Underwater Time-of-Flight Camera for Remotely Operated Vehicle Applications

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Abstract: Grove City College researchers have worked on developments in the use of a time-of-flight (ToF) camera for 3D imaging aboard underwater vehicles. We have modified a commercial camera for use underwater with green illuminators and have packaged and deployed this camera as payload aboard a BlueROV2. We describe the system hardware, including the 525 nm laser diode illuminator modules, the signal breakout board, and the wide field of view optics. We also show imaging and ranging results from laboratory and field tests with the 3D camera and discuss the challenges introduced by absorption and scattering in turbid water. We show preliminary results from a method for improving imaging in turbid water via backscatter subtraction.

Background: Time-of-Flight Cameras for 3D Imaging Underwater

Time-of-flight (ToF) cameras are finding many applications as 3D mapping, navigation, and modeling tools. These cameras simultaneously generate amplitude and depth images by measuring both the reflectivity and distance of every pixel of every frame. ToF cameras are particularly well suited for deployment on small vehicles because they provide video frame rates, centimeter depth resolution, and ambient light rejection, with low computational burden and a small footprint.

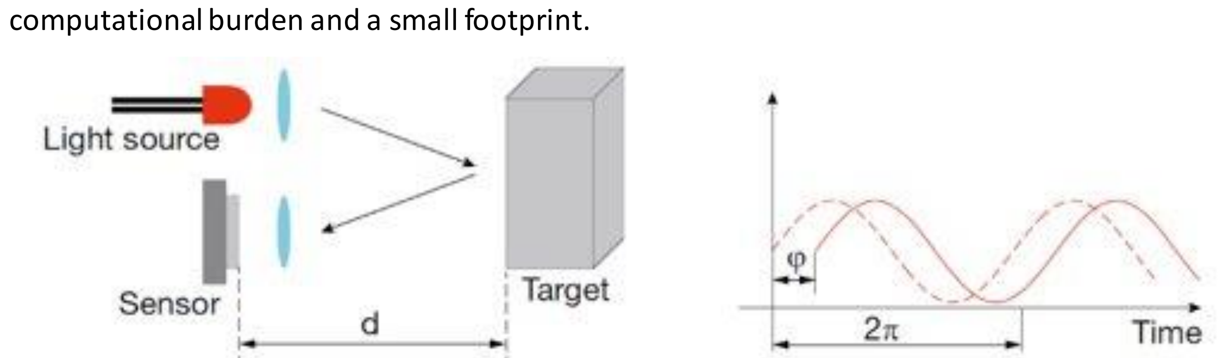


Figure 1. Indirect ToF measurement using phase of intensity modulation from Osram, "ToF Measurement using Pulse Lasers"

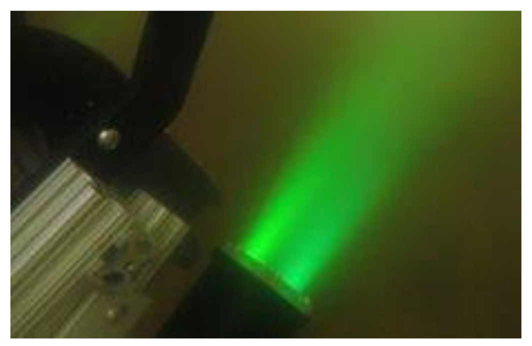


Figure 2. An image showing a green laser illuminating in turbid water.

The initial obstacle preventing underwater use is that most ToF sensors are designed to use infrared light. Previous work on this project has demonstrated the use of green lasers and modified camera optics to allow underwater imaging. Previous work has also shown that the next challenges are low signal-to-noise ratio (SNR) due to the low power density per pixel when using flood illumination. In turbid water, this SNR problem worsens due to absorption, while range errors develop due to multi-path interference (MPI) from scattering particles

System Testing

The first field test of the ToF system deployed on the ROV was performed in a pool to establish a clear water benchmark and confirm depth accuracy (Figure 5). In this experiment, a diver was positioned at varying distances away from the stationary camera. The diver moved throughout the full range of the camera operating at 24 MHz.

Next, a more quantitative distance test was performed in a laboratory water tank. Images were taken of a diffuse white object in clear water, and the measured distance to the object was compared to the actual distance to the object (Figure 6). The turbidity of the water was then increased using liquid antacid. Distance is given in attenuation lengths "cz", *i.e.* the product of the distance *z* and the 532 nm exponential attenuation coefficient *c* of the water as measured by a Sea-Bird Scientific c-star transmissometer.

A field test was also performed in which we attempted to image a Secchi disk in a highly turbid lake to get another view of the effects of backscatter (Figure 7). In this case, the return from the object and the return from the backscatter sum at each pixel. When the object return is strong, as in the image of the disk close to the camera, the object return dominates and the Secchi disk pattern is visible (albeit blurred). When the object return is weaker, the backscatter return dominates and the Secchi disk pattern is not clear. Moreover, the distance measured is actually *closer* to the ToF camera when the object moves away, because the camera is primarily measuring the distance to the backscatter.

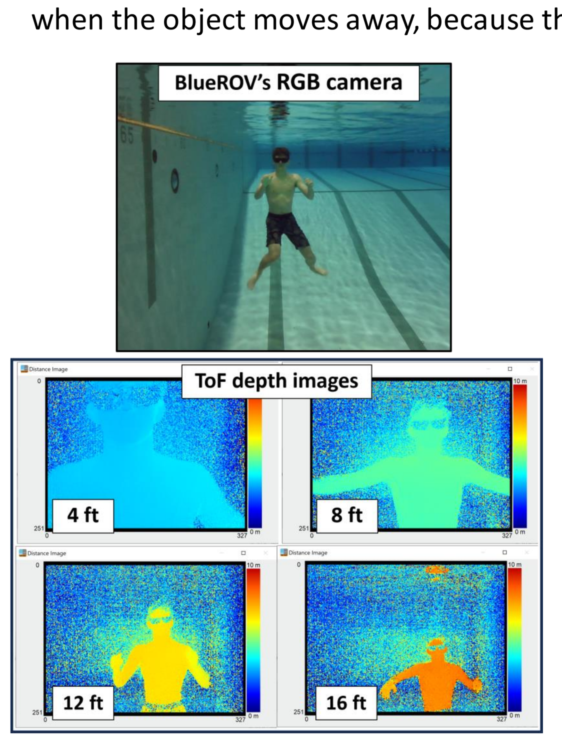


Figure 5. Clear water images from testing in pool. *Top:* Establishing shot of swimmer with BlueROV's RGB camera. *Bottom:* Depth images taken with ToF camera at various distances. The swimmer's color changes with distance.

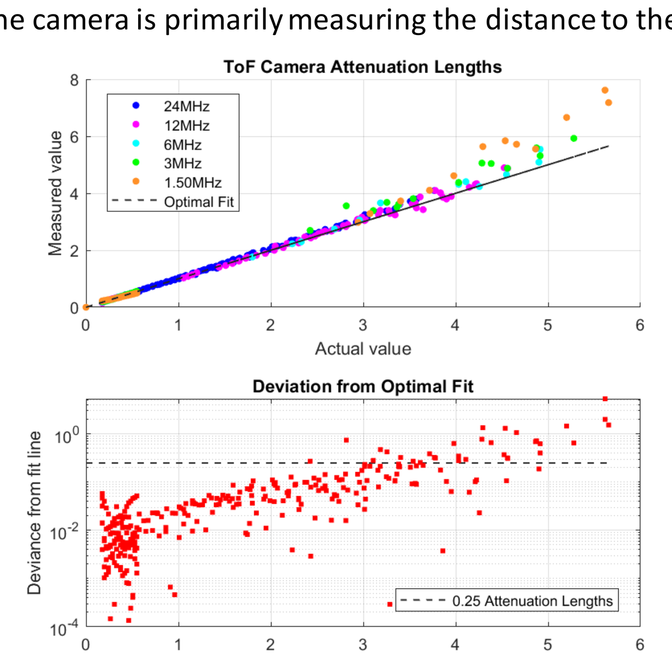


Figure 6. Test of distance accuracy imaging a diffuse white object in increasingly turbid water. Illuminator modulation frequency is varied and the exposure time is fixed at 4 ms. *Top:* Measured distance versus actual distance of a single pixel on the object. *Bottom:* Error in distance measurements. The data trends show that all frequencies increase in error as turbidity increases. There are different slopes for different frequencies, perhaps indicating that backscatter's effect differs with modulation frequencies.

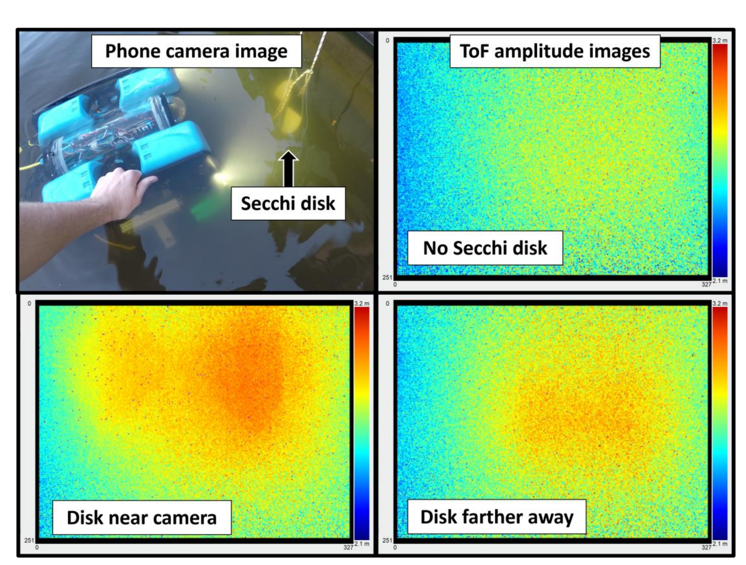
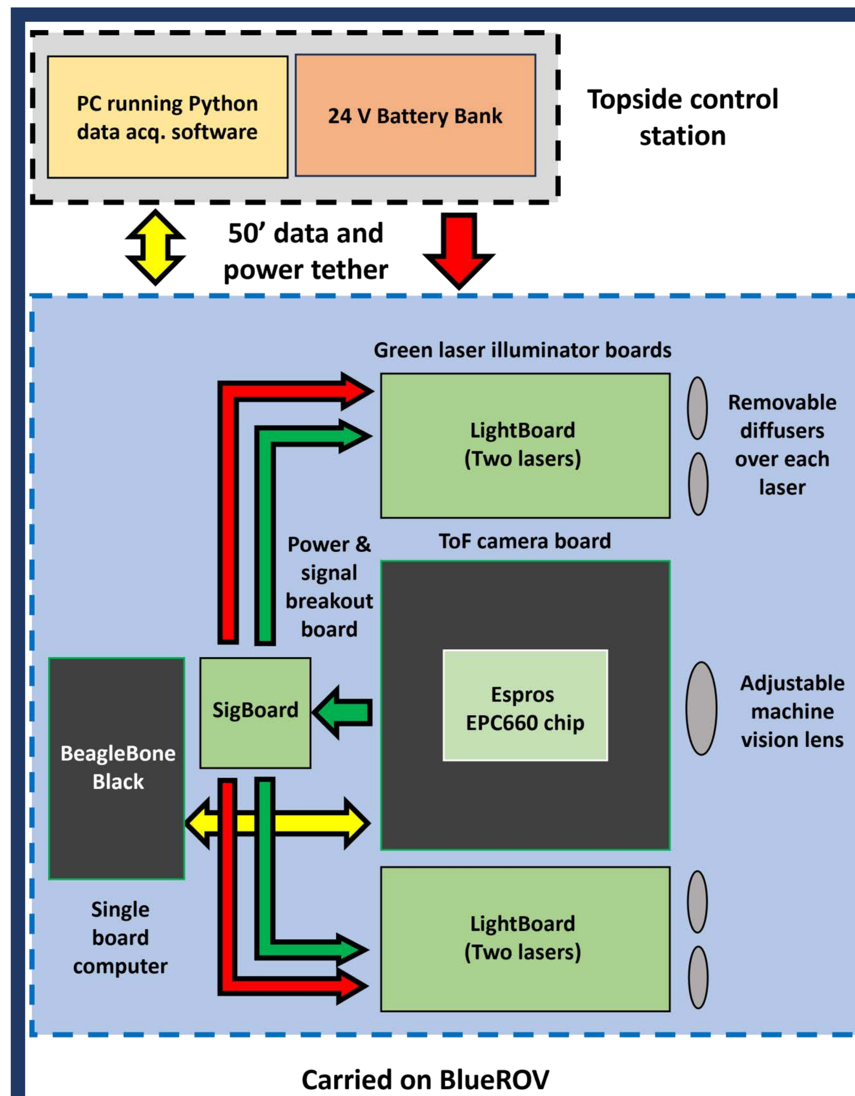


Figure 7. Scatter-limited imaging in turbid water. *Top left:* Establishing shot of system on ROV imaging a Secchi disk. *Top right:* ToF camera amplitude image when Secchi disk is removed. This image is only backscatter. *Bottom left:* Amplitude image when Secchi disk is placed at 3' away. The object region appears farther away (redder) than the backscatter, since the object is behind the center of the volumetric backscatter. *Bottom right:* Amplitude image when Secchi disk is placed at 4' away. The object region appears closer than it did at 3' away, since the distant object's return is now weaker relative to the closer backscatter.

Camera System Design



Our underwater ToF camera is built around an Espros EPC660 evaluation kit. The stock EPC660 kit uses infrared (IR) lasers for imaging and uses bursts of continuous-wave (CW) intensity modulation of up to 24 MHz. Since IR is quickly absorbed by water, we use green light instead of IR in order to use the EPC660 sensor underwater. To do this we first removed the sensor's IR filter and disabled the kit's IR lasers. We then routed the camera's laser drive signal through the "SigBoard" to two green laser illuminator "LightBoard" modules, each loaded with two 525 nm green lasers. We use the kit's existing BeagleBone Black single-board computer with the Espros API to provide an Ethernet connection to the camera. Power and control of the camera are provided by a topside control station over a wired tether. A Python data collection program running on the PC interfaces with the BeagleBone to control the camera.

The submersible packaging of the camera and illuminator modules is designed for deployment on a Blue Robotics BlueROV2. The camera stack is enclosed in a 6" PVC tube fitted with end caps containing laser-cut acrylic windows. The two illumination modules are attached to 3D-printed sleds inside of aluminum tubes and are mounted on either side of the camera enclosure.

Figure 3. ROV-mounted time-of-flight system block diagram. Connection arrows are color coded by signal type: yellow for digital data, red for power flow, and green for laser timing.

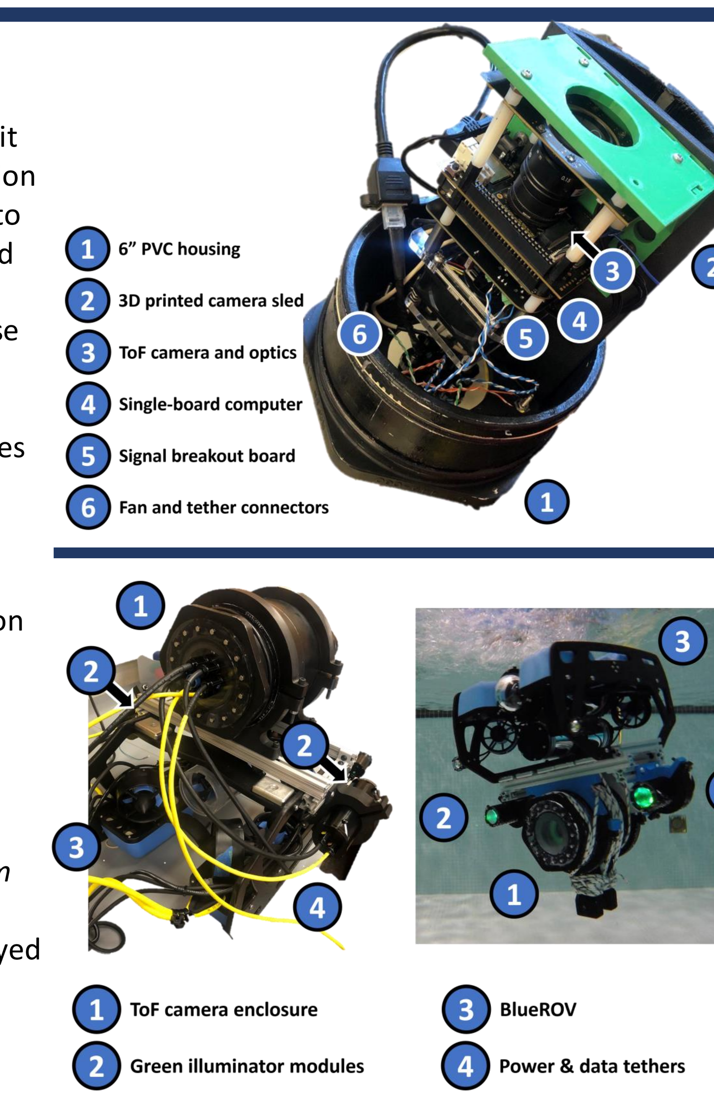


Figure 4. *Top:* Camera electronics tube. *Bottom Left:* Benchtop assembly, with the BlueROV upside down. *Bottom Right:* ToF system deployed in pool.

Backscatter Removal

Previous work indicates that homogeneous, statistically stationary backscatter in turbid water can be treated as a competing clutter "object" interfering with submerged objects and can be removed to a large extent using a phasor backscatter subtraction method. We performed a laboratory water tank experiment with the ToF camera to investigate the effectiveness of this approach (Figure 8). The turbidity was varied from clear water to harbor-like conditions using liquid antacid. The clear water images were validated by manual measurement and then used as a baseline ground truth for the following turbid water experiments. Figure 9 shows an example of the improvement when backscatter subtraction was used when the object was 4 cz from the camera. Before correction, the ToF depth measurement is nearly 1 cz closer than the clear water ground truth. After correction, the measurement is a reasonable match for the ground truth since the backscatter's contribution is largely gone. Figure 10 shows a more extreme example in which the object is 6.5 cz from the camera. Here, correction allows the target to be seen "through" the backscatter in the ToF amplitude measurement. The uncorrected ToF depth measurement has an error of over 5 cz, but this is reduced to 0.3 cz after correction. Thus, the correction should improve both object detection and ranging.

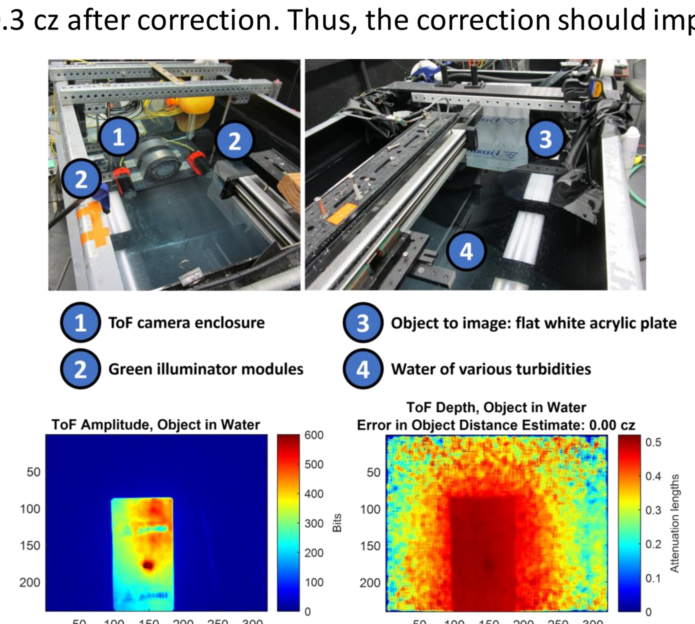


Figure 8. Experimental setup for backscatter subtraction testing. *Top:* The ToF camera is submerged in a water tank and used to image a flat plate through water of various turbidities. *Bottom left:* Baseline ToF amplitude image of the object in clear water. *Bottom right:* Baseline ToF depth image of the object. The clear water measured distance to the object matches manual measurements and is considered ground truth.

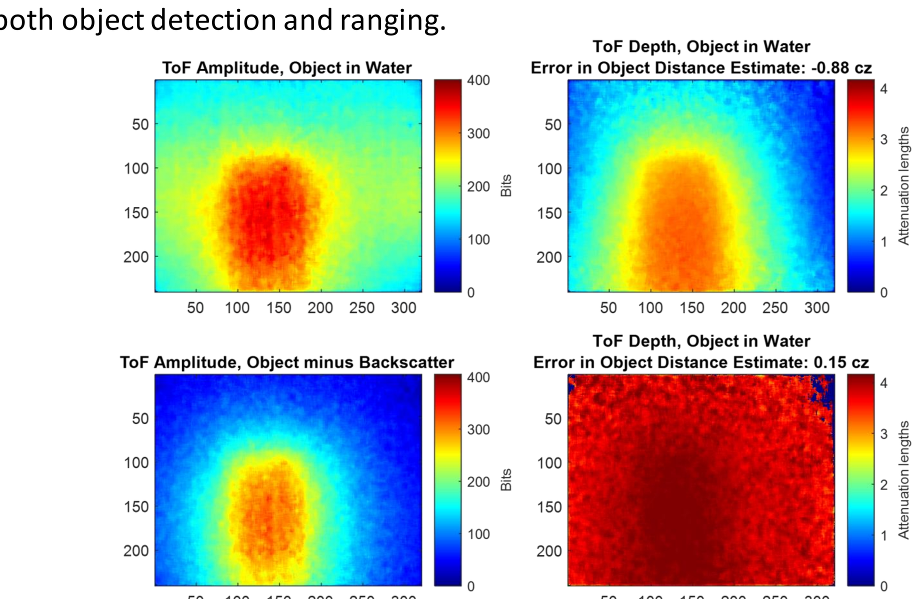


Figure 9. Background subtraction for ToF images at 4 attenuation lengths. *Top left:* ToF amplitude, uncorrected. The object is blurred but clearly visible. Backscatter is emerging on the sides of the image. *Top right:* ToF depth, uncorrected. The blurred object is clear but the distance is skewed towards the camera by almost 1 cz. *Bottom left:* ToF amplitude, corrected. The object is blurred but visible. *Bottom right:* ToF depth, corrected. The depth estimate of the object is much closer to the ground truth.

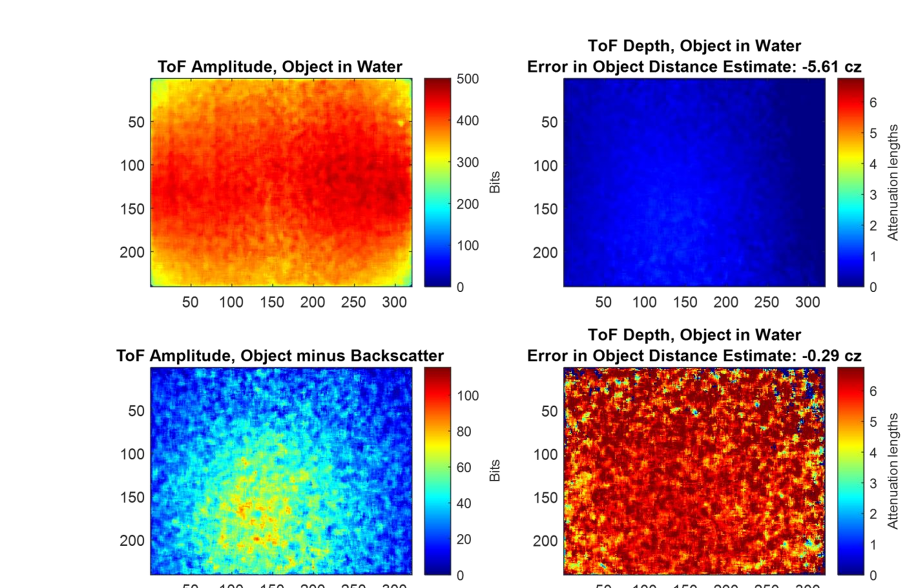


Figure 10. Background subtraction for ToF images at 6.5 attenuation lengths. *Top left:* ToF amplitude, uncorrected. The object is no longer visible behind the backscatter. *Top right:* ToF depth, uncorrected. The blurred object may still be visible but the distance is skewed towards the camera by over 5 cz. *Bottom left:* ToF amplitude, corrected. The object is visible once the backscatter is removed. *Bottom right:* ToF depth, corrected. The depth estimate of the object remains close to the ground truth.

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