Playing with light: optics relevant for remote sensing June 2023

1. Introduction and Lab Goals

This first lab is meant to be a fun and informative set of activities that will introduce students to nomenclature and concepts associated with marine optics. The concepts presented will provide answers to the following questions:

- What processes determine the colors we observe?
- What are absorption, attenuation, scattering, and fluorescence?
- What are reflection, diffraction, and refraction?
- What is a spectrophotometer and how does it work?
- How do we decompose white light into its spectral components?
- What is polarization and why it is useful for remote sensing?

2. Laboratory Safety Issues

There are no hazardous chemicals used in this laboratory. That said, maintain general laboratory safety protocols. This includes protecting your eyes at all times! Never look directly at the sun <http://eclipse.gsfc.nasa.gov/SEhelp/safety2.html>; never point a laser pointer at your or anyone else's face or eyes (the classic laser lab warning sign is "Do not look at LASER with remaining good eye"!); never look directly at the LED from any of our sensors. While some are visible and safe, others are close enough to UV to cause eye damage.

3. Lab directions:

This is a free-flowing lab with multiple stations designed to remind you things you already know and tease you to explore things you don't know. Choose one or two classmates and migrate through the activities. Make sure to discuss the process and results with each other. If you are not sure about your understanding of a concept, talk to an instructor.

Station 1. **Decomposing white light into its spectral components**. Relevance: many sources and detectors in optical instruments use these methods to obtain or radiate light for a specific portion of the visible spectrum.

Substation 1a. Prisms, diffraction gratings and lasers.

a. Use a prism to decompose visible (white) light into its components (use either sunlight or a flashlight). For which wavelengths (blue or red) is the index of refraction of the prism higher (the ray's propagation angle is bent the most by the prism)? This process is called normal dispersion.
b. Use a diffraction grating to decompose visible (white) light into its components using a tube with the grating mounted at one end and a slit at the other; look into the tube on the grating side. Which wavelength (short-blue or long-red) has constructive interference closest to the center?

c. Shine a red laser through a diffraction grating transmission slide onto a piece of white paper and observe the spots that form due to constructive interferences. How would the results differ for a blue wavelength? Try it. How do they differ for a diffraction grating with more/fewer lines per mm? Try it.
d. Can you think of applications for which you would want to separate light into its spectral components?

Substation 1b. Using a handheld spectroscope to qualitatively analyze the color transmitted through a substance:

a. Look through a spectroscope at white light in the lab and natural light outside (the source has to be seen through the slit; do NOT look directly at the sun!!!). Describe any observed difference in color.
b. Predict what you will see if you looked through a container of water with food coloring.
c. Test your prediction by putting a test tube of water with food coloring in front of the small slit of the spectroscope. Describe the change in the color spectrum seen. Note: the spectroscope used here is analogous to the tube used in Station 1.

Station 2. Processes that determine the color we perceive. Relevance: our eyes are very effective radiometers; we can perceive very slight changes in the color and intensity of both reflected and transmitted light as it interacts with a medium. Understanding how the processes of absorption and scattering lead to variations in perceived color can help us use our eyes (and ultimately, expensive radiometers) to discern those underlying processes and gain information about the composition and concentration of matter in the sea.

Substation 2a. Color attenuation, using red, blue, and green LED lights and containers of red, blue and green dyed water.

a. Predict which wavelengths are likely to be most absorbed in each container and which are most likely to propagate through with least attenuation.
b. Test your prediction with LED flashlights. Which colors propagate through which container? Qualitatively compare intensities of transmitted light for each combination of LED light and water color.

Substation 2b: Color of an object. Understanding what determines a color we observe is key to understanding ‘ocean color’.

Shine a red light on a ‘white’ wall. What color do you observe? Shine a white light on a red page. What color do you observe? What color will the red page have if illuminated by blue light? Repeat the above viewing the object through colored transparent papers positioned in front of your eye (the receiver).

How do the absorption by the paper, the reflection by the paper, the properties of the light source and off the receiver (your eye + filter in front of it) affect the color observed? How is this activity relevant to the color of the ocean as observed from a satellite?

Station 3. Scattering of light by particles. Relevance: scattering occurs when light traveling through one medium interacts with matter comprised of a different medium such that the light propagates with a different speed, causing it to either speed up or slow down. That change in the speed of light means that the two media have different indices of refraction, and generally causes light to change direction.

Substation 3a. Scattering of light by particles part 1.

a. Shine the laser through air at the wall. Can you see the laser beam in air (do NOT look directly at the laser)?
b. Do the same in a tank filled with tap water. Is transmission different than in air?
c. Shine the laser in a tank filled with water where a few drops of Maalox were added (Maalox contains small particles). How did the appearance of the laser change? Why?
d. Can you relate your observation to lasers shooting in space in science fiction movies?

Substation 3b. Scattering of light by particles part 2.

a. Shine the laser at carbohydrate beads in air.
b. Shine at the laser at these same beads in water after they have swelled up (grown by absorbing water).
c. Which scatters more light: the swelled or upswelled beads?
d. Why do you think there is a difference?
e. These beads in water are a great analog for phytoplankton in the ocean; they are particles that are filled with their surrounding medium. Their other component than water are actually made of materials with highly different index of refraction than water (e.g. sugars, lipids, silica etc'). What does this tell you about how phytoplankton scatter light?

Substation 3c. Index of refraction matching.

a. Put a dry glass rod in water. Can you see it?
b. Now, wipe the rod and put it in a glass with mineral oil. What happened to the rod?
c. What is different about water versus mineral oil and how did it impact your ability to see the glass rod?

Station 4. Remotely observed color. Relevance: the intensity of light emitted from water is proportional to scattering and inversely proportional to absorption (for a given intensity of impinging light).

Fill the containers to about 700 ml with tap water.

a. Analogue to deep ocean color: Add about 20 drops of green food coloring into the container with a black bottom. What color is the water when viewed from above?
b. Add Maalox into the colored water. What color is the water when viewed from above?
c. Now repeat this experiment (same amount of water and drops of color and Maalox) in a tank with a reflective bottom. How is it different from the previous one? How might it be related to the concept of optically deep and optically shallow waters (waters where the bottom contributes to space-based observation of color)?

Station 5. Fluorescence. Relevance: fluorescence the phenomenon whereby a material absorbs light at one range of wavelengths and emits light at another, less energetic, wavelength range (called the Stokes' shift). A few well-known, fluorescing compounds include some phytoplankton pigments, such as chlorophyll a, and some components of organic matter, such as tryptophan and tyrosine. Fluorescence is a powerful tool for quantifying the concentration of fluorescing compounds.

Substation 5a. Fluorescence emission of a column with different fluids

a. For each column with fluid, shine white light at the column. What is the color of each fluid?
b. Shine UV light at the column by sliding the switch of the light below the columns to the left. Does is the color of each fluid change?
c. Think about the light that your eye is detecting, describe the direction of the light source compared to direction of the light coming to your eye. How does that explain the differences in color?

Substation 5b. Fluorescence emission of spinach extract.

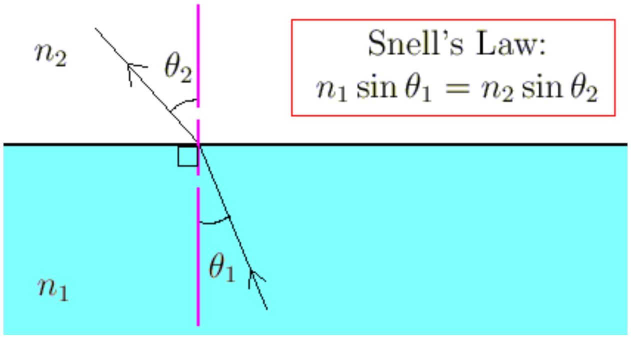
Observe the color transmitted through a spinach extract in 90% acetone. What does the color tell you about its absorption properties?

a. Shine a violet laser at the extract and observe the light emitted. What color do you observe?
b. Hold the red filter between the light and the spinach extract. Observe the light emitted at a 90° angle and place a blue filter between the tube and your eye. What color do you observe?
c. Now reverse the position of the filters (blue filter between light and spinach extract; red filter between extract and your eye). What color do you observe?

d. Can you use this observation to design an instrument to measure the concentration of a fluorescing pigment?

Station 6. Refraction, reflection, diffraction. Relevance: Conceptualizing the different ways particles scatter light leads to a better understanding of how a measurement of scattering is decomposed into these different processes and further into how to use scattering measurements to gain information about particles. When sunlight crosses interfaces between two media of different indices of refraction (see station 3), such as the air/sea interface or from the water/sensor interface (or the water/eye interface), the speed of light changes and the beam is refracted (bent) through the interface and reflected from the interface. This process impacts how light penetrates into the medium (e.g., sunlight from atmosphere into the ocean), and in the case of sensors, the acceptance angle of detected light as well as how light traverse from source to medium through a window and from this medium into the detector.

Substation 6a. Refraction of waves passing through media with different transmission properties.



Shine a laser pointer into the center of the side of the water tank (do NOT look directly into the laser). Observe the angle change due to refraction.

a. At which angle does the light beam change direction the most?

b. Which angle gives the least effect?

c. What is the maximum angle for the light beam in the water?

d. Through the sides of the tank, shine the laser towards the air from the water side. You will observe that at some angles the light completely internally reflects, no light passes the interface. This process is called *total internal reflection*. This angle, called the critical angle, defines a circle for an observer looking at the water surface from below beyond which (that is, at higher angles of observation) all the light comes from below the surface.

A diver looking at the ocean surface from below will see a circle separating light coming mostly from above the surface and light at higher angles of observation reflecting down from below the surface (Fig. 1).

Fig. 1 Snell's circle as viewed by a diver (http://www.bsoup.org/Beginners_Portfolio/2005/BP2005.php).

e. Still shining the laser up through the side of the tank, rotate the laser by 90 degrees. How does the intensity of the beam coming out of the water change? (to explain this observation, you will need to know something about polarization, which you will examine in Station 7).

Substation 6b. Refractometer. A refractometer is a device used to infer properties of a material by looking at the angle light refracts as it passes through the material. The refractometer you will use is designed to provide estimates of salinity (the amount of dissolved salts).

a. Put a drop of fresh water on the refractometer and read the salinity by looking through the refractometer.
b. Repeat with a drop of salt water from the dock. What is the approximate salinity at the dock?

Note: the ratio of the indices of refraction of two media for a given wavelength is inversely proportional to the ratio of the speeds of light in both media. In which medium does light propagate faster: Water or air? Fresh water or salt water?

Substation 6c. Diffraction.

a. Direct the laser pointer at a white wall and turn it on. Observe the shape of the beam where it reflects off the wall.
b. Examine your hair – it is about 100 μm in diameter. In a moment, you will place a hair between the laser and the wall so that it crosses directly through the

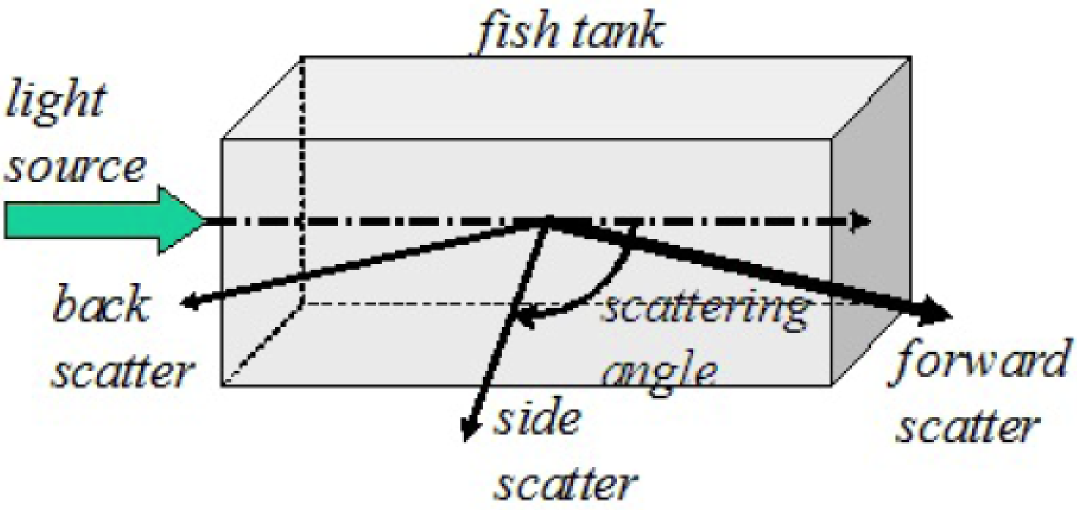
beam. Before doing so, predict how the shape of the beam's reflection on the wall will change with the wire running through the beam.

c. Place the wire so that it intersects the laser beam. How do your observations compare to your prediction?

Station 7. Polarization. Relevance: polarization describes the orientation of propagating electromagnetic waves. Scattering and reflection affect the polarization state of light interacting with matter. Polarization is a relatively new frontier in ocean optics and has been shown to be useful to avoid glare (the basis for polarized sunglasses) in remotely sensed imagery and to help characterize the composition of particulate materials in the ocean.

Substation 7a. Scattering of a light beam.

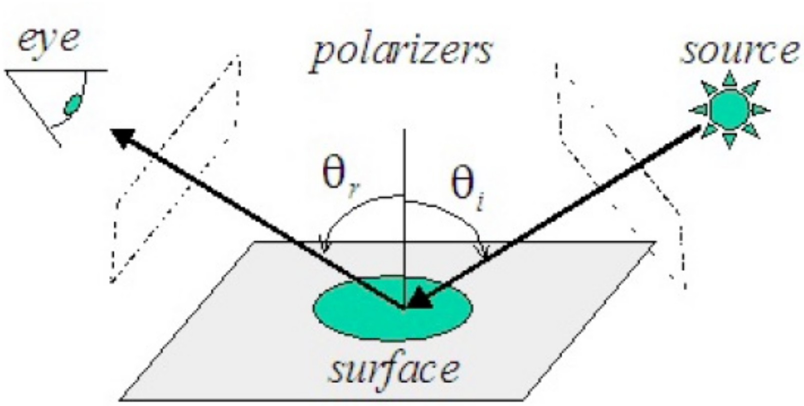
a. Shine a collimated light source (comprised of parallel beams) through the sides of an aquarium. Add a few drops of Maalox and observe the intensity of the beam as function of scattering angle (relative to the direction of propagation, see diagram) and azimuth angle. How does the intensity change?



b. Now hold a linear polarizer to your eye and observe the beam at the 90° scattering angle while rotating the polarizer on its axis. Does the intensity change with the axis of your polarizer? Now observe the beam from other scattering angles. How does the relative change in intensity (between the two axes of polarization) vary with scattering angle?

c. Do the same experiment but with a laser as the light source. Observe the beam through the polarizer from a 90° scattering angle as you rotate the laser on its axis (shining in the same direction). Can you explain the observation given the fact the laser is linearly polarized?

Substation 7b. Reflection from surfaces. Look at the specular reflection (reflection off an interface, like a mirror) of a collimated, unpolarized light from a smooth, non-metallic surface (e.g. plastic, wood, or water). View the surface through a linear polarizer.



a. How does the intensity vary with the direction of the polarizer?

b. What if you use a polarizer in front of the source before it interacts with the surface?

c. How different are the results for a metallic surface?

Station 8. **Converging and diverging lenses.** Relevance: imaging systems and instruments often require that the source and receiver optics need to be collimated (propagating in nearly parallel lines) or that the light needs to be redirected (e.g. to a detector). Lenses provide a means to do it with little loss of energy.

a. Shine two laser beams through a lens onto a white paper (or wall). Can you make their beam converge at a single location?

b. Change the relative position of source and lens and see how the image size is affected.