Underwater Time-of-Flight Camera

Joshua Thomson, John Will, Dr. Luke Rumbaugh

Department of Electrical and Computer Engineering,

Grove City College, Grove City, PA 16127

Abstract: Grove City College researchers are collaborating with the Navy (NAWCAD, Patuxent River, MD) and Clarkson University (Potsdam, NY) in investigating the use of time-of-flight (ToF) cameras in underwater environments. This summer, GCC researchers built a novel underwater ToF camera and tested it in the water tank laboratory at Clarkson. Images were taken in both clear water and turbid water. The resulting images were processed in several different ways in order to provide high quality images even when the images had low illumination levels or significant backscatter. Notable findings from this work include: quantifying the accuracy of the ToF camera's distance measurements as a function of image brightness; developing an effective fixed pattern noise filter that removed noise while preserving image features; showing that turbid water images have multipath interference; demonstrating that image averaging techniques cannot replicate the image quality provided by long image illumination times; and observing that the scatter components of an image change with modulation frequency.

Background: Time of Flight Cameras for 3D Imaging

When used above water, ToF cameras typically use infrared light to create 3D representations of a scene such as the point cloud seen in Figure 1. They are being rapidly adopted for navigation, mapping, and 3D modeling because they are small, inexpensive, and fast, and they output 3D data directly. However, the infrared light typically used cannot travel through water efficiently. Green light travels through water with less attenuation, motivating development of an underwater ToF camera that uses green lasers for illumination.

Figure 1. Motivation for a green-laser ToF camera for 3D imaging underwater. *Left:* A 3D point cloud image of a student in our lab taken by an infrared ToF camera. *Middle:* A brightness image of a partially submerged ruler taken by an infrared ToF camera. The ruler is bright in the air but dark in the water, showing the attenuation of infrared light in water. *Right:* An image of a white star target illuminated by green laser light. This image was taken by a regular camera and shows that green light can be readily used to illuminate objects underwater.

Experimental Results: Amplitude and Range Images in Clear Water

GCC's green ToF camera recorded both amplitude and range images of the submerged plate target shown in Figure 4. Several aspects of camera performance were tested. Images were taken at a variety of illumination levels, water turbidities, optical configurations, and modulation frequencies. Figure 5 shows a typical pair of amplitude and range images recorded in clear water. The amplitude image shows the reflected brightness for every pixel, while the range image shows the distance to the reflection for every pixel. Figure 6 shows how the depth image measurements vary as the object is moved along the tank. The distance to the submerged object as shown in the depth image is plotted versus the known object distance. For this high-illumination scenario, the measured distance tracks the actual distance well, with an accuracy of $\pm 2\%$.

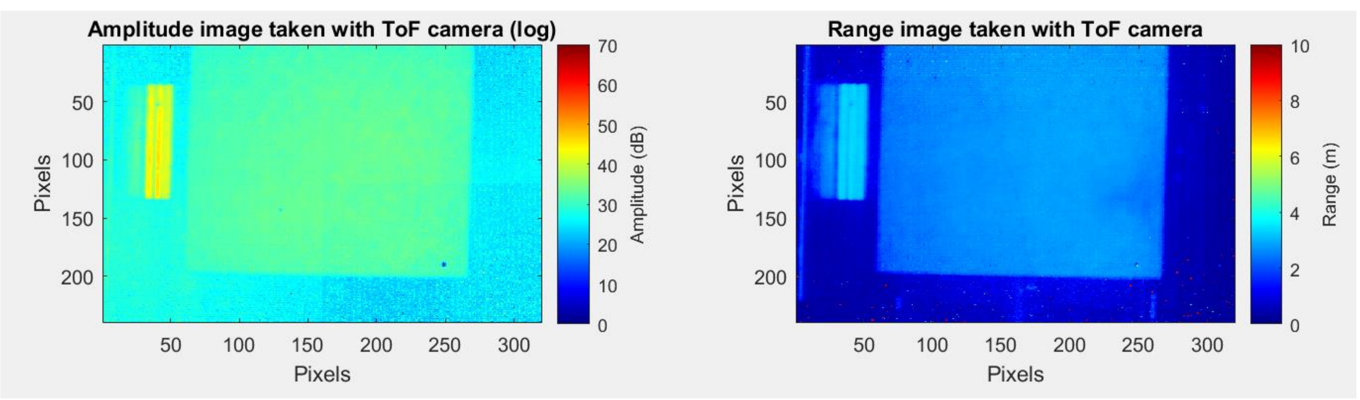

Figure 5. Typical images taken by the camera. *Left:* Amplitude image showing the brightness of each pixel. The square gray object shows up as clearly brighter than the dark back of the tank. A shiny metal piece to the left of the gray object is brighter still. *Right:* Range image showing the distance to each pixel. The object is correctly shown to be located 3 m away.

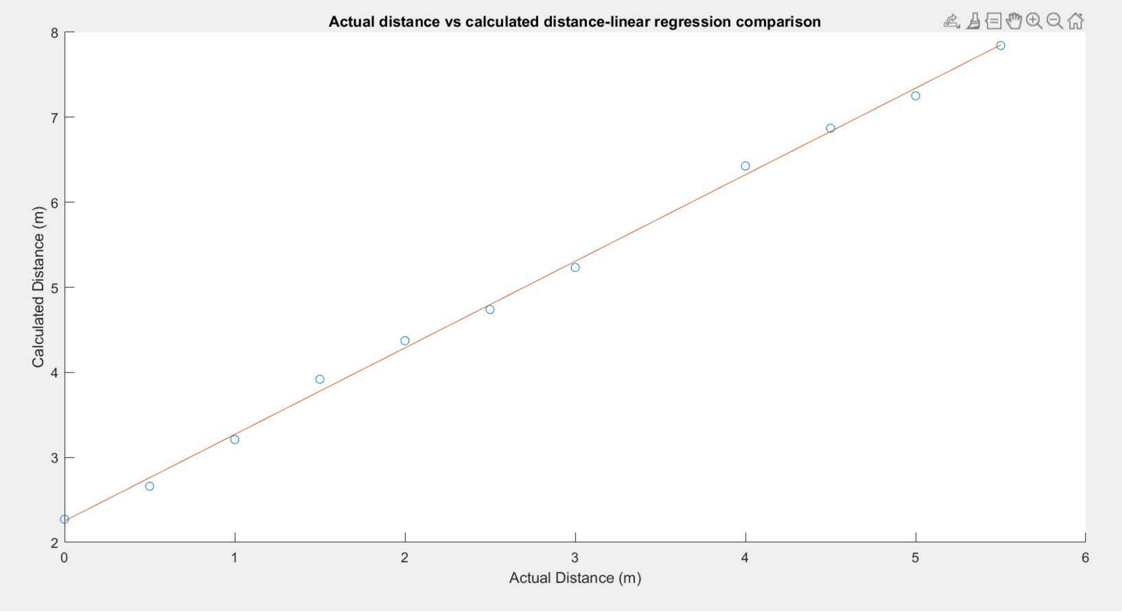

Figure 6. Measured distance of the submerged object versus actual distance. The blue points are range measurements, while the red line is a linear trend.

Experimental Setup: Testing GCC's Underwater ToF Camera at Clarkson University

A green-laser ToF camera for 3D imaging underwater has been in development at Grove City for the past few semesters, as seen in Figure 2. Last year, a prototype was used in field tests in local waterways. This summer, we built a 3-laser version of the camera and brought it to Clarkson University's water tank lab. We performed experiments using the setup outlined in Figure 3. Figure 4 shows the Clarkson tank, which is designed for careful underwater optics experiments. The tank is 24' x 6' x 6' and has an overhead motorized gantry on which a target can be suspended and moved. The tank also has filtration systems and attenuation meters that allow the water turbidity to be carefully changed and measured.

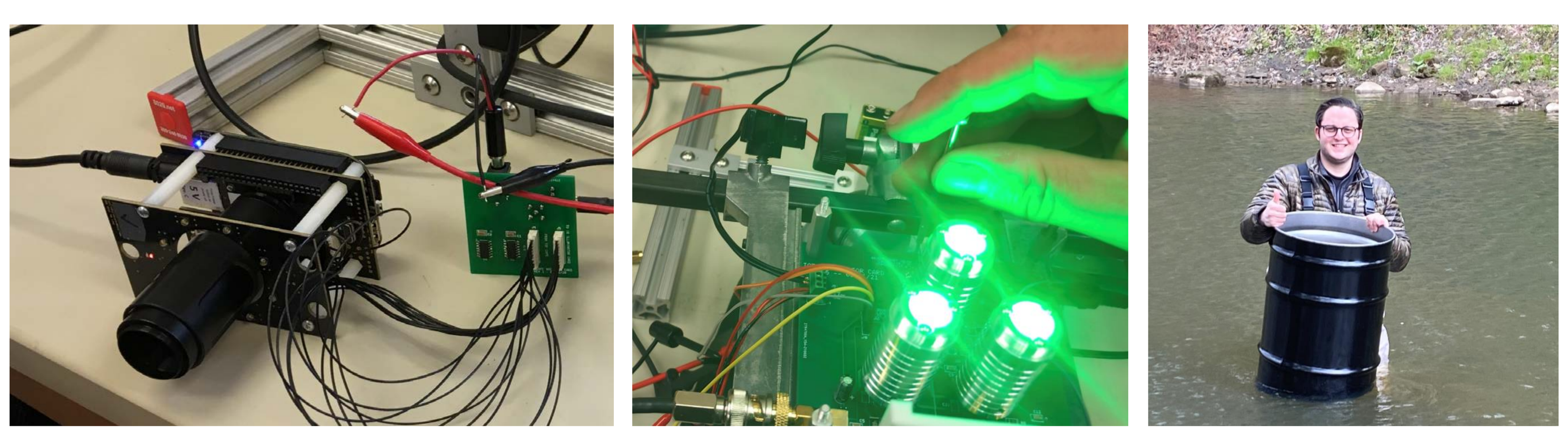

Figure 2. Custom underwater ToF camera developed at GCC. *Top:* The camera is a modified version of the Espros EPC660 evaluation kit. *Middle:* A custom PCB interfaces the camera to 3# 525 nm laser diodes. *Bottom:* Previous GCC researchers have used the camera for field tests in local waterways. Here, Armand Ignelzi operates in Wolf Creek.

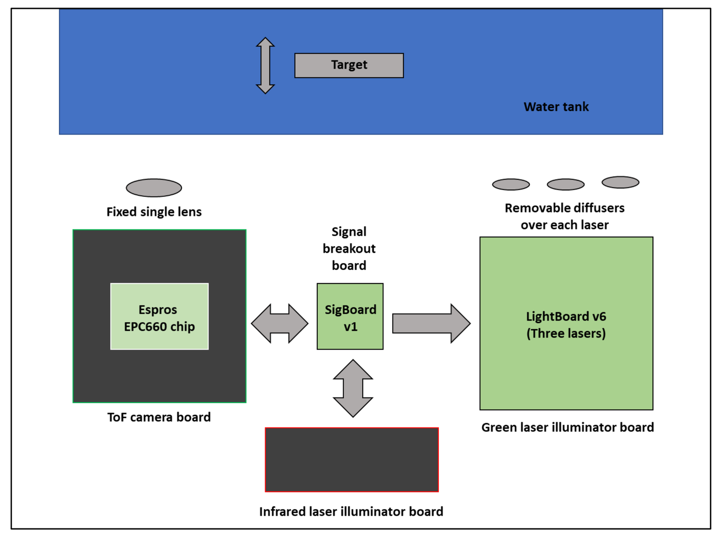

Figure 3. Block diagram showing how the ToF camera illuminates a scene using three green lasers, and observes the scene using the Espros ToF camera sensor.

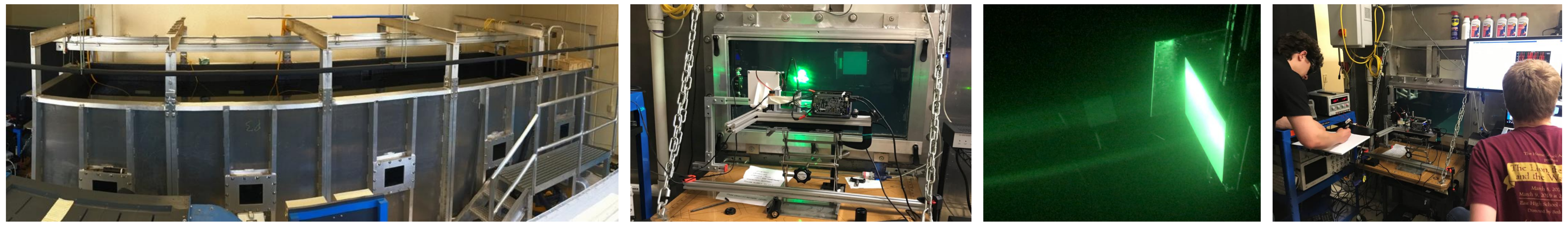

Figure 4. Experimental setup in Clarkson's underwater optics lab. *Left:* The 24' long water tank. *Middle left:* The input window at the end of the water tank, through which the camera can illuminate and observe submerged objects. The ToF camera is shown mounted on the aluminum frame. *Middle right:* Overhead side view of the submerged gray target illuminated with green laser light. *Right:* John and Josh record data and capture images using the ToF camera.

Experimental Results: Analysis and Image Processing

Several important trends were identified in the data. Figure 7 shows what happens when the image brightness is reduced. The image loses features, exhibits strong fixed pattern noise (FPN), and eventually is lost in the noise floor. Moreover, the accuracy of the distance measurements degrades as the brightness falls. Figure 8 shows how FPN was reduced in a low-illumination image. While not shown, we also noted that image averaging cannot make up for low illumination time, turbid water images exhibit multipath interference effects, and the backscatter from a laser beam seems to have different distance measurements depending on modulation frequency.

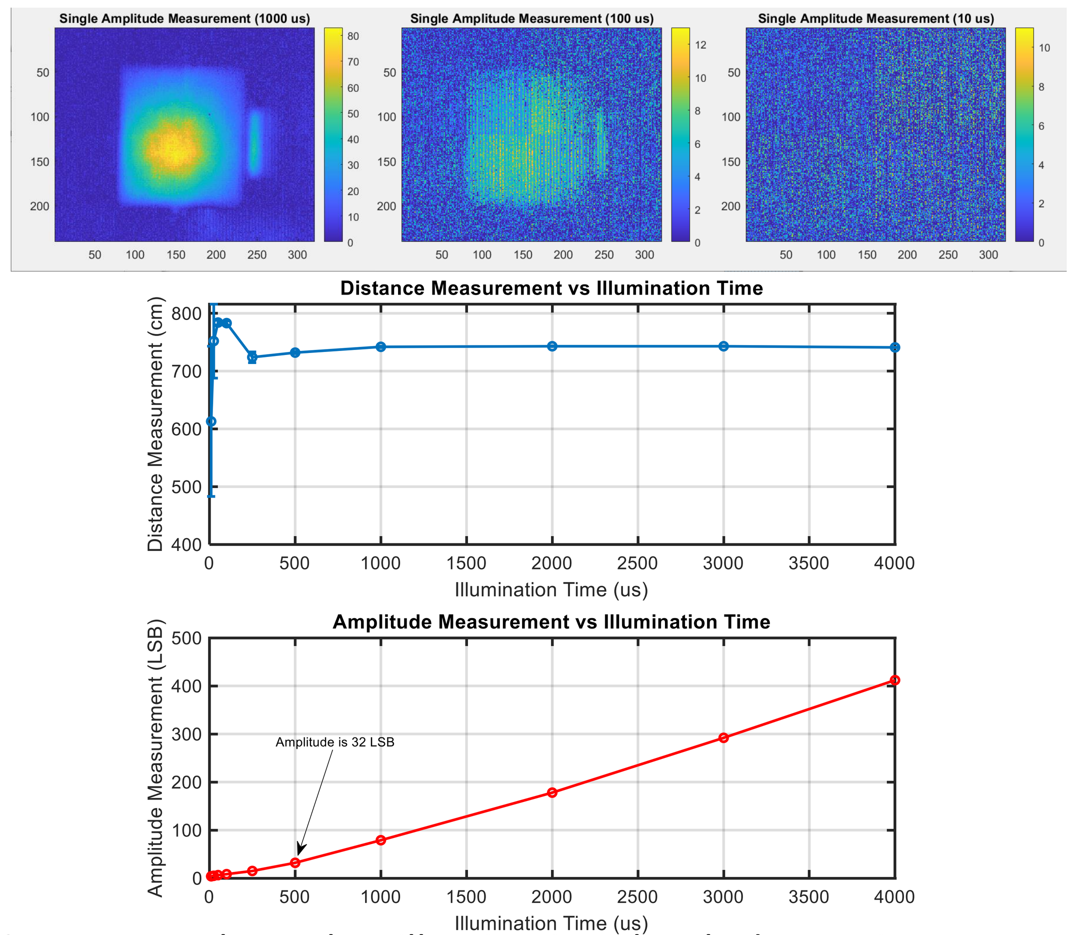

Figure 7. When the illumination level drops, image quality and distance measurement accuracy both suffer. *Top left:* With an exposure time of 1000 μs, the object is seen clearly. *Top middle:* When the exposure time drops by 10x, object features are lost and a strong FPN appears. *Top right:* When the exposure time drops by another 10x, the object disappears. *Right:* The amplitude is linearly related to illumination time, as might be expected. But while the distance measurements are accurate at high illumination times, they become erratic at low illumination levels. Eventually, they are no longer usable.

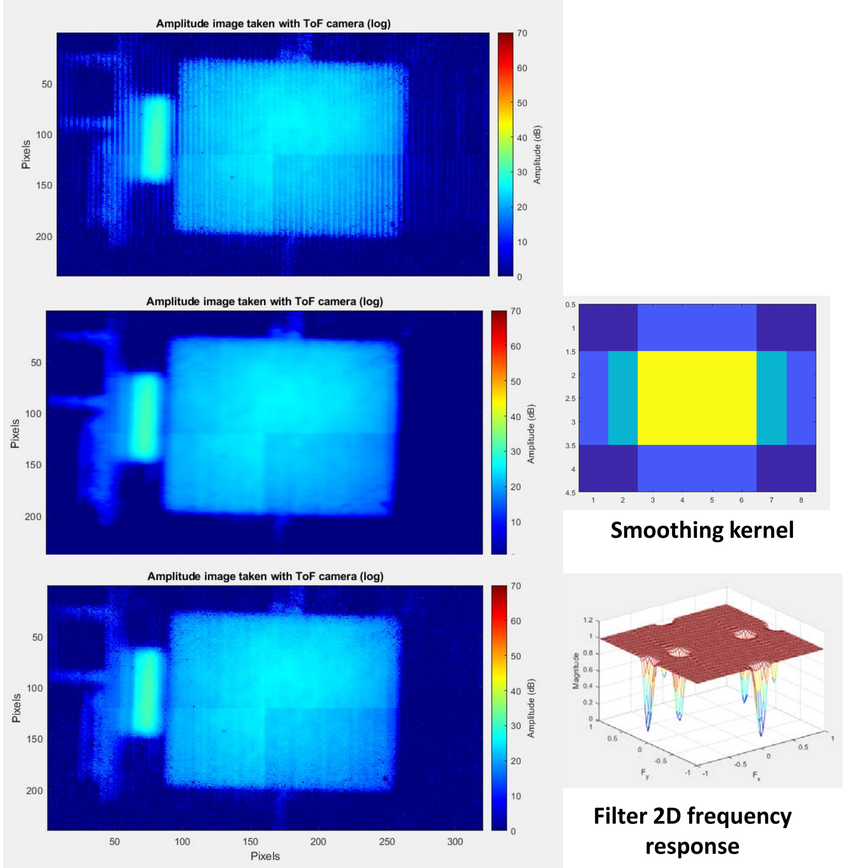

Figure 8. Removing fixed pattern noise (FPN) from low-illumination ToF images. *Top:* Raw image with vertical banding FPN. *Middle:* Conventional image filtering could be used to smooth the image, but features are lost. *Bottom:* A 2-D frequency domain FIR filter was designed and used to reduce FPN without losing image feature clarity.