Sea-thru: A Method for Removing Water from Underwater Images

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Motivation

- Robust recovery of lost colors and contrast in underwater images remains an unsolved problem.

3 common Failures of existing methods

Raw image | 1. Change colors | 2. Subtract incorrect backscatter | 3. Correct colors in short ranges

- A major reason behind the instabilities of these methods is the unknowing use of an image formation model formulated for the atmosphere.
- We proposed and validated a revised model derived for the ocean [Akkaynak & Treibitz 2018].

Sea-thru is the first color reconstruction algorithm that uses the revised underwater image formation model, and outperforms all existing methods that use the former model.

The Revised Underwater Formation Model
(Akkaynak & Treibitz CVPR 2018)

Nayar & Narasimhan (1999) formulated an image formation model for bad weather, commonly referred to as the atmospheric dehazing model. This model was later adapted for underwater, and it assumes:

» The attenuation coefficient β_c is constant in each color channel

» Backscatter and attenuation are governed by the same scalar coefficient.

Eq. 1 Former Model

$$\underbrace{I_c}_{\text{attenuated Image}} = \overbrace{\underbrace{J_c}_{\text{unattenuated Image}} \cdot e^{-\underbrace{\beta_c}_{\text{wideband attenuation coefficent}} z}}^{\text{direct transmission}} + \overbrace{\underbrace{B_c^{\infty}}_{\text{veiling light}} \left(1 - e^{-\underbrace{\beta_c}_{\text{wideband attenuation}} \underbrace{z}_{\text{range}}}\right)}^{\text{backscatter}}$$

This model does not hold underwater as it ignores the wavelength-dependent attenuation of light. We proposed and validated a revised model which showed:

» The attenuation coefficient varies with distance in a given scene.

» It also varies with reflectance, optical water type, and camera sensor response (these dependencies were ignored by the former model).

» Backscatter is governed by a coefficient that is different than the attenuation coefficient (the former model assumed them to be the same).

» The backscatter coefficient depends on ambient light, camera sensor response, and optical water type (these dependencies were ignored by the former model).

Eq. 2 Revised Model

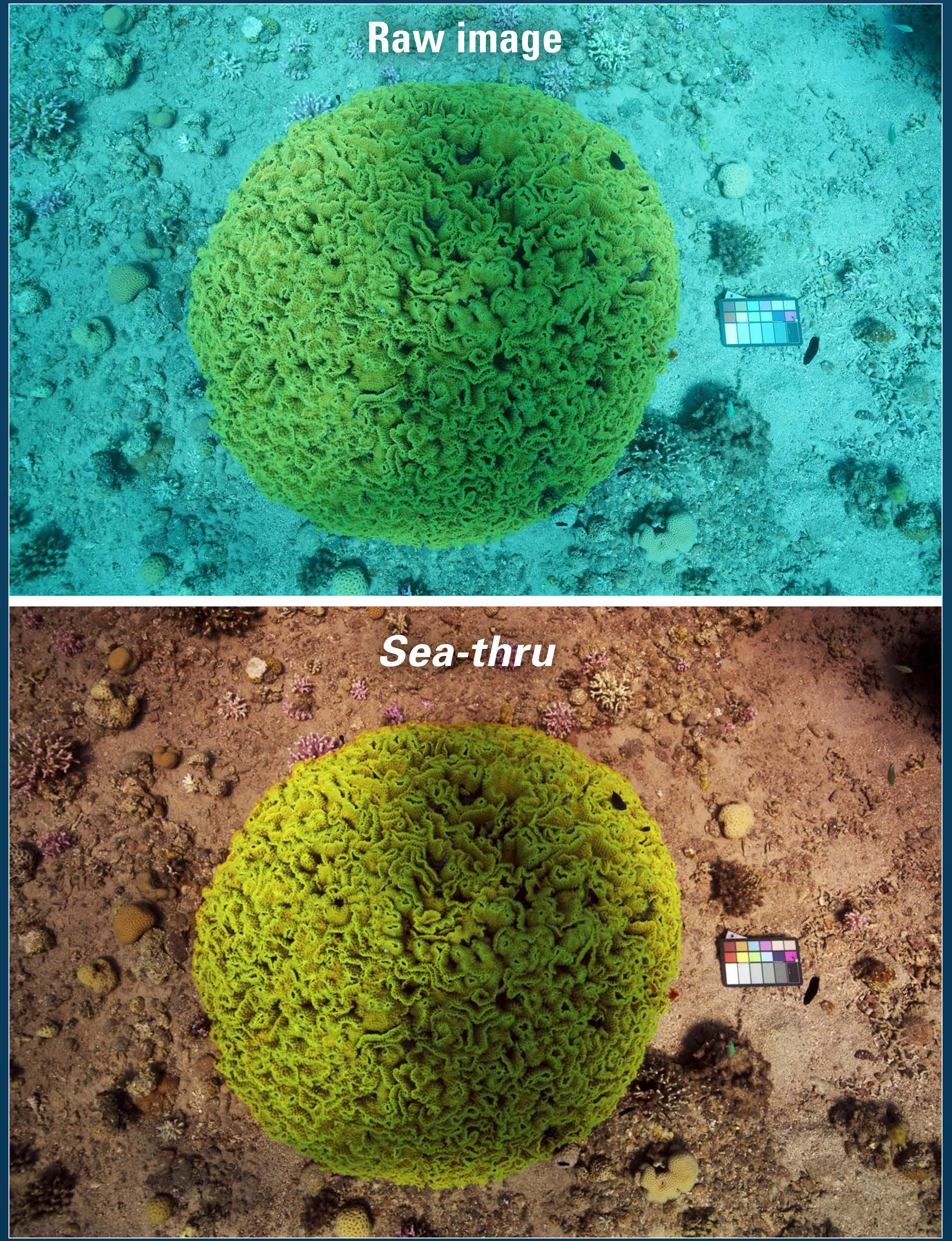
$$I_c = J_c \cdot e^{-\underbrace{\beta_c^D(\mathbf{v}_D)}_{\text{wideband attenuation coefficent}} z} + B_c^{\infty}\left(1 - e^{-\underbrace{\beta_c^B(\mathbf{v}_B)}_{\text{wideband backscatter coefficent}} z}\right)$$

$$\mathbf{v}_D = \{\underbrace{z}_{\text{range}}, \underbrace{\rho}_{\text{reflectance}}, \underbrace{E}_{\text{ambient light}}, \underbrace{S_c}_{\text{camera response}}, \underbrace{\beta}_{\text{physical attenuation coefficent}}\}$$

$$\mathbf{v}_B = \{E, S_c, \underbrace{b}_{\text{physical scattering coefficient}}, \beta\}$$

What is it?

Sea-thru is a physics-based color reconstruction algorithm designed to work on underwater RGBD images. It is a significant step towards opening up large underwater datasets to powerful computer vision and machine learning algorithms, and will help boost underwater research and exploration at a time when our oceans need it the most.



Underwater images suffer from lost colors and contrast due to the way water attenuates light, masking many computationally useful features. Taking its strength from an image formation model formulated for the ocean, *Sea-thru* removes the water from a scene, revealing the underwater world in a way we have never seen before.

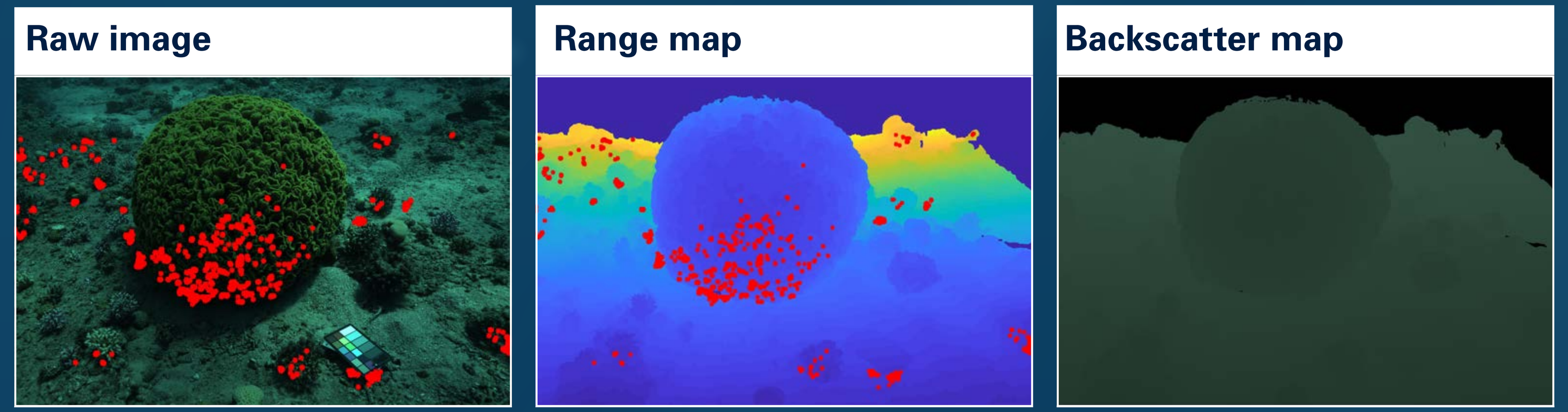
How does it work?

- The Sea-thru method requires a range map (z) for a given image. Range maps can be obtained from stereo imaging, structure-from-motion (SFM), or specialized sensors.
- We estimate backscatter by searching the image I_c for very dark pixels (reflectance —> 0) or shadowed pixels (light —> 0), since those satisfy I_c —> B_c. This way of obtaining backscatter might be subject to a small residual in the form of the direct signal, so we model it as:

Eq. 3 Backscatter Estimation

$$\hat{B}_c = B_c^{\infty}\left(1 - e^{-\beta_c^B z}\right) + J_c' e^{-\beta_c^{D'} z}$$

» We use non-linear least squares fitting to solve for B_c^{∞} and β_c^B .



* Darkest pixels used in backscatter estimation are shown in red.

- Once backscatter is subtracted and we obtain the direct signal D_c, all we need to recover the scene J_c is the attenuation coefficient β_c^D:

Eq. 4 Attenuation Coefficient Estimation

$$D_c = J_c e^{-\beta_c^D(z) z}$$

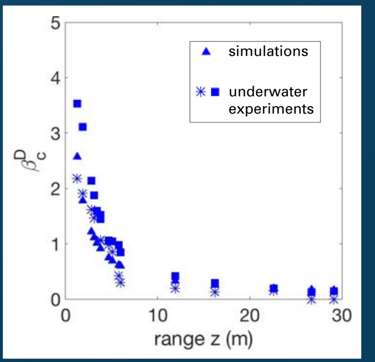
» Note here that we explicitly wrote the z dependence of the attenuation coefficient, as this is the strongest dependency revealed by the revised underwater image formation model. But how does β_c^D change with z?

- Our simulations and experiments suggest that β_c^D decays as a 2-term exponential with z:

» the former model assumed β_c^D was a constant for a given scene

Eq. 5 β_c^D as a Function of Range (z)

$$\beta_c^D(z) = a e^{bz} + c e^{dz}$$



- Next, we identify that the exponential term in Eq. 4 is nothing but the local, spatially varying illumination $\hat{E}_c$. We estimate $\hat{E}_c$ using depth-constrained version of Local Space Average Color (LSAC) by Ebner & Hansen 2013. Taking advantage of our known range map z, we minimize:

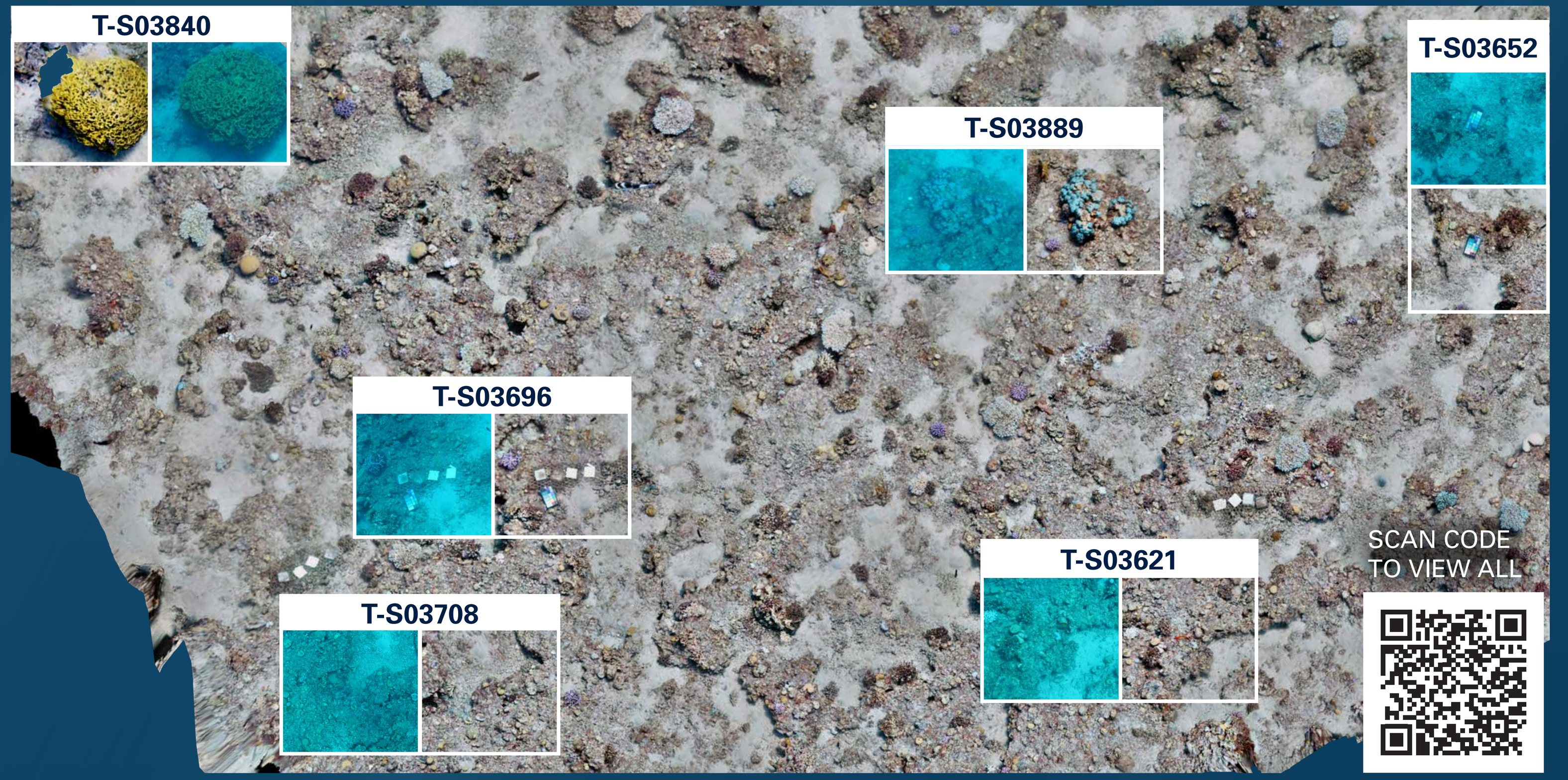
$$\min_{\beta_c^D(z)} \|z - \hat{z}\| \quad \text{where} \quad \hat{z} = -\log \hat{E}_c / \beta_c^D(z)$$

» and solve for a,b,c,d to get β_c^D (Eq. 5), and recover the scene using Eq. 4

Experimental validation

- We tested ***Sea-thru*** in three optically different bodies of water: Red Sea (very clear water), Mediterranean Sea (moderately turbid water), Molucca Sea (turbid water).

3D Photomosaic of a Red Sea reef at 10m depth



* 1,100 RGBD images were collected among five datasets.

Comparison to other methods

- We used our datasets **D1-D5**, and the stereo dataset from *Berman et al. 2018* to test ***Sea-thru*** on the following scenarios:

» **S1.** Simple contrast stretch

» **S2.** Former model with incorrect estimate of B_c, using the Dark Channel Prior method, which overestimates Bc underwater.

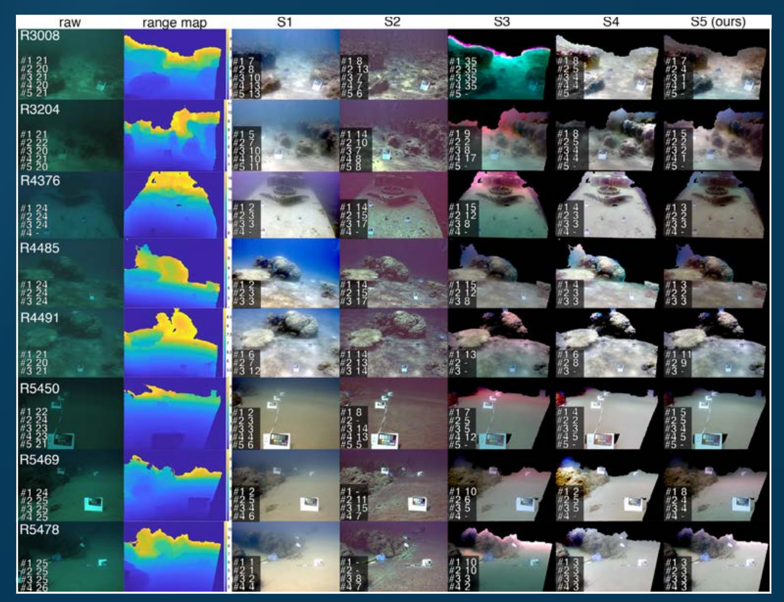
» **S3.** Former model, with a correct estimate of B_c, assuming $B_c = \beta_c^D = \beta_c^B$

» **S4.** Revised model, with a correct estimate of B_c , and J_c obtained as $J_c = D_c e^{\beta_c^{D(z)} z}$

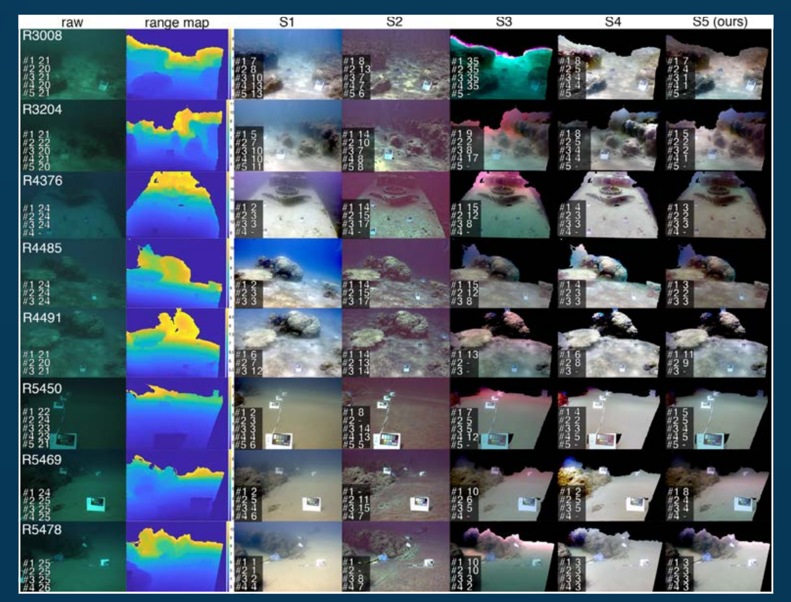
» **S5.** Sea-thru, which uses the revised model where $\beta_c^B \neq \beta_c^D$, and $\beta_c^D = \beta_c^D(z)$

- For evaluation, we used RGB angular error (in degrees, given in in inset of each image) between the six grayscale patches of each chart and a pure gray color, averaged per chart: $\bar{\psi} = (1/6)\cos^{-1}\left[I_c/(\sqrt{3}\|I_c\|)\right]$

Our dataset



Stereo dataset of *Berman et al. 2018*



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