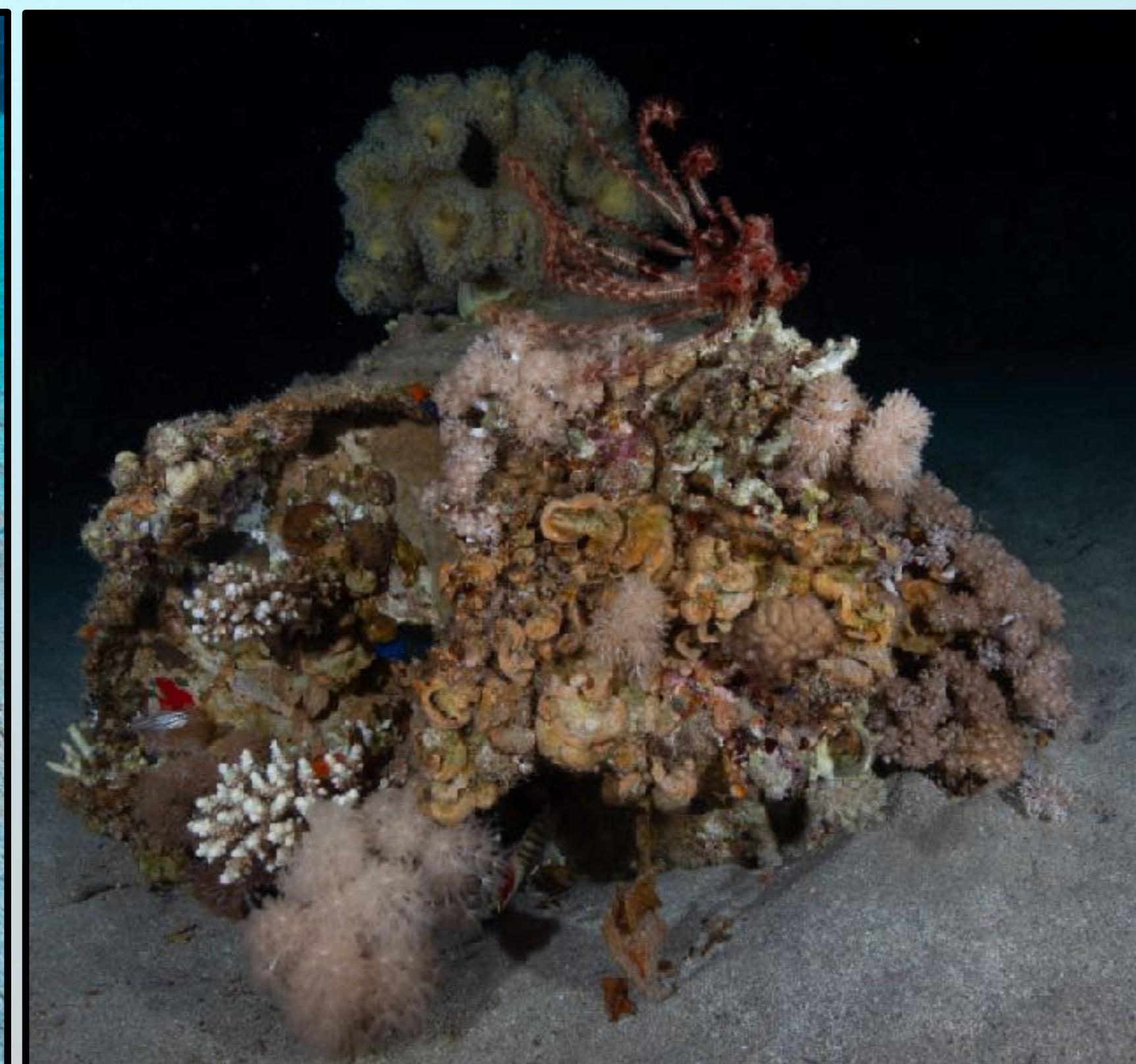
Natural light imaging



Natural + artificial light imaging



Artificial light imaging



# Challenge #2

There is no ground truth.

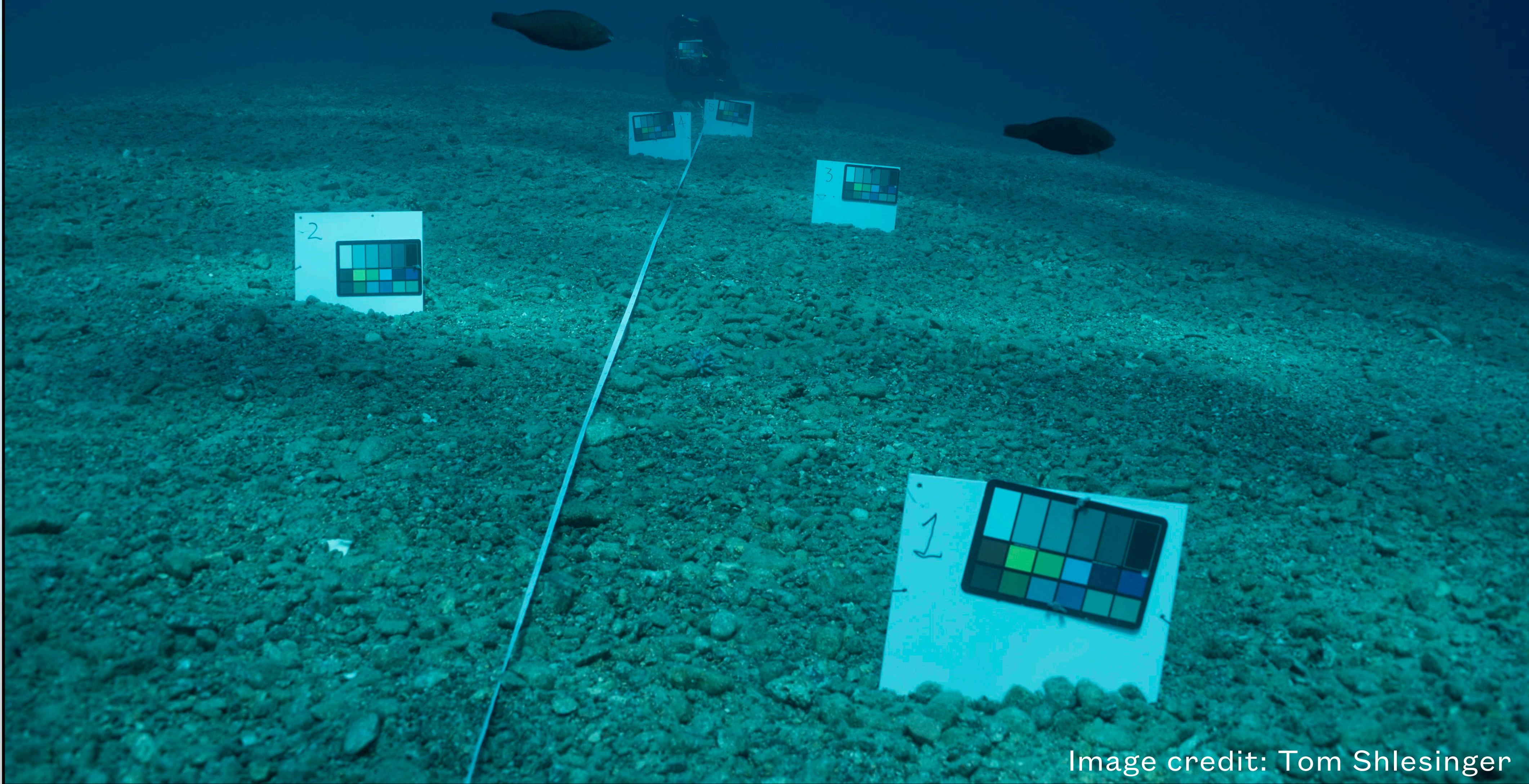
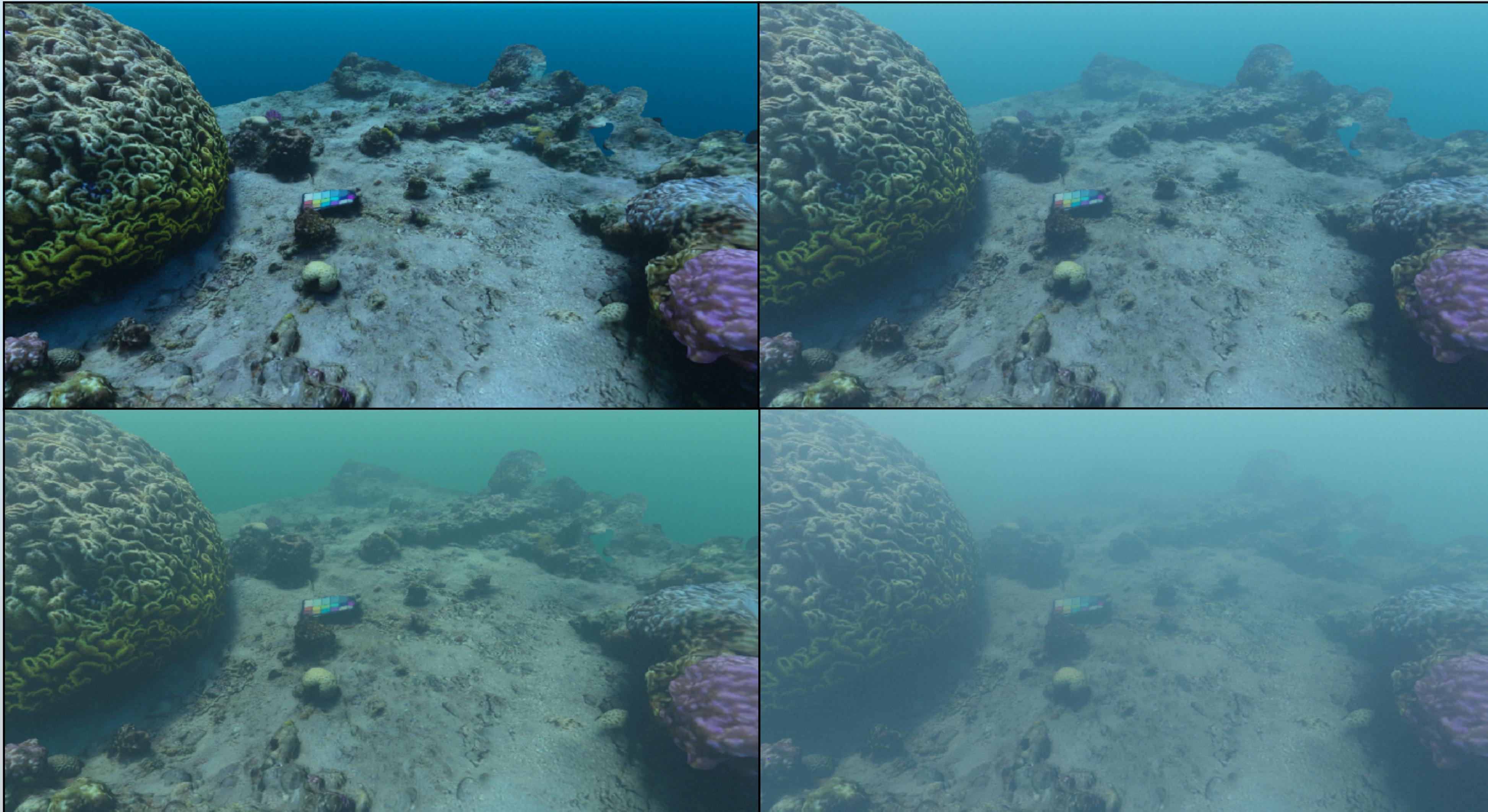


Image credit: Tom Shlesinger

# Challenge #3

Generating synthetic data is expensive.



# Challenge #4

Optical properties of water vary in space and time.



# Challenge #5

Measuring optical properties is expensive & ocean science is underfunded.



# Challenge #1

No generalizable image formation model.

# Challenge #1

No generalizable image formation model.

# + Challenge #2

No ground truth.

# Challenge #1

No generalizable image formation model.

## + Challenge #2

No ground truth.

## + Challenge #3

Generating synthetic data is expensive.

# Challenge #1

No generalizable image formation model.

## + Challenge #2

No ground truth.

## + Challenge #3

Generating synthetic data is expensive.

## + Challenge #4

Optical properties vary a lot!

# Challenge #1

No generalizable image formation model.

## + Challenge #2

No ground truth.

## + Challenge #3

Generating synthetic data is expensive.

## + Challenge #4

Optical properties vary a lot!

AI doesn't work!

# Challenge #6

Color & visibility loss depend heavily on imaging geometry (scene depth).

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**Color in clear air**

$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

# Challenge #6

Color & visibility loss depend heavily on imaging geometry (scene depth).

## Color in clear air

$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

## Color underwater

$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) e^{-K_d(\lambda)d} e^{-c(\lambda)z} d\lambda +$$

$$\frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \frac{b(\lambda) E(\lambda) e^{-K_d(\lambda)d}}{c(\lambda)} S(\lambda) (1 - e^{-c(\lambda)z}) d\lambda$$

# Challenge #6

Color & visibility loss depend heavily on imaging geometry (scene depth).

## Color in clear air

$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) d\lambda$$

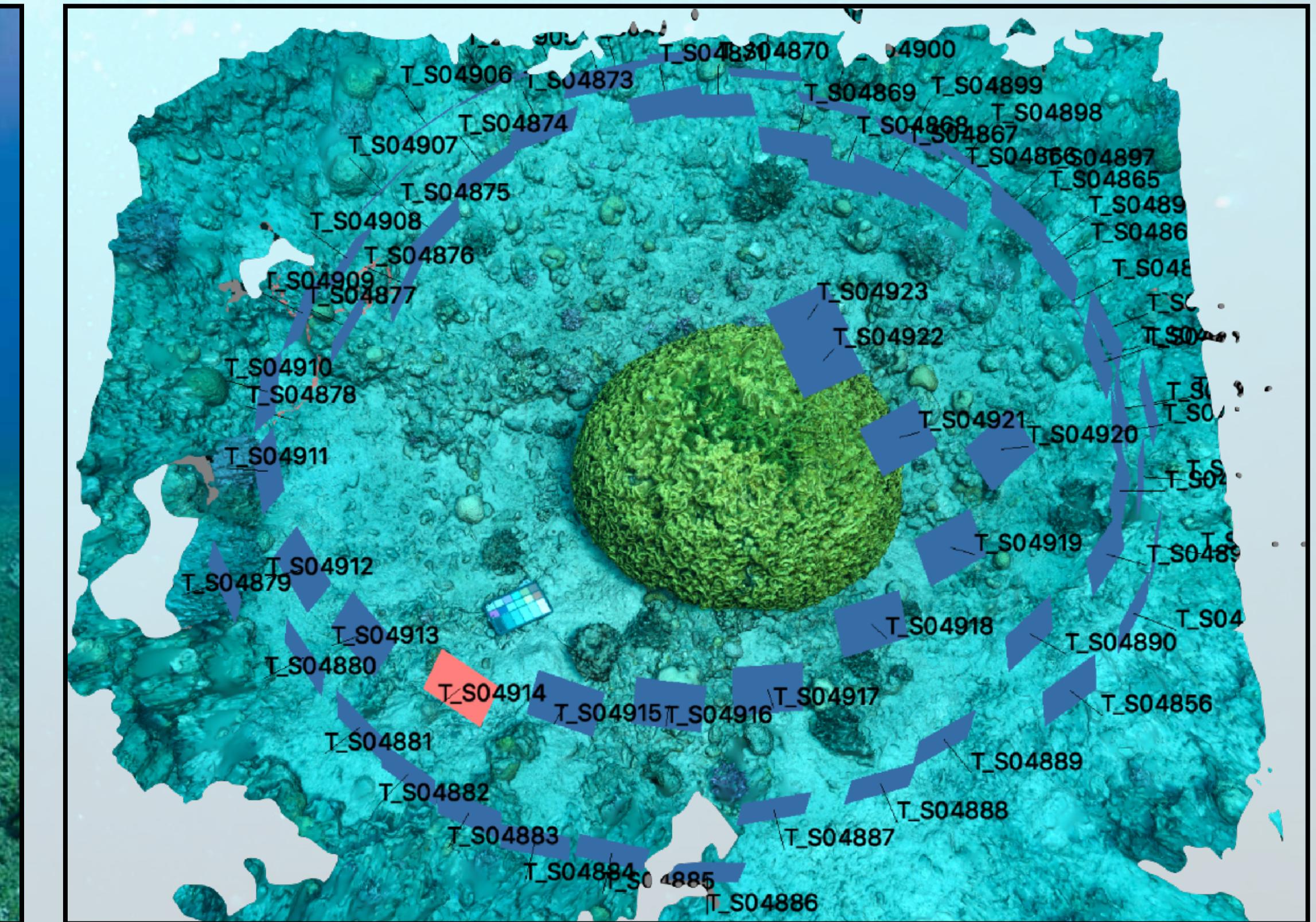
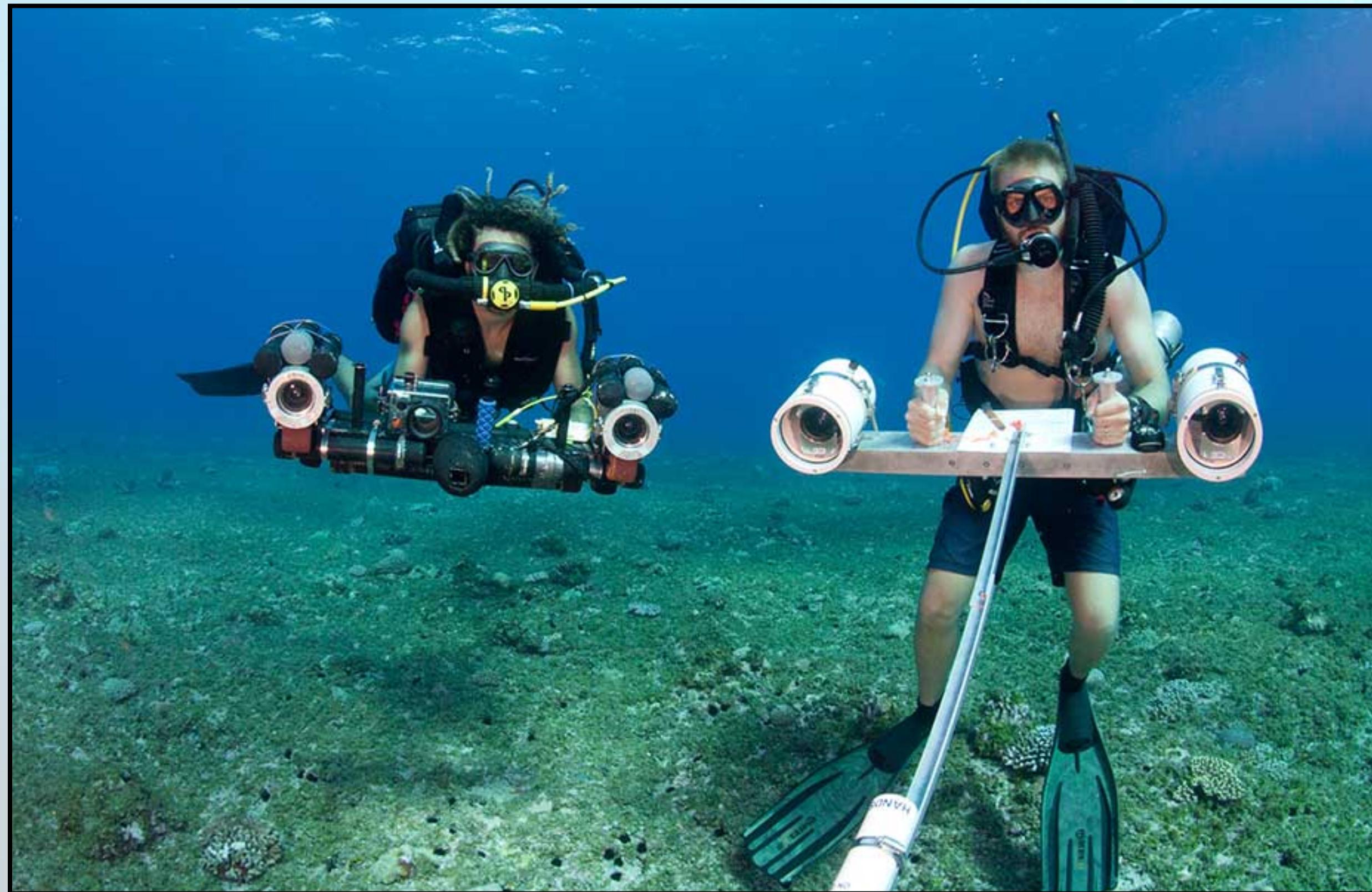
## Color underwater

$$Color = \frac{1}{\kappa} \int_{\lambda_1}^{\lambda_2} \rho(\lambda) E(\lambda) S(\lambda) e^{-K_d(\lambda)d} e^{-c(\lambda)z} d\lambda +$$

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# Challenge #7

There is no good way to get real-time scene depth underwater.



# Challenge #8

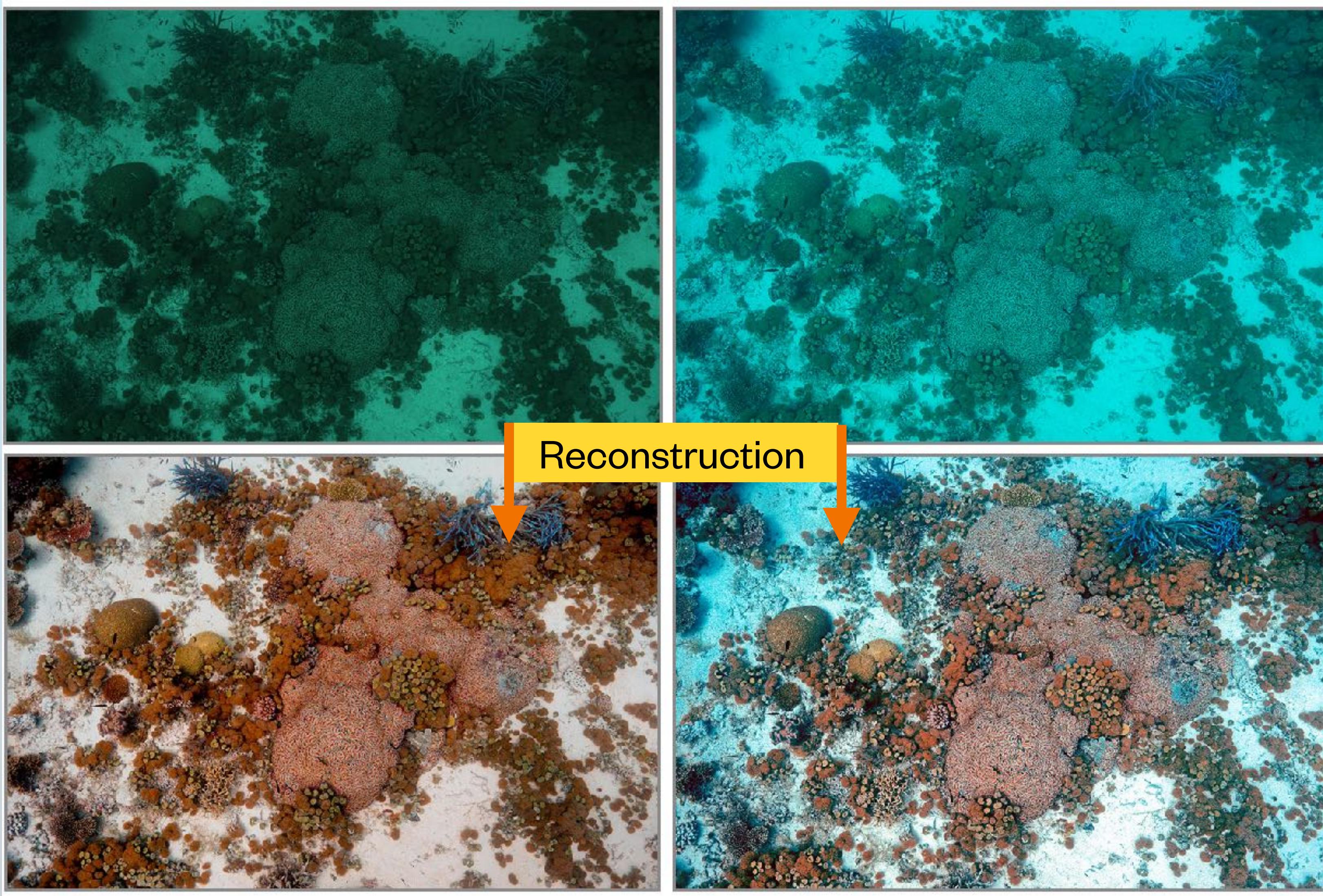
We have no understanding of color statistics of underwater scenes.



Color-corrected by Sea-thru. Original images: Tom Shlesinger & Derya Akkaynak

# Challenge #9

Proper color reconstruction cannot be done on non-linear images & video.



# Challenge #10

Semantic segmentation: even experts can't do it!

