Deployable Scintillometer for Ocean Turbulence Using Superluminescent LED

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ABSTRACT

Researchers from the Naval Information Warfare Center Pacific (U.S.) and the University of Central Florida have designed and developed new algorithms and a portable scintillometer to characterize ocean turbulence for imaging and free-space optical communication applications. Suspended particulates scatter light and organic material absorbs light in the ocean, but ocean turbulence can limit resolution of imaging due to temperature gradients (thermocline) or salinity. As turbulence is not constant in relation to water depth, a real-time characterization of turbulence conditions is needed. With the scintillometer consisting of a superluminescent light emitting diode (SLED) and a camera using two differently sized detectors, the refractive-index structure parameter (C_n^2) and the inner scale of optical turbulence (ℓ_0) were measured at 1.9×10^{-11} m$^{-2/3}$ to 2.3×10^{-10} m$^{-2/3}$ and 0.1 to 0.3 mm, respectively, correlating to measured thermocline parameters.

OCEAN TURBULENCE

The use of imaging and free-space optical communication is increasing in underwater applications. Optical communication and inspection of piers, pilings, or ship berthing areas requires overcoming the constantly changing characteristics of the water, especially in the ocean.

Certain ocean variables challenge the effectiveness of imaging and communication: scattering, absorption, and turbulence.[1] Scattering occurs when emitted light is deviated from its straight path when colliding with suspended particulates. Absorption occurs when organic material captures the emitted light and converts it into internal energy, usually heat. Both of these decrease transmitted light used for imaging and communication in natural water. However, in clearer water, resolution and visibility are often limited by optical turbulence (**Figure 1**).

Figure 1. Optical turbulence is generally characterized by gradients of temperature or salinity. In clearer ocean water, it negatively impacts imaging and communication.

Because media with different optical properties are being mixed by the ocean turbulence, the resolution is limited by differences in refractive index. This makes the turbulence optically active.[2] Optical turbulence is most common in places with temperature gradients (thermocline) or salinity gradients (halocline).[1] Ocean water attenuates light, gradually decreasing its intensity. Thus, turbulence in the ocean can drastically degrade optical communication. Characterizing ocean optical turbulence can aid imaging and communication in ocean waters. As turbulence is not a constant in relation to water depth or location, a real-time quantification of turbulence conditions must be designed.

Currently, post-processing techniques are used to enhance imaging in waters with turbulence, but these can only slightly improve results. The operator cannot anticipate or directly quantify turbulence conditions with mitigation techniques.[1] Once optical turbulence is measured, these results can be applied to deployable systems for better imaging and high-data communication.

MEASUREMENTS AND GOALS

There are two main parameters critical to characterizing optical turbulence in the ocean: refractive-index structure parameter (C_n^2) and the inner scale of optical turbulence (ℓ_0). To measure turbulence, a laser beam propagation apparatus can be placed in naturally occurring ocean turbulence. The effects of the turbulence on laser propagation can be quantified and collected. The index of refraction structure, C_n^2, is widely used in atmospheric optics and can be used in ocean turbulence applications, as well. The inner scale is related to the strength of the turbulence.

There have only been a few experiments to measure optical turbulence in the ocean, specifically quantifying the refractive-index structure parameter, C_n^2. The effects of turbulence on laser beam propagation was investigated with a 8.75 m laser, revealing a C_n^2 range of 1×10^{-14} $m^{-2/3}$ to 1×10^{-10} $m^{-2/3}$.[2] However, because of the long laser path, the system as well as other long path systems, requires significant infrastructure and personnel to develop and deploy.[1] The long path design is not ideal for simple deployment with a portable design. Other smaller and more portable designs have measured temperature variance dissipation in the ocean, but did not quantify optical turbulence directly.

Experiments and simulations in labs have verified the degrading effects ocean turbulence has on optical communication, especially high-data-rate communication. In-situ awareness of optical conditions is needed so imaging operators have the ability to anticipate or quantify ocean turbulence conditions.

METHOD

Researchers from the Naval Information Warfare Center Pacific (U.S.) and the University of Central Florida have designed and developed new algorithms and a portable scintillometer to characterize ocean turbulence for imaging and free-space optical communication applications.[1] The design of the scintillometer is based on a divergent optical beam and two photodetectors of different sizes.

Typically, laser sources are used for measuring optical turbulence in atmosphere and ocean. However, non-laser sources, such as light emitting diodes (LEDs) can be a viable source when coupled with spatial filtering to provided the necessary coherence. By using a superluminescent light emitting diode (SLED), the source can maintain coherence, low power usage, and increase system safety for the operator. The blue SLED emits 450 nm wavelength, 5 nm bandwidth, and 10 mW maximum optical power output. To further test the SLED against a typical laser diode source, both light sources were tested for turbulence imaging in **Figure 2**. As depicted in the images, both light sources were successful, verifying the implementation of the SLED source in the portable scintillometer design.

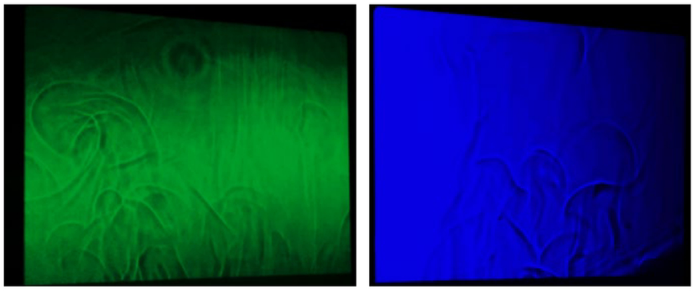

Figure 2. Lab experiments of turbulence imaging using (i) a green 520-nm laser diode as a control test (left panel) and (ii) the spatially filtered blue 450-nm SLED source (right panel).[1]

Many scintillometers use discrete photodiodes for turbulence detection. Although these provide the simplest solution for detecting light, they cannot be adjusted. In this turbulence experiment, researchers use camera-based pixel arrays that allow the user to numerically define spacing or detection regions as well as the relative size of each region.[1] The camera has a total sensor size of 11.3 mm x 7.0 mm, 2.3 megapixels, 4.5 W max power consumption, and 5.86 µm pixels in a 1920 x 1200 array. The frame rate was increased to 1 kHz by reducing the number of active rows from 1200 down to 150. The two different sized detectors or aperture windows have the following sizes: 150 x 150 pixels (0.88 mm x 0.88 mm) for the large aperture and 30 x 30 pixels (0.18 mm x 0.18 mm) for the small aperture. The final detector spacing was 10.7 mm by arranging the two arrays at opposite ends of the camera sensor.

By using two different sized detectors, multiple parameters of ocean turbulence can be measured. The smaller detector can be used to find the ℓ_0 parameter. The larger detector can be used to measure the scintillation index (SI). From this measurement, using the Weak Fluctuation Theory, the C_n^2 parameter can be estimated. Researchers theorized extending atmospheric propagation calculations to ocean applications by substituting the appropriate mean refractive index value for seawater. For this theory to be valid, the resulting range of validity for C_n^2 is approximately 1×10^{-11} $m^{-2/3}$ (lower turbulence) to 1×10^{-9} $m^{-2/3}$ (higher turbulence).

The small size, low weight, low power consumption, hand-deployable design consists of the transmitter (Tx) and receiver (Rx) housing. The Tx assembly contained the SLED, mounts, opto-mechanics, drivers, and temperature controller. The Rx assembly contained the camera with two different apertures, filters, and a single-board computer for data acquisition and storage. Both Tx and Rx are powered by a battery module that contains two independent channels. Testing revealed the battery housing delivers 40 hours of continuous operation to the SLED transmitter and 4.5 hours of continuous operation to the camera receiver. Although vastly different, the receiver operation and battery life times met all requirements.[1] The complete portable setup can be seen in **Figure 3**.

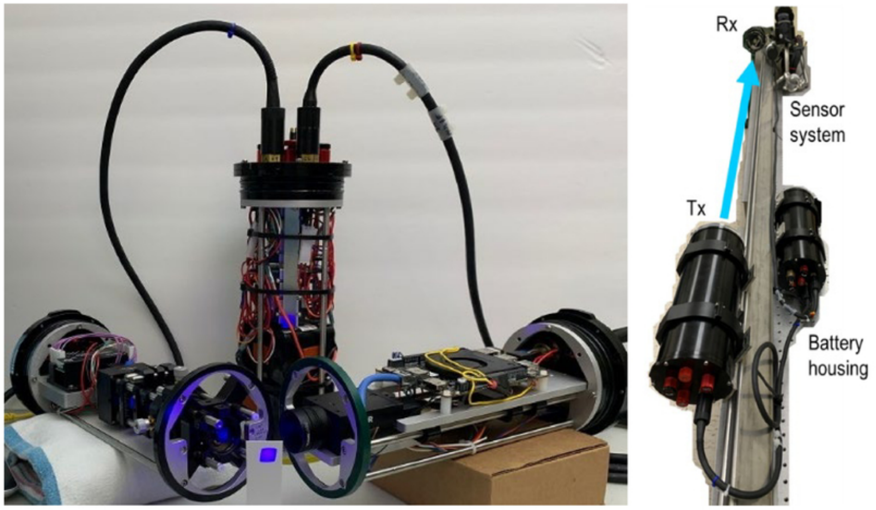

Figure 3. Left panel: this image shows the Tx (left), Rx (right), and battery (center) assemblies with aluminum housings removed. The white card depicts the 10 mm x 10 mm SLED beam. Right panel: the complete deployment system is shown on the bench, viewed from the bottom of the assembly toward the top. The system weighs less than 45 kg, enabling transportation and deployment by hand. By adjusting two bolts on the rail, the propagation distance can be changed within minutes.[1]

RESULTS

To test the scintillometer and sensor assembly, the system was deployed in 428 m Pacific Ocean waters west of San Diego, CA. **Figure 4** shows the scintillometer deployed in 1 m water with depth test profile. The system reached 179 m depth for measurements of turbulence with five other measurement depths to the surface.

After image batches were taken and stored, a computer analyzed the data. **Figure 5** shows sample camera imagery in small strips, large-aperture integrated camera signals (red), and small-aperture integrated camera signals (green) for four selected propagation cases. The first batch was in air, the second in deeper ocean (179.0 m), the third in moderate ocean (62.0 m), and the last in shallower ocean (16.1 m). From these images, the high turbulence observed correlates to the major variations in both large and small apertures.

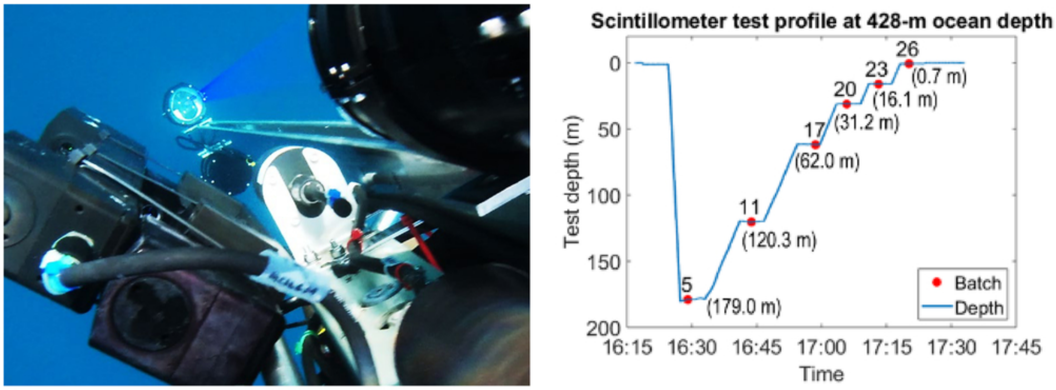

Figure 4. Left panel: this image shows the scintillometer and environmental sensor assembly prior to deep-water deployment, held 1 m below the ocean surface. The assembly is suspended vertically in the water column; this image shows the top-down view. Blue light from the SLED propagates from the Tx housing up toward the Rx housing. Right panel: this plot provides the test depth and individual scintillometer batches of interest as functions of time. After deployment to the full test depth, the system was held in place for five minutes at each of the six depth stations.[1]

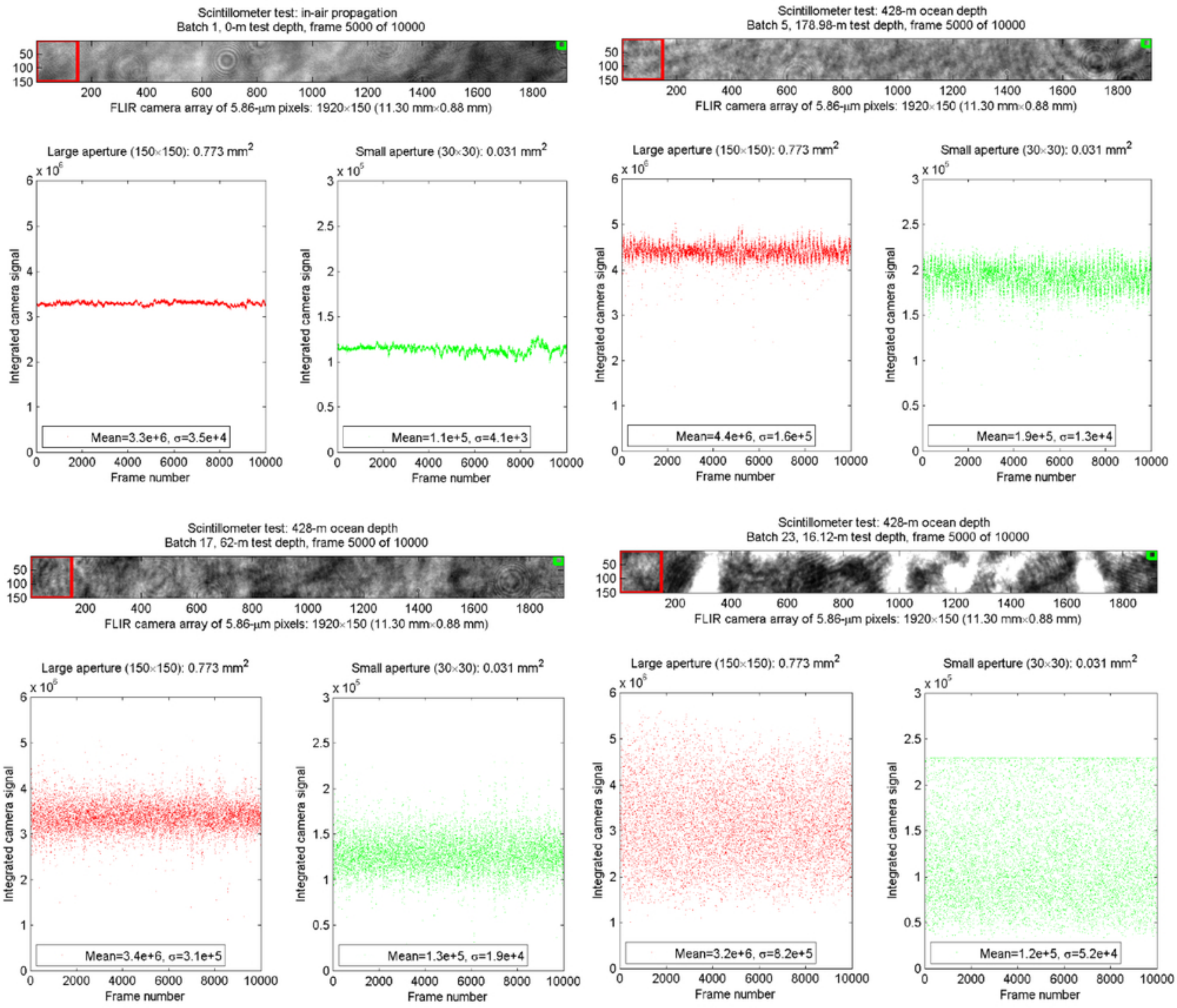

Figure 5. Camera imagery, large-aperture integrated camera signals (red), and small-aperture integrated camera signals (green) are shown for four propagation cases: in air (batch 1, 0-m depth, upper-left panel), deeper ocean (batch 5, 179.0-m depth, upper-right panel), moderate ocean (batch 17, 62.0-m depth, lower-left panel), and shallower ocean (batch 23, 16.1-m depth, lower-right). The camera images provide the median frame from each batch for visual comparison. Plots of integrated camera signal vs. frame number facilitate test-case comparisons of frame-to-frame similarity.[1]

Supporting sensors also measured temperature, beam attenuation, backscattering, and temperature gradient in **Figure 6**. The thermocline region shows a significant change in ocean temperature and gradient which is related to the refractive index structure and inner scale of turbulence. In this region, the effect on beam propagation is clear. The beam attenuation and backscattering are both at extreme maximums, diminishing the resolution of imaging in the thermocline region.

When temperature and temperature gradient have minimal changes, the beam attenuation and backscattering also decrease. The thermocline upper and lower limits are seen at 15 m and 70 m, respectively, highlighted in yellow. The pronounced attenuation and scattering in plots result from biological matter and particulates residing within the thermocline.[1]

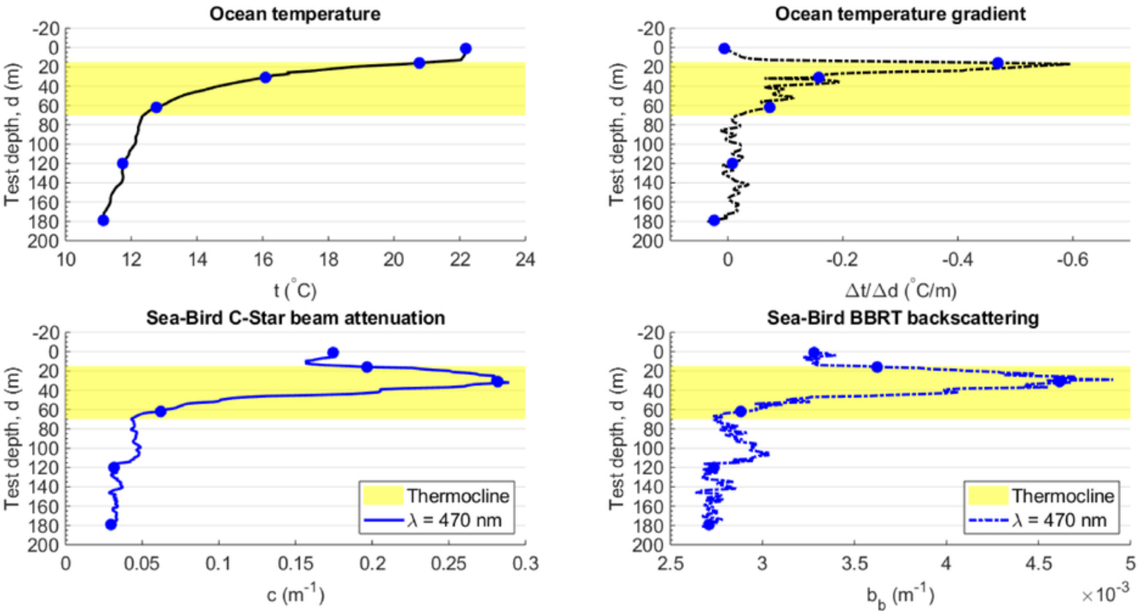

Figure 6. The Bar30 sensor (ocean temperature; upper-left panel), 470-nm C-Star transmissometer (beam attenuation; lower-left panel), and 470-nm BB backscatter meter (optical backscattering; lower-right panel) provide environmental awareness. The calculated ocean temperature gradient indicates thermocline boundaries in the water column (highlighted in yellow). Beam attenuation and backscattering are highly correlated with the temperature gradient. The six scintillometer batches are indicated as blue points.[1]

In **Figure 7**, the scintillometer data was analyzed for both large and small aperture results. Mean values and standard deviations of the camera signals are plotted in the upper two images. The most significant effects occur at the thermocline boundary, correlating to the ocean temperature and temperature gradient plots in **Figure 6**.

The two largest values of C_n^2 (2.3×10^{-10} $m^{-2/3}$ at 16.1 m and 2.8×10^{-11} $m^{-2/3}$ at 62.0 m) are related to the two largest regions of optical variations.[1] The moderate value of C_n^2, in between these two maximums, is 1.9×10^{-11} $m^{-2/3}$ at 31.2 m depth. Given the range of validity for the Weak Fluctuation Rytov theory, measurements inside the thermocline are included in valid data. Remaining batches fall below the valid range, indicating too low of turbulence to accurately measure with this system.

The inner scale of optical turbulence can be seen in the bottom right image of **Figure 7**. There is a maximum ℓ_0 of around 0.3 mm correlating to the bottom of the thermocline. The computed, valid ℓ_0 values range from 0.1 mm to just under 0.3 mm. Future studies will explore possible effects of increasing or decreasing the small-area aperture size and scale. The ℓ_0 maximum at the bottom of the thermocline provides an interesting and noteworthy discovery for future exploration.

The results of C_n^2 and ℓ_0 validate the effectiveness of this hand-held, portable scintillometer for ocean optical turbulence characterization. By developing robust algorithms and data logging methods, correlations between the ocean's thermocline (temperature changes and gradient) and optical disruption is found. The deployed system integrated compact optics and electronics for wireless control and analysis. Future studies include field testing at locations with different sea depths to help shine more light on optical turbulence in different regions. Further studies will help solidify real-time effects of ocean optical turbulence on imaging and communication.[1]

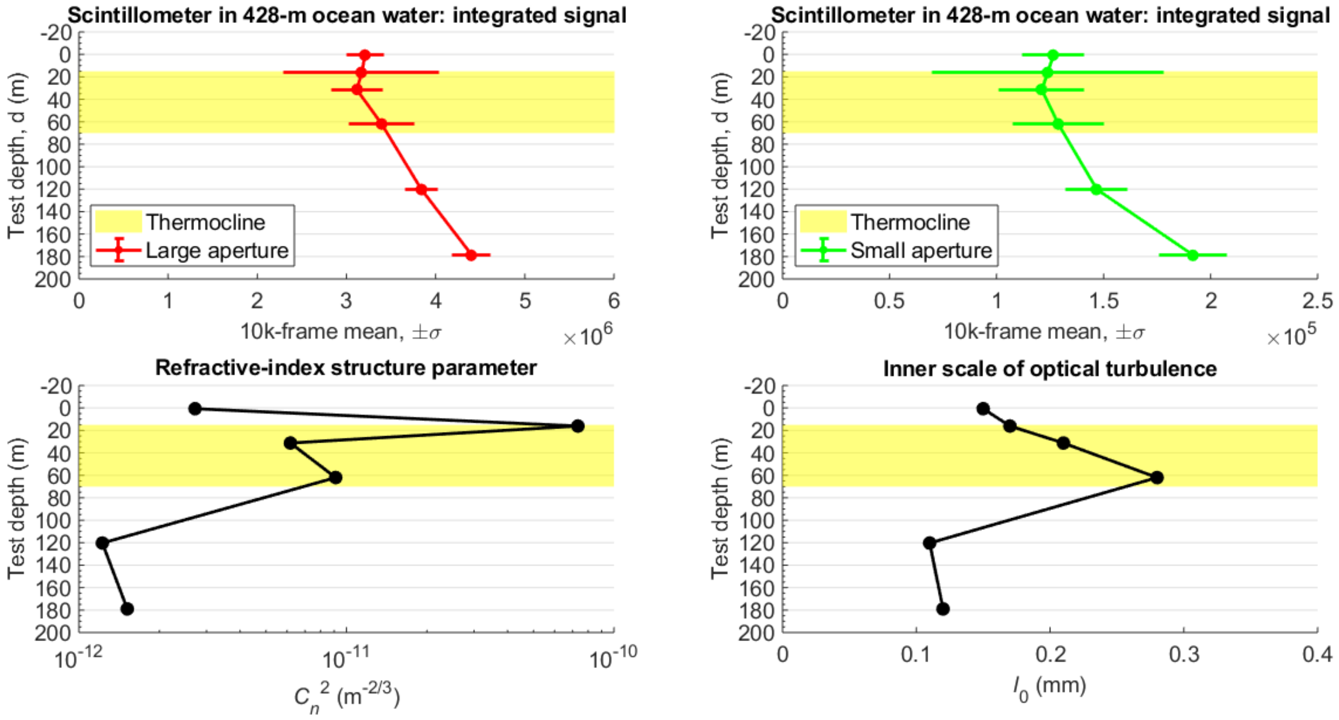

Figure 7. Mean values and standard deviations of the integrated camera signals are plotted above, with the large-aperture results in red (upper-left panel) and the small-aperture results in green (upper-right panel). The refractive-index structure parameter (C_n^2) is plotted in the lower-left panel. The inner scale of optical turbulence (ℓ_0) is plotted in the lower-right panel.[1]

WAVELENGTH'S ROLE

A superluminescent light emitting diode (SLED) served as the scintillometer source for optical ocean turbulence characterization in place of the commonly used laser diode. The SLED still requires stable current and temperature control in the portable design. Wavelength Electronics' LDTC1020 laser diode and temperature controller provided the closed-loop control of the SLED's drive current and temperature with minimal noise and high temperature accuracy. The LDTC1020 provides up to 1.0 A output current to the laser or LED as well as up to ±2.2 A to the thermoelectric cooler or resistive heater.

The LDTC1020 aided in the small footprint required for the portable system with a size of approximately 6 cm x 7 cm x 3 cm and a mass of 88.7 g. The LDTC1020 was able to fit both the small size and the low mass requirements of the scintillometer housing.

As both the transmitter and receiver housings were powered by independent battery modules, the LDTC1020 ensured safety and stability of both current and temperature to the SLED system. With low noise of 22 μA RMS and current stability as low as 35 ppm at 25ºC for 1 hour, the LDTC1020 delivered constant current to the SLED for constant output power for optical measurements. The precision temperature stability of the temperature controller at 0.005ºC at 25ºC for 1 hour also provided system stability.

The LDTC1020 driver and temperature controller enabled sensitive ocean optical turbulence characterization with low noise and stable current and temperature output. This makes the developed deployable scintillometer system a reliable tool for exploring the effects of turbulence on practical applications of imaging and optical communication.

REFERENCES

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USEFUL LINKS

- LDTC1020 **Product Page**

PERMISSIONS

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PRODUCTS USED
LDTC1020

KEYWORDS
Scintillometer, oceanography, turbulence, thermocline, scattering, absorption, superluminescent, LED, laser diode driver, temperature controller, LDTC1020, imaging, free-space optical communication

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