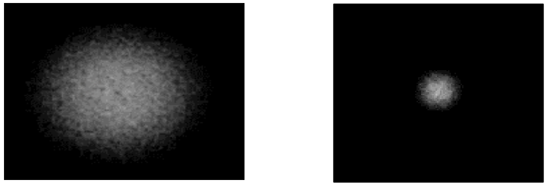
Lasers in maritime environment

- **Lead researcher**

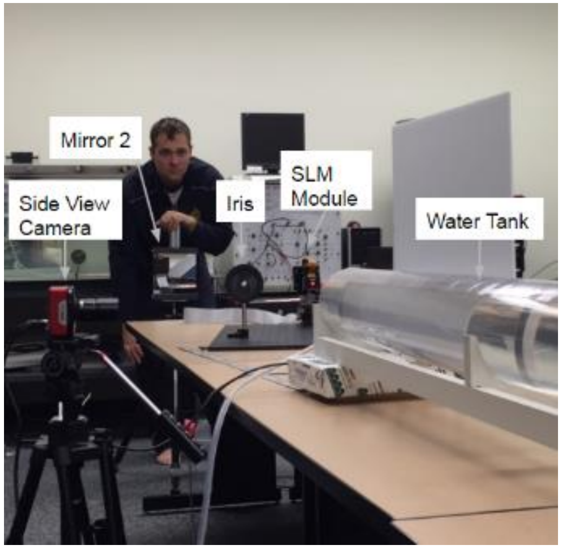
Svetlana Avramov-Zamurovic

- **Objective** Generate laser beams propagating in maritime environment with improved scintillation properties
  - On the grounds at the USNA experimentally generate spatially partially coherent beams and measure the intensity profiles and fluctuations on the target and along the path.
  - Develop an underwater test bed to emulate complex maritime medium, model its optical turbulence properties and investigate laser beam propagation and scattering performance.

The phase of a Gaussian beam is modulated spatially: effectively breaking the laser beam into beamlets with each having statistically prescribed phase while traveling through complex medium. On average these spatially partially coherent beams have less intensity fluctuations on target.



Far field realization for more and less diffused partially coherent beams.



Introduction to Laser Research

ES285 Spring

co-taught S. Avramov-Zamurovic, and C. Brownell

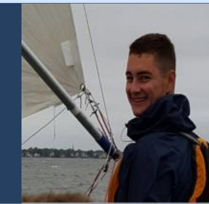
- Objective: Introduce laser research to plebes at the USNA.
- Focus: on the experiments with lasers and mathematics of light.
- The program is offered in the past 6 years, and this year the record number (14) of students successfully completed the class.
- Students performed two experiments and wrote reports on their findings:
  - Taking apart a laser source and documenting its components
  - Propagation of the laser beam over a 20 meters link and observing the beam spreading and influence of optical turbulence
- As a new motivation, this year lectures started with experimental demos. The simple experiments ranging from laser excited fluorescence, laser propagating thorough icy water, comparison of laser propagation with an expanded beam and not expanded beam, were just demonstrated and students were given an assignment to explore any resource and find out what happened in the given scenario. Next class time the phenomenon was discussed and students demonstrated very high level of engagement. Instructors believe that this type of exercises contributed to perfect retention rate.
- At the end of the semester 6 teams of students were assigned final projects.

Lasers in maritime environment

ES495A Fall, Svetlana Avramov-Zamurovic

- For the first time systems major elective was offered to introduce students to the engineering of lasers beam propagating in maritime environment.
- This is the only engineering course offered at the Academy that has 2 hour laboratory exercise and 2 lecture meetings during the week.
- Hands on experience on generating the laser beams, propagating them in various environments, analyzing the recorded observations and processing the data, is the most valuable experience to students.
- The development of the course and teaching 3 credits was a **major undertaking**.
- Students presented their final projects at the Academy Research Day in December 2016.
- Stents also presented their observations on laser beam propagation under water, at the DEPS conference in Huntsville, AL, in February, 2017
- Preregistration for the next semester is complete at the Academy, and the course will run again with larger group of students.

Laser Beam Propagation in Fog



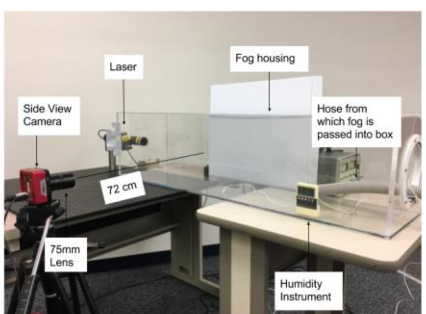
Midshipman 1/C Collins and 1/C Stabler

Professor Svetlana Avramov-Zamurovic, Systems Engineering

Motivation

- Directed Energy Applications
  - Directed Energy Weapons
  - Laser Communication Systems
  - Goal -To direct energy onto a given target with a calculated effect
- Beam Propagation
  - As the beam propagates through space, it begins to scatter, diffract, refract, reflect, etc.
    - Difficult to predict the laser beam propagation through the complex and ever changing the medium
    - Laboratory experimentation provides close to ideal conditions so that proof of principle of a given effect, could be studied
- In Naval applications, dense fog is a common environment
  - Naval laser with the 30 kW laser mounted aboard the USS Ponce
  - Some Adversaries, such as China, are developing mobile "fog machines" mounted on trucks, to disrupt a use of directed energy weapons.
- Experimenting with laser beam propagating in fog
  - Objective :To observe scattering of a laser beam propagating in fog by changing the radius of the beam .
  - Laser source used
    - Wavelength 632.8 nm, Power 2 mW
    - unexpanded beam diameter = 0.63 mm
    - expanded beam diameter = 12.6 mm

–Chinese Smoke Truck



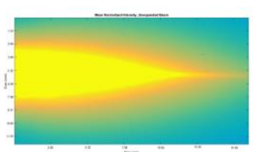
Laboratory Setup

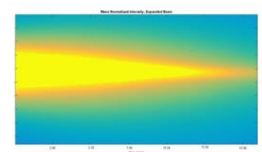
Results

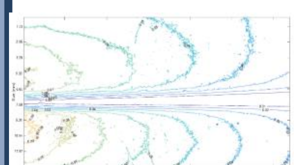
- Scintillation Index
  - Way to measure the relative change in intensity over time.
  - Superior to simply measuring variance in that the scintillation index is normalized, not skewed if power levels are varying
  - $Scintillation\ Index = Variance/mean^2$
- Measuring scenarios unexpanded and expanded beams
  - Beam Scattering (Side View)
    - Used focused 75 mm lens from 72 cm away perpendicular to the laser propagation path
    - Focused to most clearly see the path of propagation
    - 40 ms exposure time
  - Beam Propagation (Direct View)
    - 1.5 power neutral density filter, red notch filter
    - 17.5 ms exposure time
- Environmental Conditions
  - Temperature between 69.3°F-69.6°F
  - Humidity-49%

Beam diameter = .63 mm

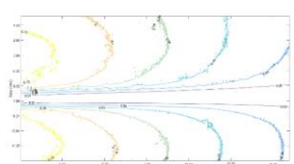
Beam diameter = 12.6 mm



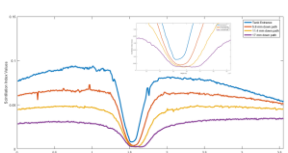


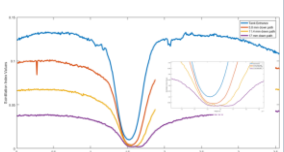


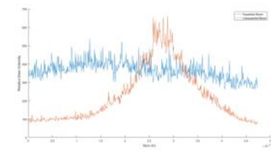
Contour map of the scintillation index of the unexpanded beam. The contours are labeled with the value levels they represent.



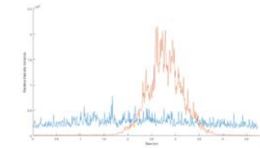
Contour map of the scintillation index of the expanded beam. The contours are labeled with the values of scintillation they represent.



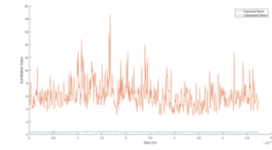




Mean intensity of the unexpanded and expanded beams shot directly into the camera.



Variance of the unexpanded and expanded beams shot directly into the camera.



Scintillation index of the unexpanded and expanded beams shot directly into the camera.

Conclusion

- Expanded laser beam performed better than unexpanded beam in the propagation and scattering scenarios.
- Intensity mean, Intensity variance, and Scintillation index were used as performance matrices. Higher scintillation equates to more fluctuations of relative intensity of the beam over time, suggesting deteriorated performance.
- Beam Propagation (Direct View)
  - Unexpanded beam size is smaller than the sensor area, as seen at the peak on the Mean intensity graph.
  - Expanded beam is larger than the camera sensor, giving a uniform intensity across the sensor area
  - Intensity Variance plots across the sensor area show increased variations of the unexpanded beam due its higher intensity
  - Scintillation index graph clearly shows how the normalized variations in the intensity of the beam are more significant for the unexpanded beam.
  - This metric establishes the superior performance of the expanded beam.
  - Although the unexpanded beam has a higher mean intensity, it is affected more when propagating through the fog compared to the expanded beam, according to the scintillation index direct view graph.
- Beam Scattering (Side View)
  - Mean intensity graph shows the amount of energy scattered by the fog
  - The unexpanded case shows more beam scattering than the expanded case
  - Noticeable level of energy absorbed by the fog in the case of unexpanded beam
  - Side View Contour Map visually shows regions of scintillation index values
  - The rate of change in scintillation for unexpanded beam is from 0.0075 to 0.002 and for the expanded beam it is 0.01 to 0.002 suggesting lower trend in scintillation on target for expanded beam over extended distance.
- Scintillation index is related to the initial beam size: At the entrance point into the fog cloud the expanded beam has higher scintillation index, both beams exit the fog enclosure with approximately the same scintillation index values at the same beam width at exit.
- When considering beam propagation, the power transfer of the expanded beam is therefore more efficient, the scintillation index of the expanded beam is more stable than the unexpanded beam.

Acknowledgements

Professor Avramov-Zamurovic-Weapons and System Department

Norm Tyson and Nick Eagle-Technical Support Division

References

http://www.popsci.com/china-plans-to-defeat-american-lasers-with-smoke
http://www.popsci.com/navy-is-going-to-test-big-laser-soon

Detecting Laser Beams Underwater

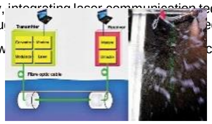
Midshipman 1/C Collins and 1/C Stabler

Professor Svetlana Avramov-Zamurovic, Systems Engineering

Motivation

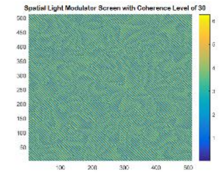
- Laser Communication Systems
  - Line of site communication between two entities
  - Unlike radio and other types of omnidirectional forms of communication, laser communications are unable to be intercepted unless they are intercepted directly through the line of site
  - To further increase the security of the communications, it is important that the friendly beam be as hard to detect as possible by the enemy and vice verse
- UNDERWATER LASER APPLICATIONS
- US Naval Underwater Applications

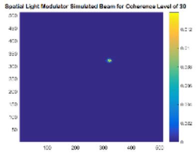
- German Naval Experimentation
  - In German Navy, integrating laser communication technologies :Data sent via a laser beam through ... used as coastal water.
  - Main challenge w... conditions in the type of water



- EXPERIMENTING WITH DETECTING LASER BEAM PROPAGATING IN WATER
  - Objective :To observe scattering from a laser beam propagating through water using four different sources under calm and turbulent water conditions
  - Laser sources used
    - Wavelength 632.8 nm, Power 2 mW
    - Unexpanded beam diameter = 0.63 mm
    - Expanded beam diameter = 6.3 mm
    - Less Coherent Beam as produced by Spatial Light Modulation
    - More Coherent Beam as produced by Spatial Light Modulation
- SLM- Spatial Light Modulation

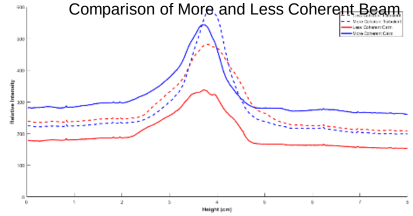
Beams Before Propagation



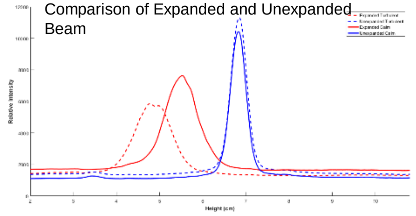


Results

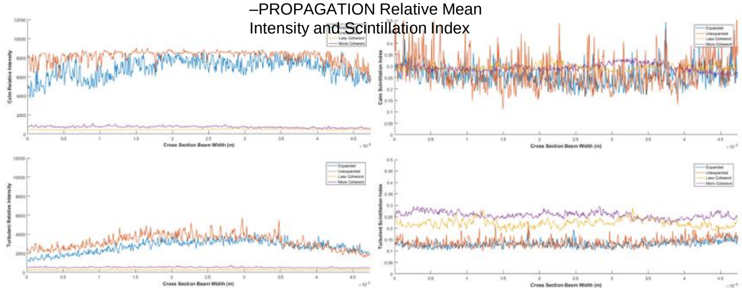
–SCATTERING Mean Relative Intensity Comparison of More and Less Coherent Beam



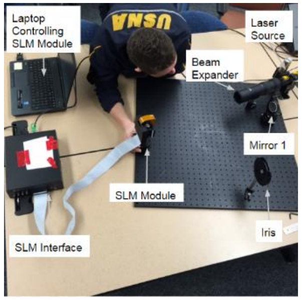
–SCATTERING Mean Relative Intensity Comparison of Expanded and Unexpanded Beam

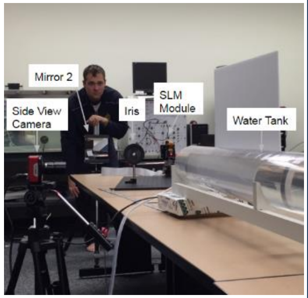


–PROPAGATION Relative Mean Intensity and Scintillation Index

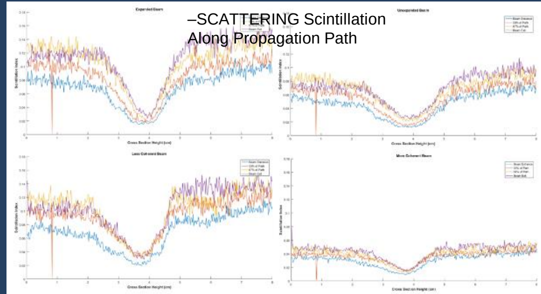


Instrumentation





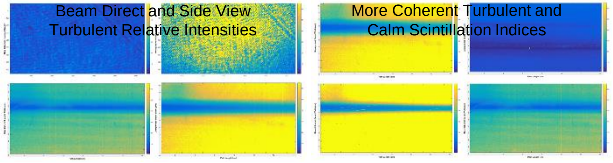
–SCATTERING Scintillation Along Propagation Path



Analysis

–More Coherent and Unexpanded Beam Direct and Side View Turbulent Relative Intensities

–Unexpanded Beam and More Coherent Turbulent and Calm Scintillation Indices



- Observing both scintillation index and relative intensity are effective methods of detection
  - The medium surrounding a beam will have a higher relative scintillation index than the beam propagation path
  - An unexpanded beam will have a lower change in scintillation index than a coherently formed beam due to the greater spreading of the beam in the surrounding medium.
  - In the beam path, the unexpanded beam has a higher change in scintillation index.
- Leaving a beam unchanged increases chances of detection underwater.
  - On average, the unexpanded beam has a higher scintillation index value in the medium surrounding the beam when compared to the coherently formed beam, allowing easier detection by sensing change in light intensity.
  - On average, the unexpanded beam scatters in the underwater medium more than the coherently formed beam, allowing easier detection by sensing light intensity.
- More coherence correlates with lower scintillation values and better intensity transmittance when observing the beam off the propagation path
  - This is not the case for direct path observations, however. When observing the beam directly, we found that the coherent beams had higher scintillation values than the Gaussian and expanded Gaussian beams.
- Higher turbulence correlates with higher scattering and scintillation values.
  - This applies to all beam types studied.
  - Comparing coherent beams, more coherence corresponds to higher intensity transmittance, suggesting less scattering occurs.
  - Comparing Gaussian beams, expansion of the beam corresponds to higher intensity transmittance, suggesting less scattering occurs.

Acknowledgements

Professor Avramov-Zamurovic-Weapons and System Department

Norm Tyson and Nick Eagle-Technical Support Division

References

https://www.sea-technology.com/features/2011/0511/laser_communication.php

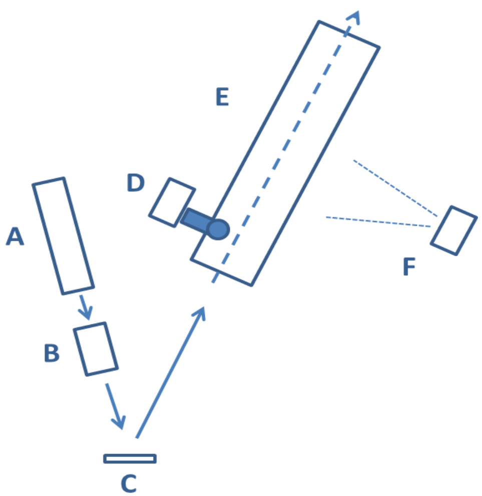
http://newlaunches.com/archives/navy_scientists_develop_underwater_laser_communication_technology.php

Laser Research Class, Spring

- MIDN Kelly and MIDN Collins are working on developing an emulator for propagating laser light underwater, as the part of their independent lasers research class.
- The emulator will serve as test equipment for constructing various scenarios of complex media.
- Controlled and measured properties
  - Salinity
  - Water flow
  - Temperature
- Full functionality is achieved by using microcontroller, conditioning circuits and data gathering.

- The objective of the research is to develop fully operational actuators and sensors suite for study of laser light propagation and scattering in complex maritime medium.

Experimental study on off-axis scattering of flat top partially coherent laser beams when propagating under water in the presence of moving scatterers



Experimental setup
A – HeNe laser
B – beam expander
C – spatial light modulator
D – mechanical agitator
E – 1 m propagation tank
F – camera

- Experiment set up in the lab to evaluate the laser beam spatially pseudo partially coherent beam (PPCB) scattering
- The coherence level (from less coherent to more coherent) were selected for Multi Gaussian Schell Model PPCB beams and they were compared to the fully coherent Gaussian beams in two scenarios
  - Calm water with specified salinity
  - Mechanically agitated water with specified salinity
- Intensity and scintillation of the scattered light was measured and analyzed
- **Objective**: Establish better scintillation performance of the partially coherent beams propagating and scattering in complex medium.

The research by Svetlana Avramov-Zamurovic, 4 weeks summer funding received

CONCLUSIONS

Results indicate that fully coherent beams have increased off-axis scattered light variations in the presence of moving scatterers as compared with a spatially partially coherent MGSM beam.

Additionally, in a stationary environment the coherent beam has less overall variations as expected due to the nature of constructing partially coherent MGSM beams.

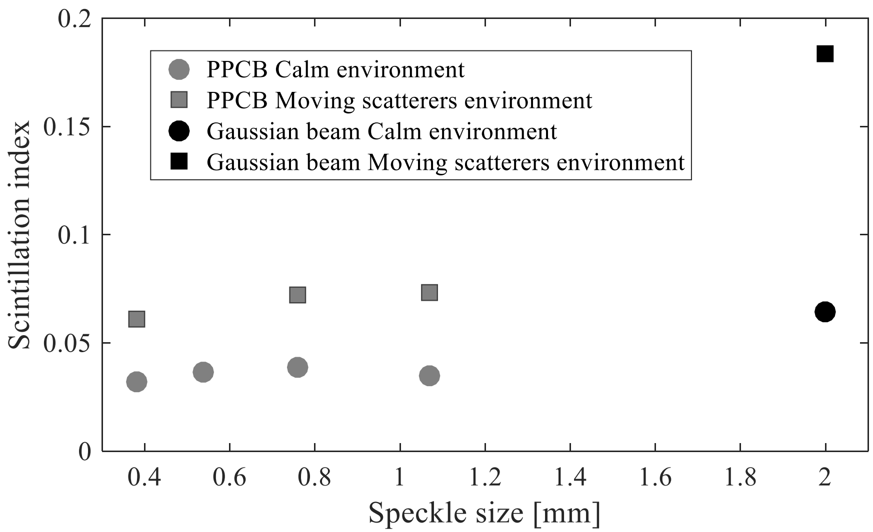
Metrics of normalized variance, scintillation index, and overall average intensity are discussed in the context of potential beam localization, reduced scattering, and off-axis detection.

The research by Svetlana Avramov-Zamurovic, 4 weeks summer funding received

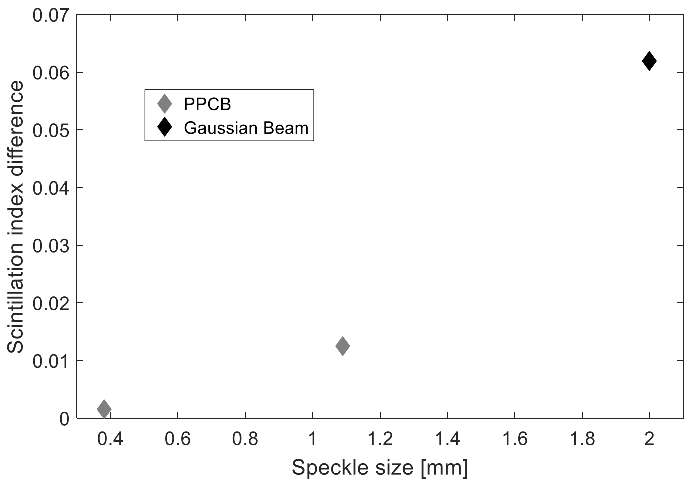
Significant Findings
Spatially partially coherent beams have favorable scintillation when propagating in complex medium

Gaussian and Spatially partially coherent MGSM beams
propagated through the environment with moving scatterers and stationary environment

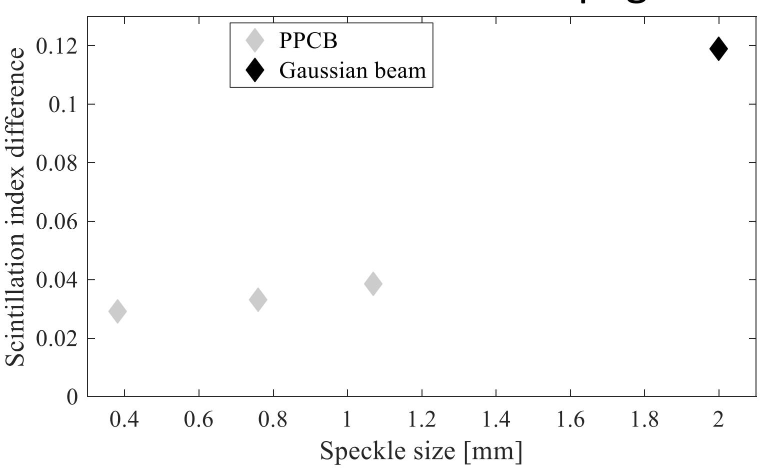
Propagation



Scattering



Propagation



Significant Findings: Publications

- S. Avramov-Zamurovic, C. Nelson, ***“Experimental study on off-axis scattering of flat top partially coherent laser beams when propagating underwater in the presence of moving scatterers”*** journal paper submitted to *Waves in Random and Complex Media*

- S. Avramov-Zamurovic, C. Nelson,***“Experimental analysis of laser beams with variable spatial coherence propagating underwater”*** Conference Proceedings *Imaging and Applied Optics Congress*, section: Propagation through and Characterization of Atmospheric and Oceanic Phenomena, 25 - 29 June 2017 in San Francisco, CA.

- C. Stabler, G. Collins and S. Avramov-Zamurovic, ***”Laser Propagation in an Underwater Environment“*** presented at DEPS conference, Huntsvile, Al, Feb 2017.

Proposed Efforts FY17 and Beyond
4 weeks summer funding, yearly

- Since the underwater emulator will be constructed this spring during the summer research time effort will be focused on characterizing the complex media scenarios.

- Based on the last year achievements in generating partially coherent beams with high fidelity, a new effort will focus on generating angular beams. The motivation for the experimental analysis is the fact that theoretical findings suggest high performance of these beams in complex media.

- The major achievement will be experimental study of propagation of electromagnetic (combined vertically and horizontally polarized) angular beams through a complex maritime environment made possible by the emulator.

New Ideas / Opportunities

- The development of the underwater emulator and the in-house expertise in generating various laser beams will provide abundant opportunities for studying complex maritime media and the interaction of lases with them.
- Bringing on board Assistant Professor Evelyn Lunasin, USNA applied mathematician, PhD in turbulence analysis, is an asset. She is expected to make significant contributions in characterization of the optical turbulence in the underwater emulator and modeling of the complex medium it delivers.
- Generation of electromagnetic beams with angular momentum and propagating them in the emulator and then in the real maritime environment at the grounds of the Academy is the next natural step in our research.
- Based on the Navy interests on interaction of lasers with living matter as a safety analysis, and students expressed interest in this topic, sveral projects will be initiated in the fall.