Experimental Performance Analysis of Spatially Modulated Laser Beams Propagating Underwater

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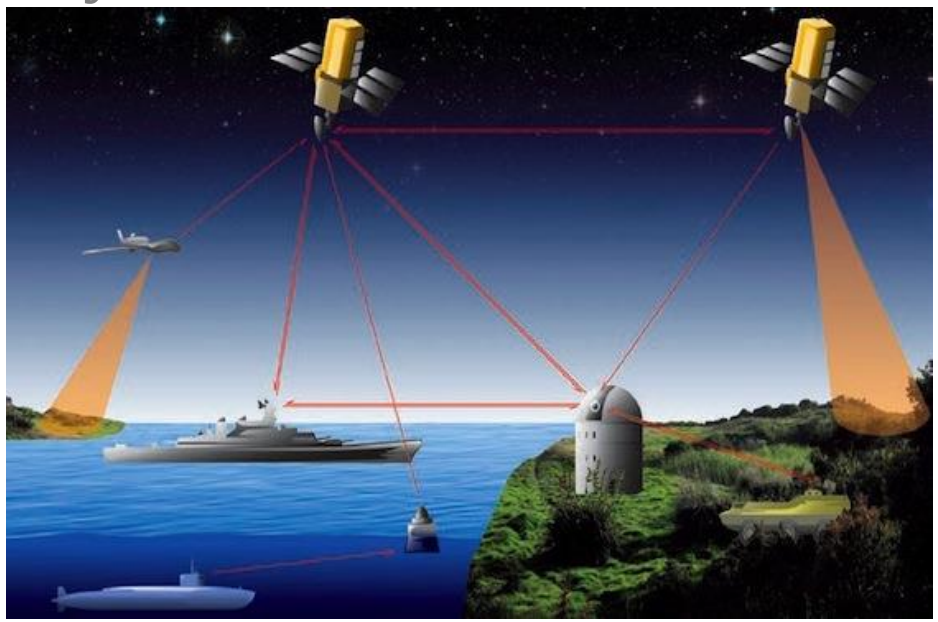


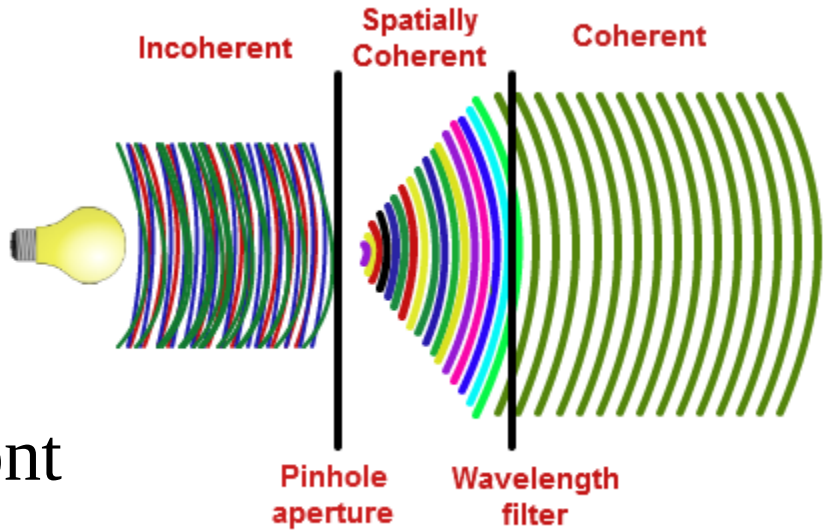
Problem Statement

- Fundamental study of laser beam propagation in complex media
- *Scalable* test bed emulator developed to simulate a wide range of underwater environments
- Statistical methods used to generate spatially partially coherent beams to combat laser light intensity fluctuations in complex media
- Apply experimental analysis of laser propagation and scattering

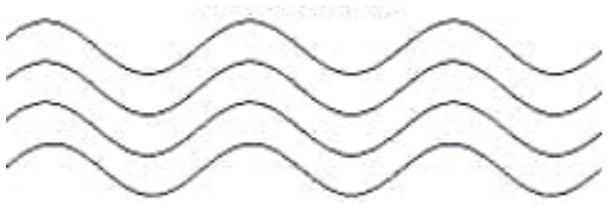
Laser Light Characterization

Light Amplification by Stimulated Emission of Radiation

- Laser Source Construction
- Monochromatic – Singular Wavelength
- Collimated – Near parallel ray paths
- Coherent (Temporal) – In phase in time
- Coherent (Spatial) – In phase in location on wave front



Coherent Light



Spatially Modulated Light
(PROJECT OBJECTIVE)

Same Wavelengths
Different Phase Relationship

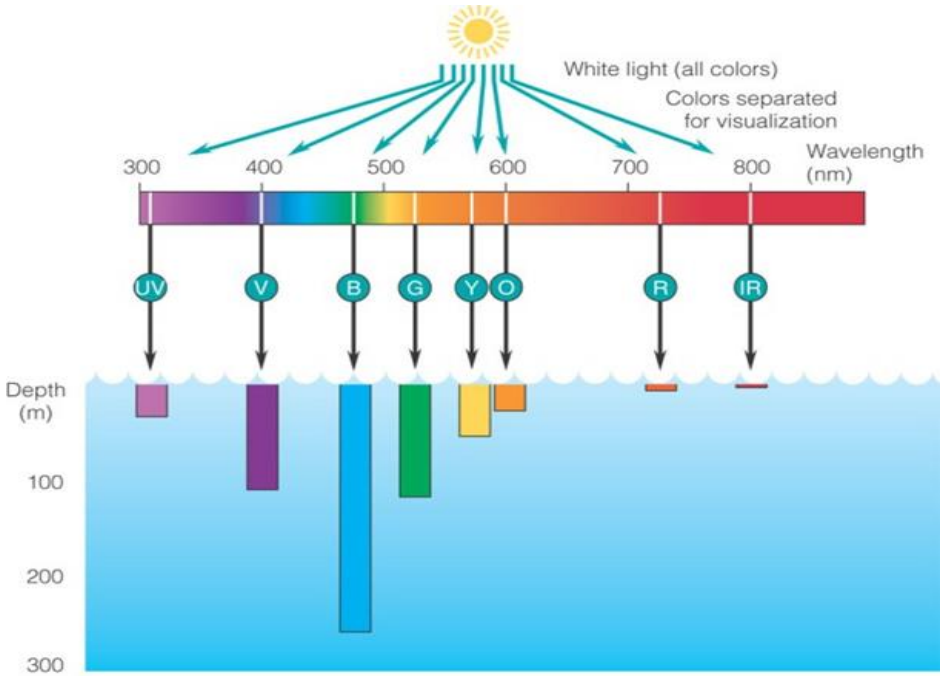
Propagation Effects - Underwater

Attenuation

$c(\lambda) = a(\lambda)+b(\lambda)$

-Absorption

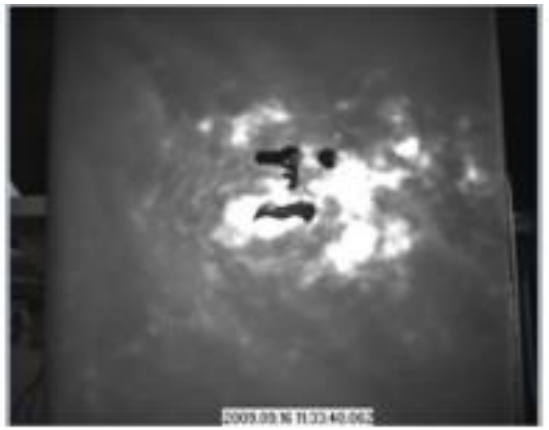
-Scattering



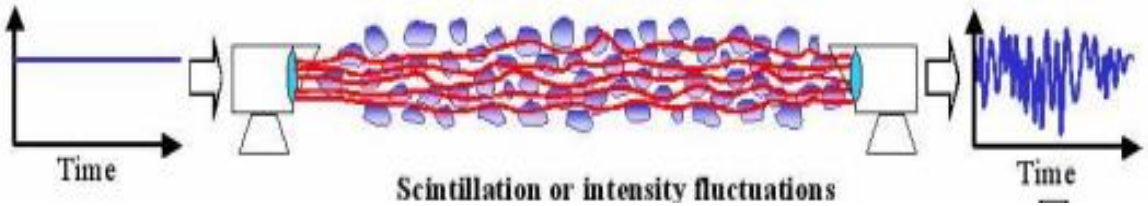
Optical Turbulence

-Temperature

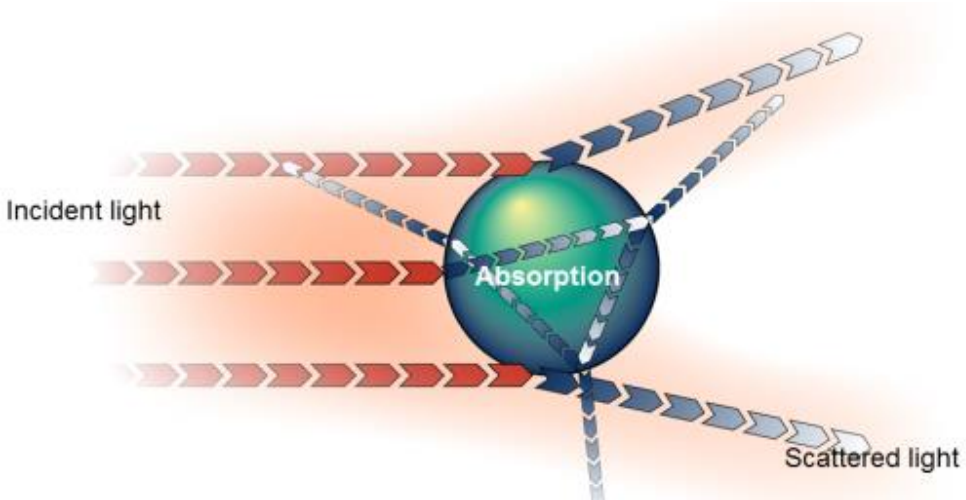
-Salinity



Constructive/Destructive Interference Pattern Gaussian Beam at 12.5km

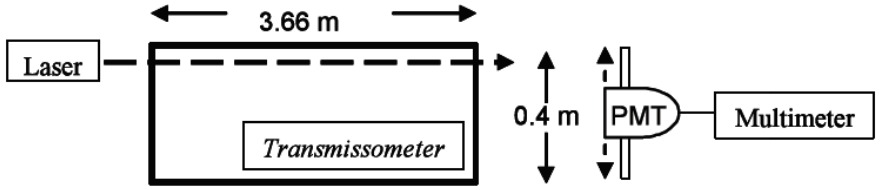


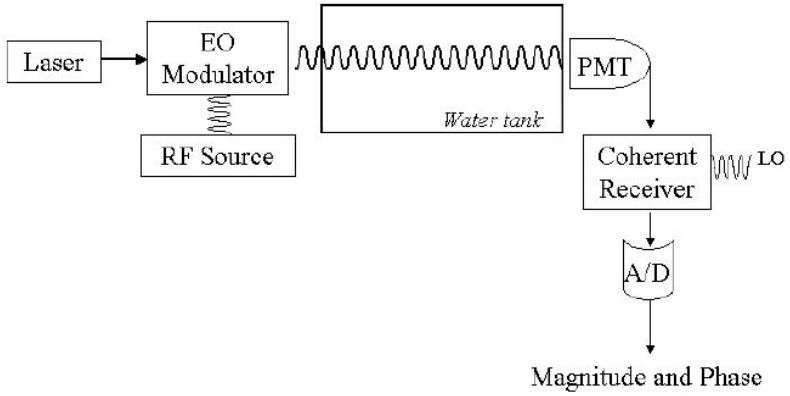
Varying Beam Paths due to Optical Turbulence



"Spatial and temporal dispersion in high bandwidth underwater laser communication links"
Laser Propagation Underwater

- 2 experiments – off-axial temporal and spatial coherence analysis
- Beam Scattering losses significant even at close range (Spatial)
- Temporal Modulation negligible at close ranges (Temporal)
- Potential challenges at longer ranges for both
- <u>Validation of experimental practices/set up</u>





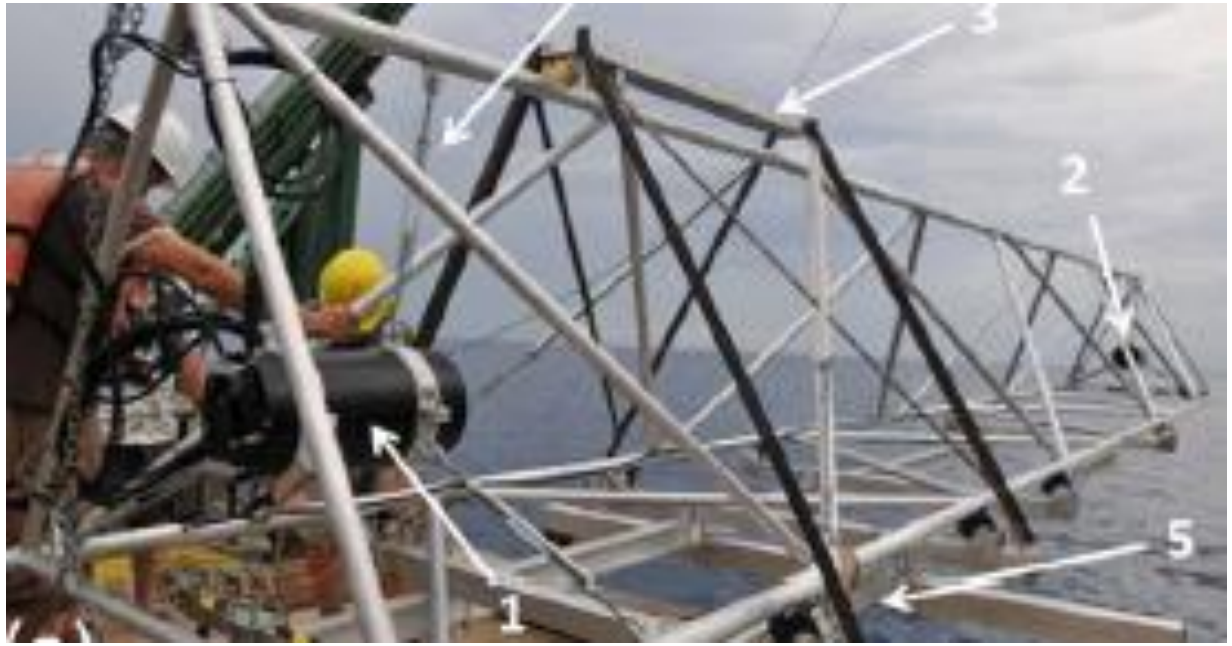
B. Cochenour, L. Mullen, and A. Laux, "Spatial and temporal dispersion in high bandwidth underwater laser communication links," in Proc. IEEE Military Commun. Conf., 2008, pp. 1–7.

"Quantification of optical turbulence in the ocean and its effects on beam propagation" Environmental Characterization

- Index of refraction structure variable C_n^2 measured in the ocean

$$C_n^2 = \left(\frac{dn}{dT} + \frac{dn}{dS} * \frac{dS}{dT}\right)^2 * C_T^2$$

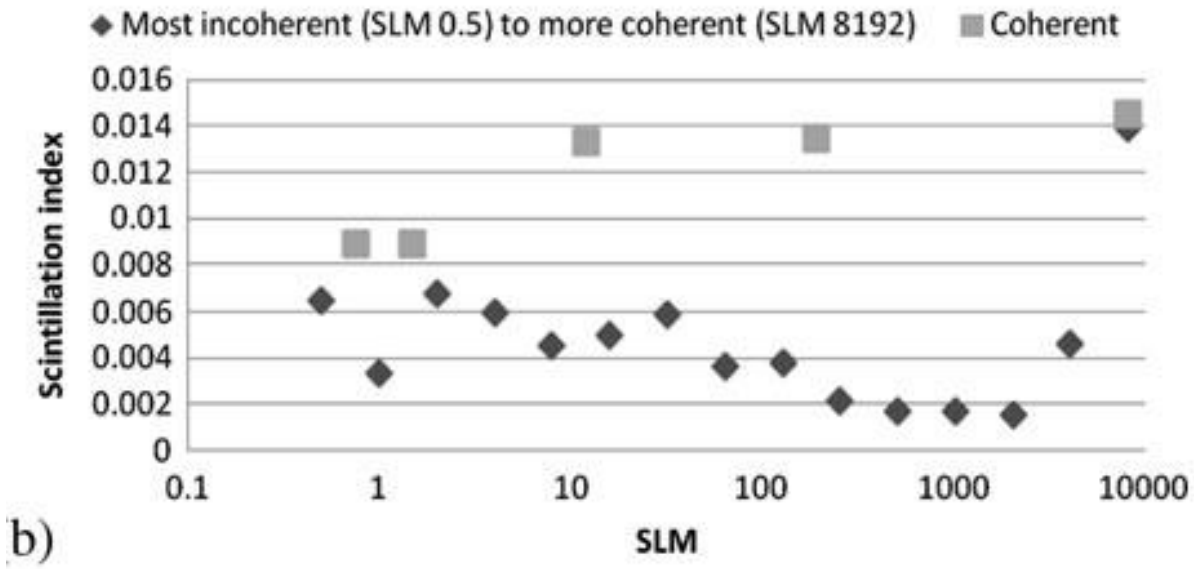
- Experimentally measured vs. environmentally calculated
- Current modeling pros and cons
  - underestimation of experimental value
- Used laser to determine turbulence in environment
- <u>Key to emulator design and characterization</u>



Gero Nootz, Ewa Jarosz, Fraser R. Dalgleish, and Weilin Hou, "Quantification of optical turbulence in the ocean and its effects on beam propagation," Appl. Opt. 55, 8813-8820 (2016)

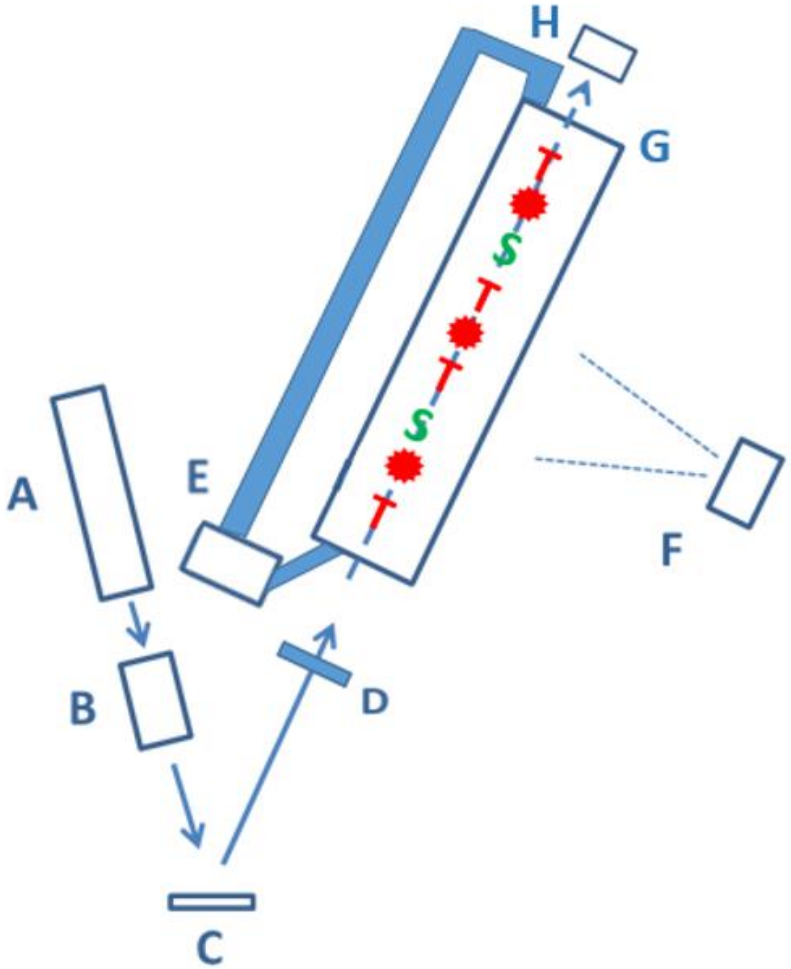
"Random Beam Propagating in the Maritime Atmosphere"
Beam Generation/Proof of Concept

- Spatially Modulated Beam generation
- Complex Medium – Air over water
- <u>Proof Of Concept – Less scintillation seen in modulated beams vs coherent beams</u>



S. Avramov-Zamurovic, C. Nelson, R. Malek-Madani & O. Korotkova (2014) "The dependence of the intensity PDF of a random beam propagating in the maritime atmosphere on source coherence, Waves in Random and Complex Media," 24:1, 69-82, DOI: 10.1080/17455030.2013.874055

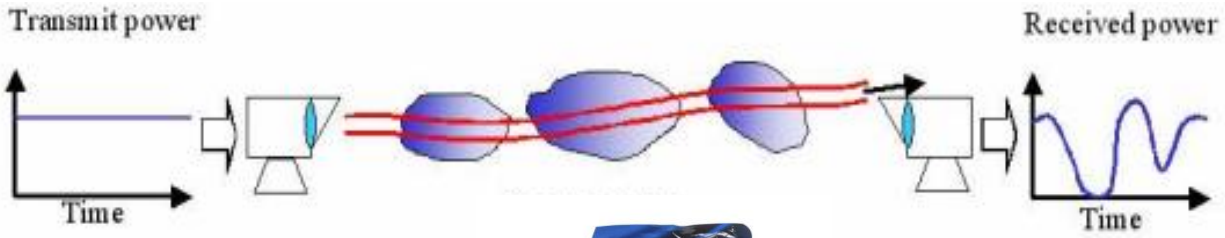
Experimental Set Up



Experimental setup –
A – Laser Source – 2mW HeNe, 632 nm wavelength,
B – Beam Expander,
C – Spatial Light Modulator (SLM) – 512x512 pixel,
D – Mechanical Iris,
E – Flow Pump,
F – Off-Axis Receiver Camera,
G – Propagation Tank,
H – On-Axial Camera,
T – Thermocouple,
S – Salinity Cell,
✸ - Heater

Test Bed Sensing/Actuating

<u>Scaled Complex Medium</u>



- Salinity
  - -Salt Addition (Salinity Level variable at will)
  - -Salinity Cell

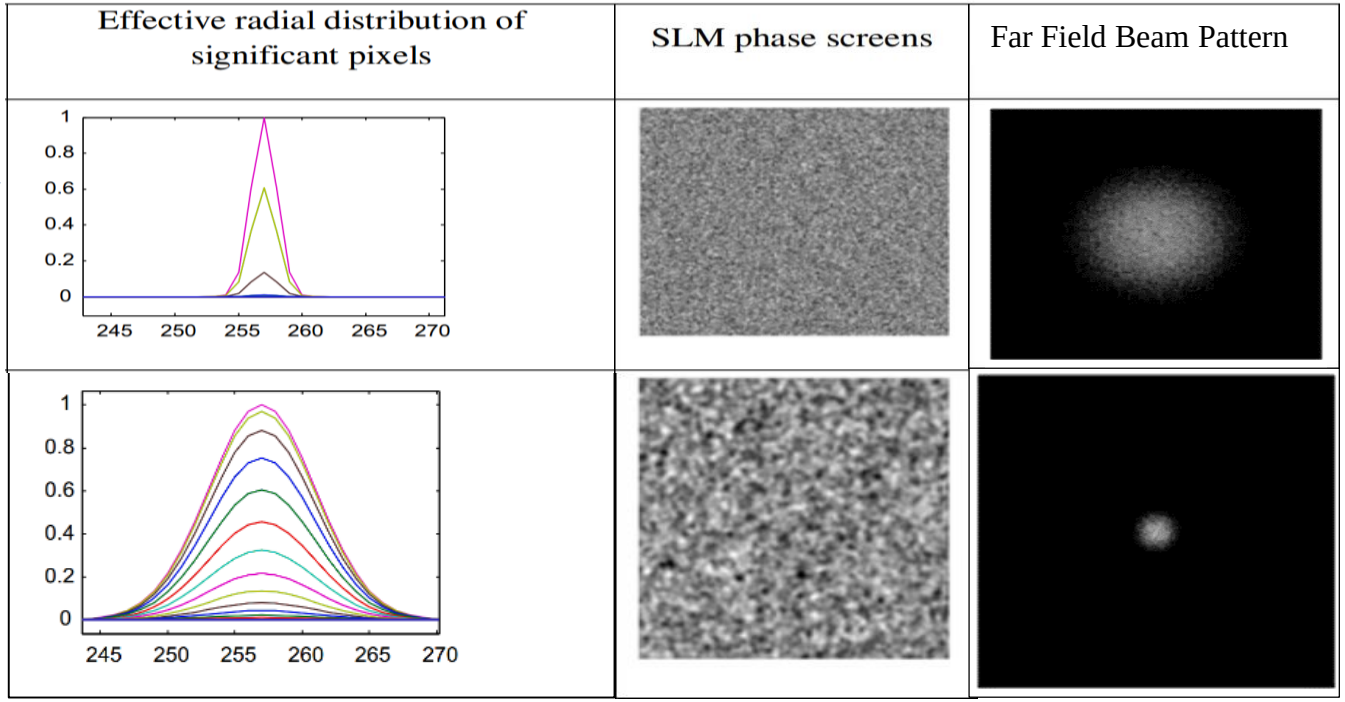
- Temperature Differential
  - -Remote Control Heaters
    - – Force desired heat distribution
  - -Temperature Probes (.1C sensor measurement uncertainty)

- Turbidity
  - -Addition of particulate matter (Turbidity Levels variable at will)
  - -Turbidity Sensor
  - -Flow Sensor
  - -Flow Pump (induced flow, no flow)

Generation of Varying Degrees of Coherence Via SLM

- Spatial Light Modulator – Prescribes phase to beamlet from each spatial location
- 512x512 pixels = 512x512 individual beamlets
- Statistical Methods
- Phase Screens

Strong Diffuser
Weak Diffuser

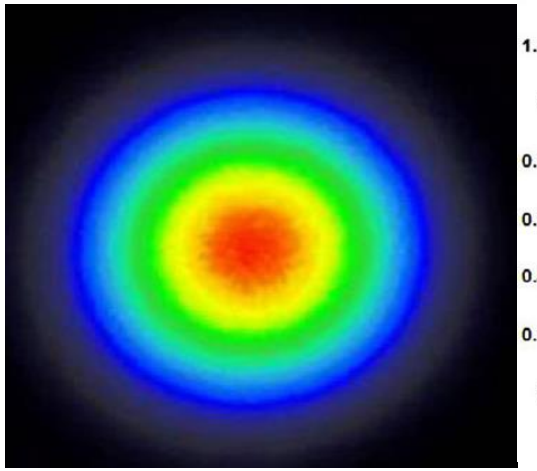


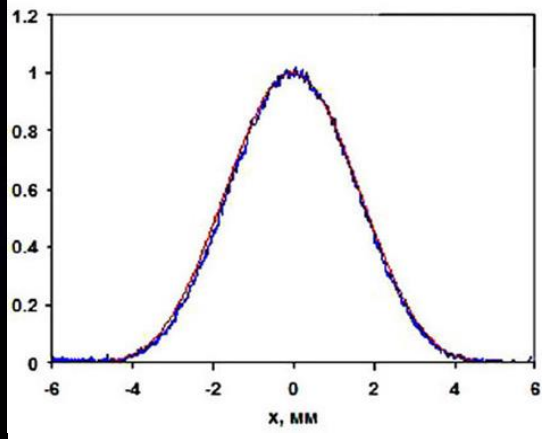
Laser Beam Types

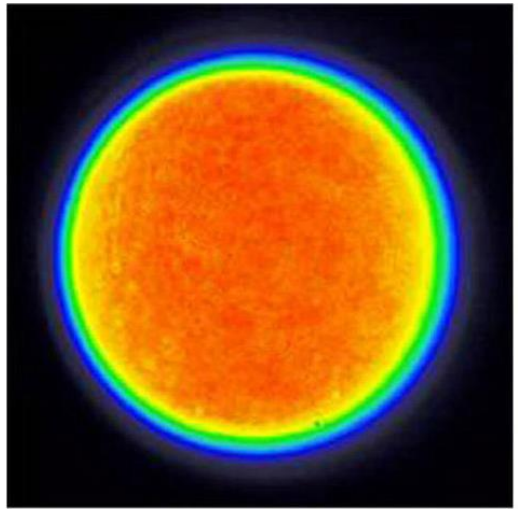
- Standard Gaussian Beam
- Spatially <u>Pseudo</u> Partially Coherent Beams

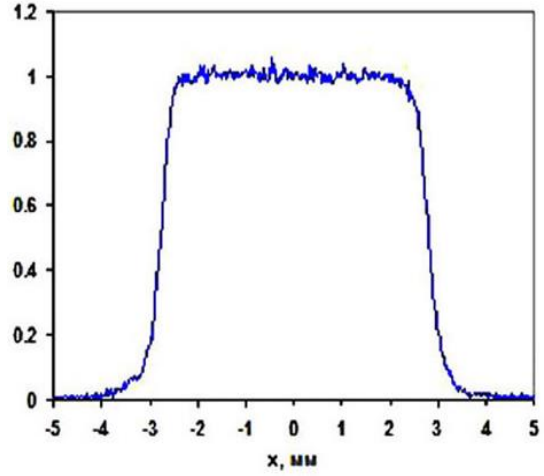
  -<u>Spatial</u> distribution = increased chance to get through medium and constructively interfere on target

  1. <u>Gaussian-Schell Model Beams</u>
     - Maintain Gaussian Statistics
  2. <u>Flat Top</u>
     - Uniform amplitude beneficial for detection vs slope of GSM Beam



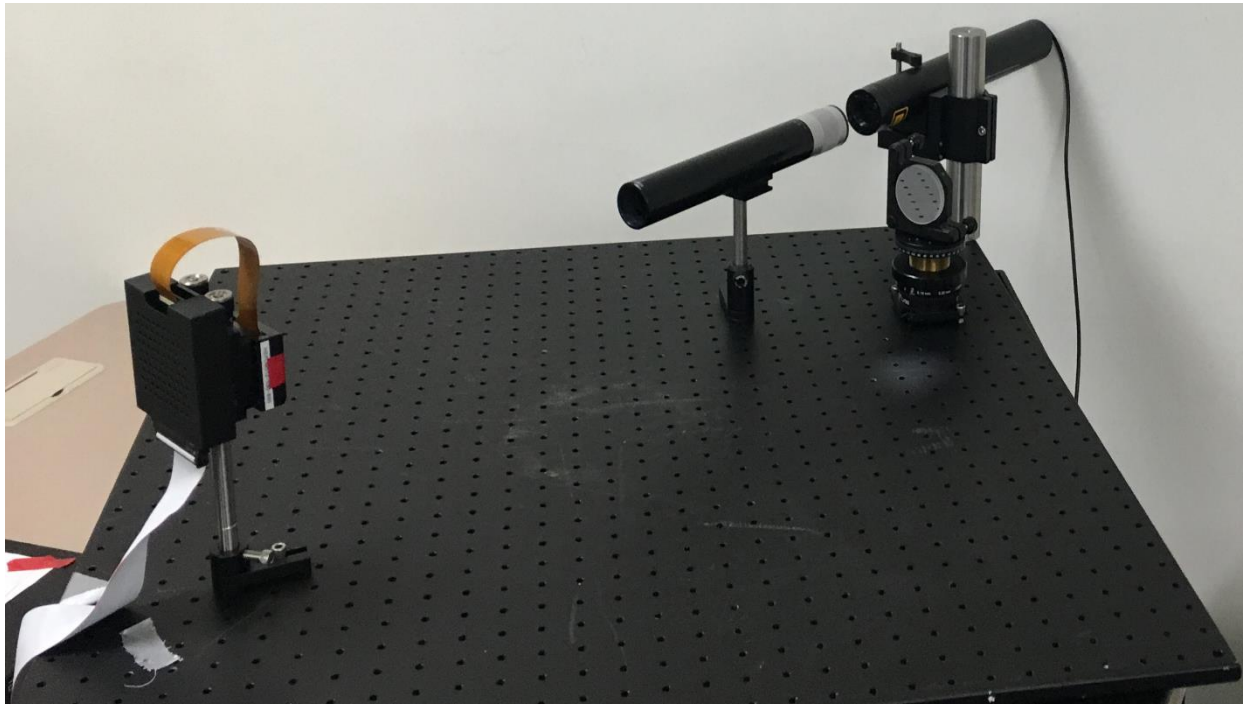






Experimental Process

- Laboratory/Equipment Set up
- Beam Generation – Laser/SLM
- Beam Isolation
- Data Collection – Camera (spatial distribution)
- Data Analysis – MATLAB



Test Plan

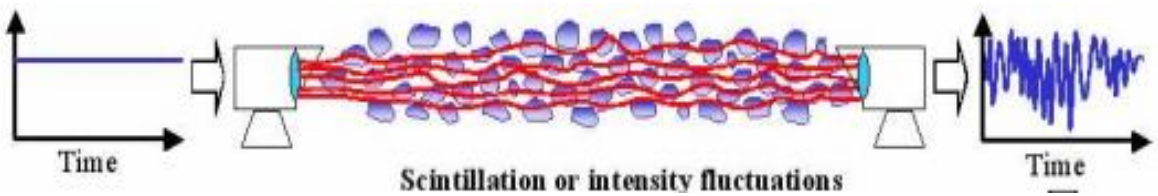
Beams	Gaussian (Control)	Gaussian-Schell Model	Flat-Top
Speckle Size (modulation)	None (Gaussian Only)	0.2 mm (SLM)	1.0 mm (SLM)
Salinity	Real Environment 1	Real Environment 2	Real Environment 3
Temperature Differential	Environmentally Determined	Environmentally Determined	Environmentally Determined
Flow	No Induced Flow	Induced Flow	

Salinity - determined by the environment

Temperature Differentials - environment determines differential sizes
- Actuator range from 77F to 210F, larger if starting from colder water
- all feasible temperature ranges within sensor accuracy

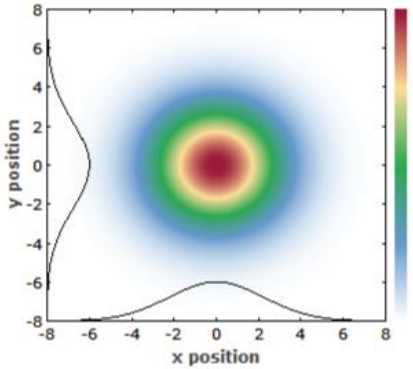
Flow - No flow induced, or flow induced (turbidity)

Data Processing



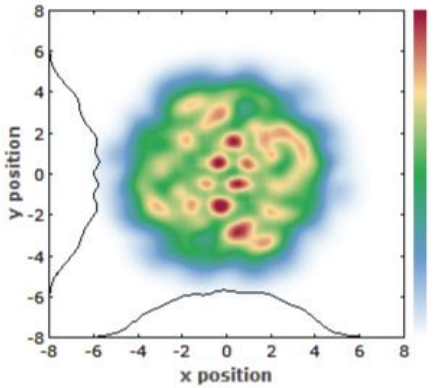
- On-Axis Propagation

Intensity



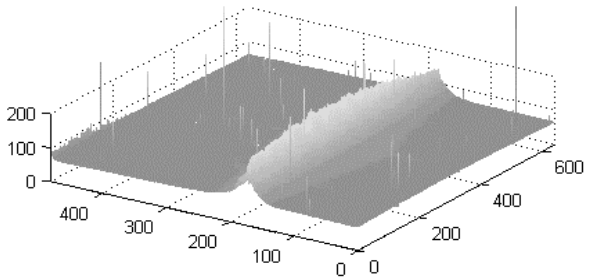
Normalized Variance (Scintillation Index)

$$\sigma_i^2 = \frac{I^2 - I_{avg}^2}{I_{avg}^2}$$

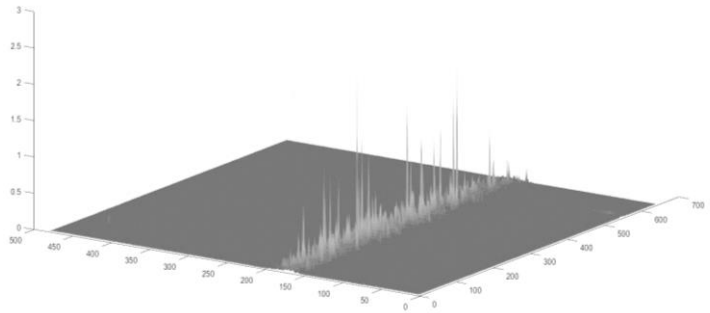


- Off-Axial Scattering

Intensity



Normalized Variance



Timeline

Task Name	Start Date	End Date	Duration (Days)
2ND CLASS SPRING – ES496 Independent Research	1/6/2017	5/11/2017	125
-Sensor/Actuator Implementation/Emulator Development	2/20/2017	5/11/2017	80
1ST CLASS SUMMER – China Lake Internship	7/1/2017	7/31/2017	30
1ST CLASS FALL	8/25/2017	12/23/2017	120
-Evaluation of Emulator	8/25/2017	10/9/2017	45
-Beam Propagation (with and without SLM)	10/9/2017	11/28/2017	50
-Interim Report Development	11/5/2017	12/20/2017	45
1ST CLASS SPRING	1/1/2018	5/8/2018	127
-Data Collection/Processing	1/6/2018	3/1/2018	53
-Final Report Development	1/1/2018	5/1/2018	120

Project Objectives

- Construct test bed to simulate underwater environment
- Characterize the emulator in order to use its characteristics in modeling
- Generate beams of varying spatial coherence for propagation within emulator
- Record data on propagation and scattering of beams
- Analyze the performance of the beams in terms of propagation and scattering

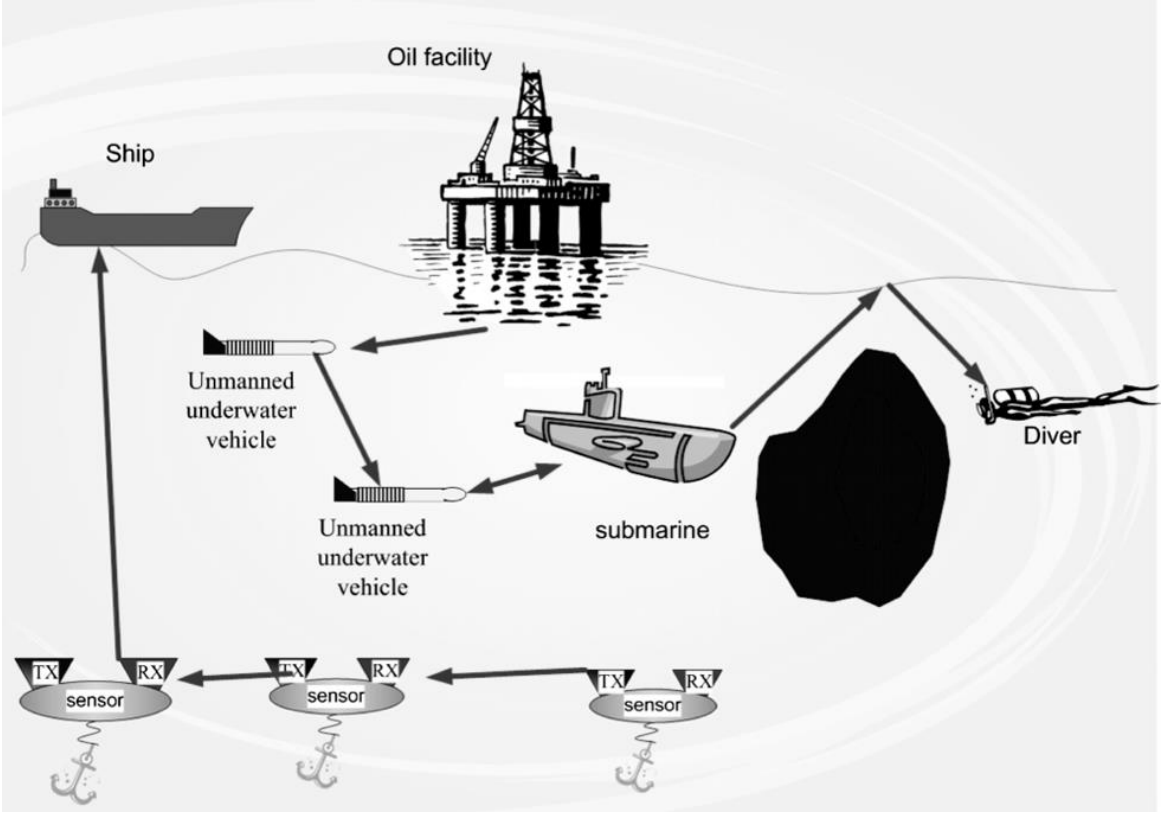
Feasibility Study/Success Matrix

- **Feasibility**:
  - Laboratory components assembled
  - All components commercially available
  - Emulator design methods established
  - Beam generation methods established
  - Work has already begun on emulator

- **Success**:
  - Well characterized emulator will provide consistent and repeatable results
  - Decrease in on-axial scintillation by 10% or more compared against Gaussian beams
  - Decrease in normalized variance of the scattering by 10% or more compared against Gaussian beams
- REACH: Provide data applicable for use in mathematical modeling of environment

Applications

- Laser Communication investigated in the air, land, undersea, and in space
  - NASA Success
- Examples:
  - Diver Communications
  - Submarine Communications
  - UUV Communications
  - Environmental Sensor Arrays



D. M. Boroson, J. J Scozzafava, D. V. Murphy, B.S. Robinson. "The Lunar Laser Communications Demonstration (LLCD)." Space Mission Challenges for Information Technology, 2009. SMC-IT 2009. Third IEEE International Conference on. 2009. 23-28. © 2009 IEEE.

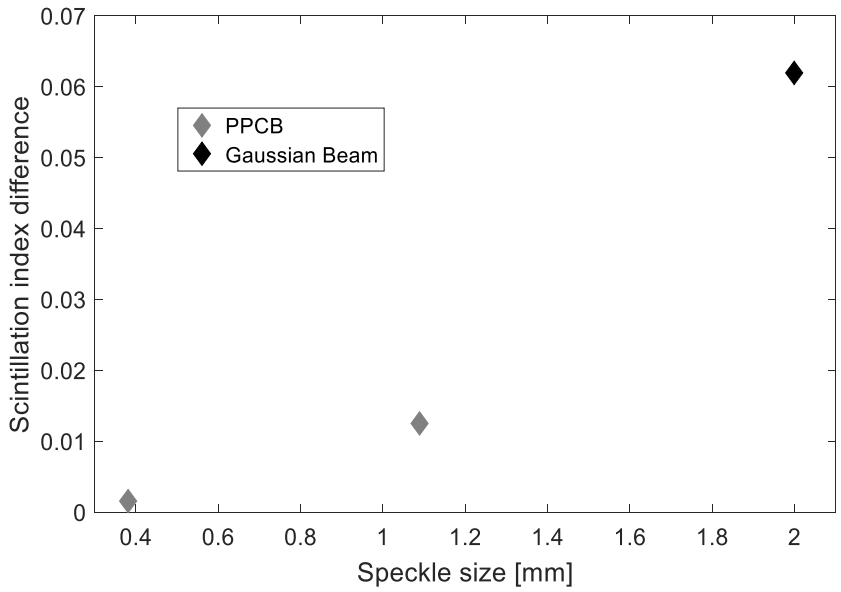
Thank You

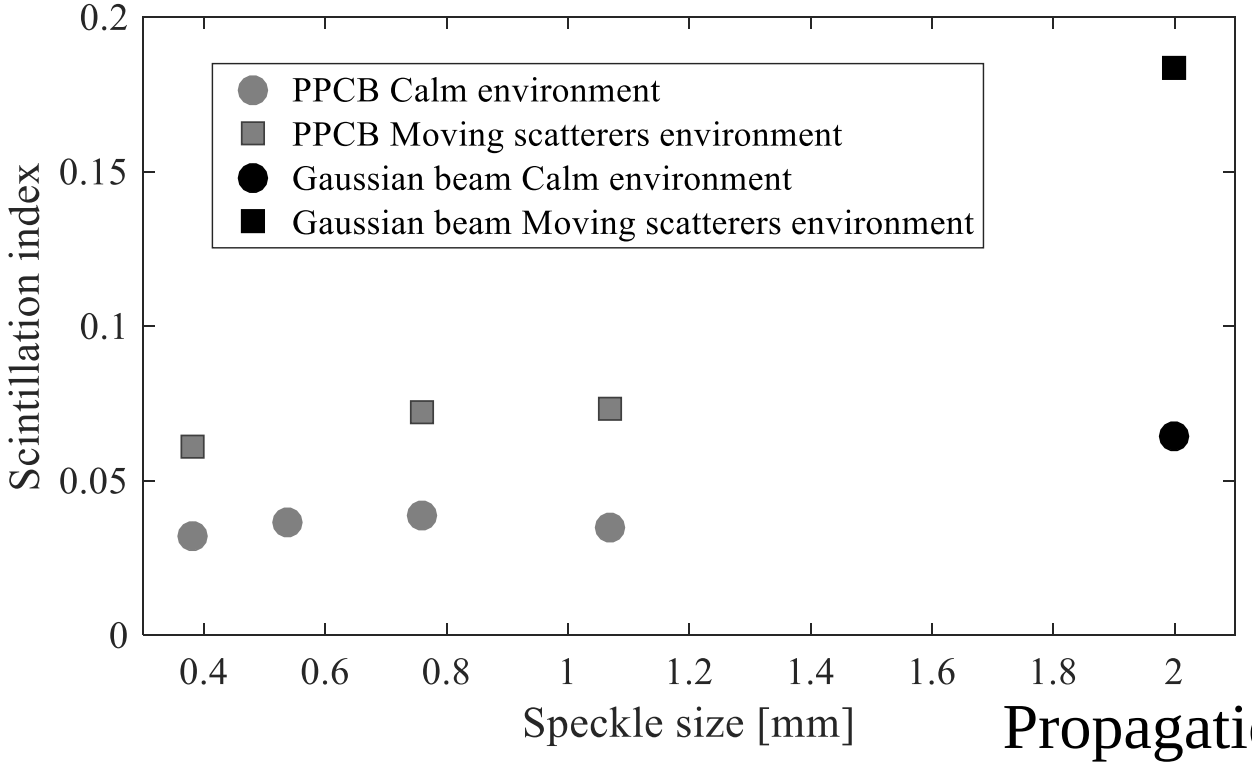
Proof of Concept

-A PPCB is a Spatially Modulated Laser Beam

-Speckle Size refers to degree of modulation/coherence

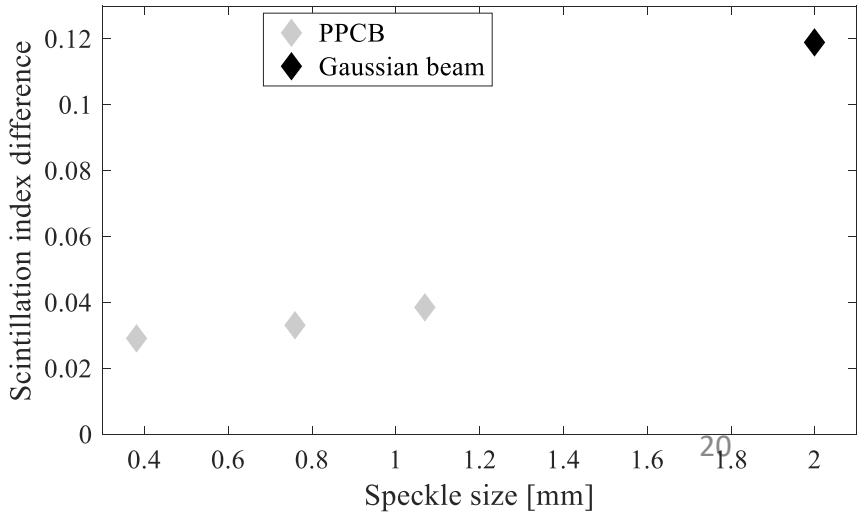
Scattering





Propagation

Propagation



Model Validation

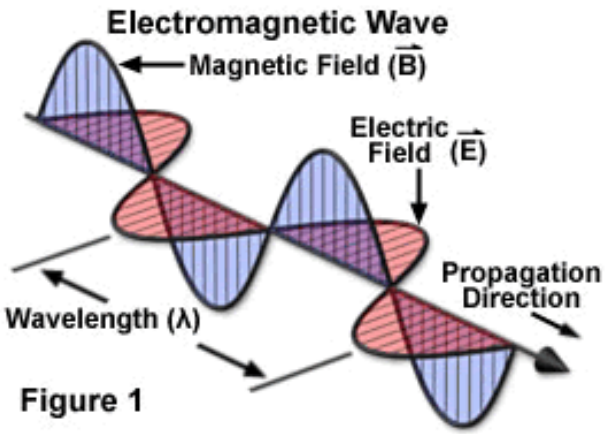
Maxwell's Equation

Traditional Wave Equation

Helmholtz Equation

Paraxial Wave Equation

Stochastic Wave Equation

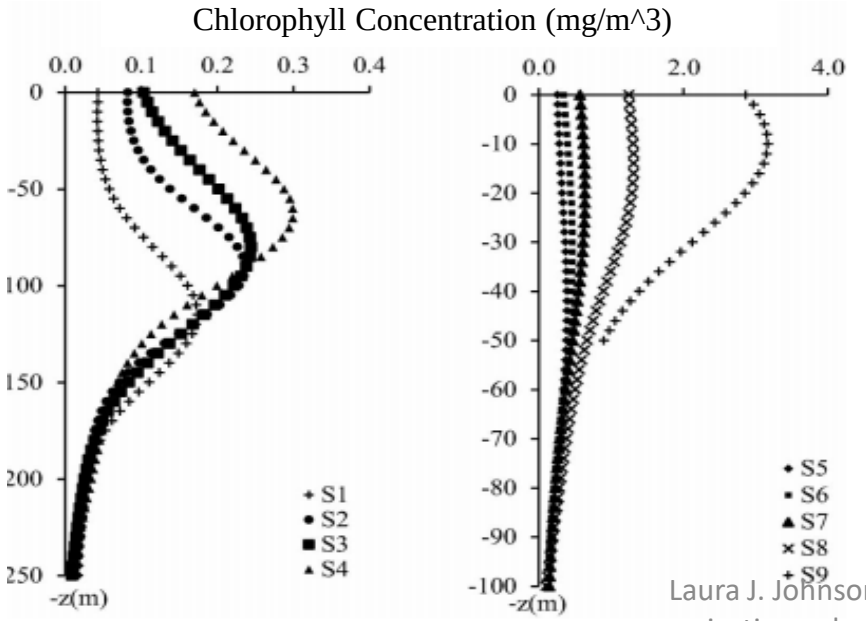


Characteristics of Underwater Propagation

- Absorption
  - Turbidity
  - Salinity
- Scattering
  - Optimal Wavelengths
- Optical Turbulence
  - Temperature
  - Salinity

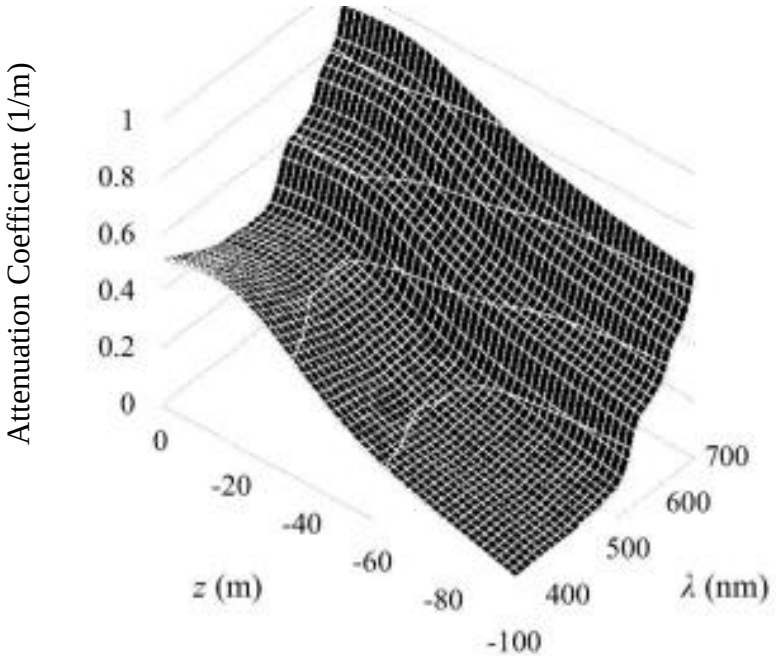
"Underwater optical wireless communications: depth dependent variations in attenuation"
Attenuation-Depth Profiles

- Mathematical creation of attenuation-depth profiles
- Particular focus on chlorophyll-concentration profiles
- Revealed difficulty with water quality/characteristic differences between surface and subsurface
- Presented challenges for vertical comms



-Useful mathematical analysis

-Understanding of Variable Environment



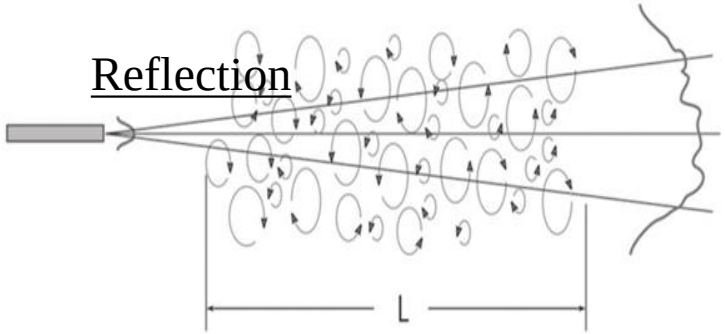
Laura J. Johnson, Roger J. Green, and Mark S. Leeson, "Underwater optical wireless communications: depth dependent variations in attenuation," Appl. Opt. 52, 7867-7873 (2013)

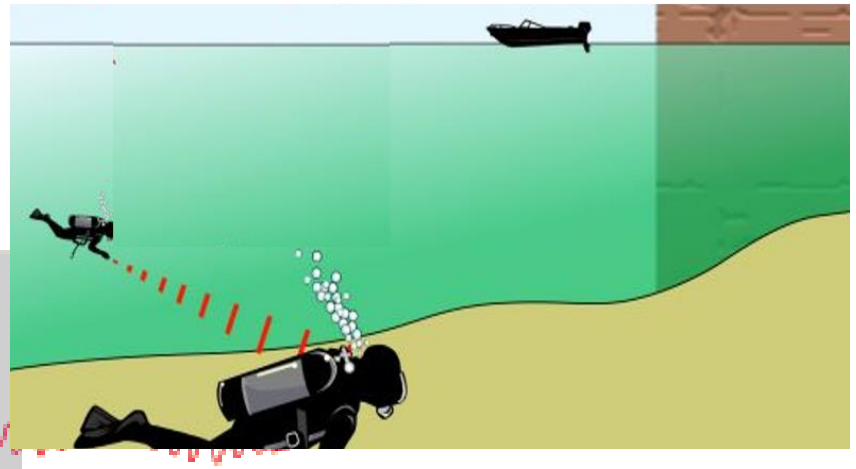
Project Objectives

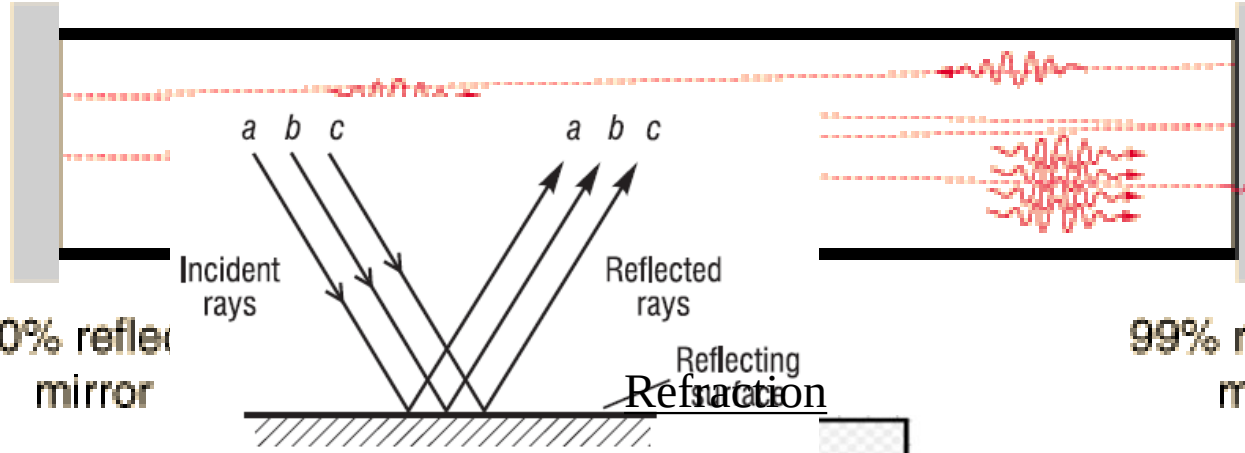
- Construct scalable test bed to simulate underwater environment
- Characterize the emulator
- Generate specific laser beams within emulator
- Record data on propagation and scattering of beams
- Analyze the performance of laser beam

Pics

Reflection



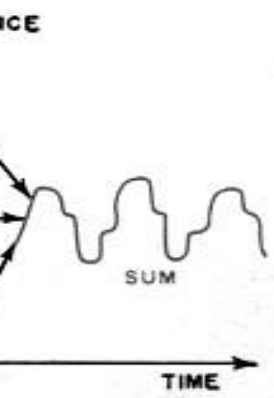


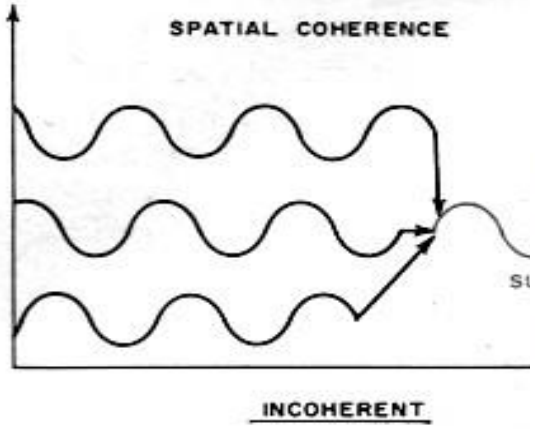


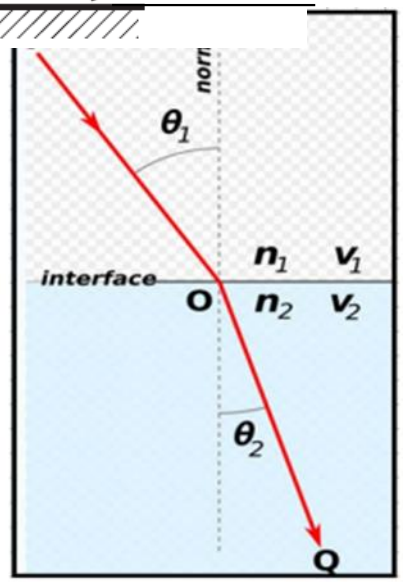
100% reflec mirror

99% reflecti mirror

Refraction







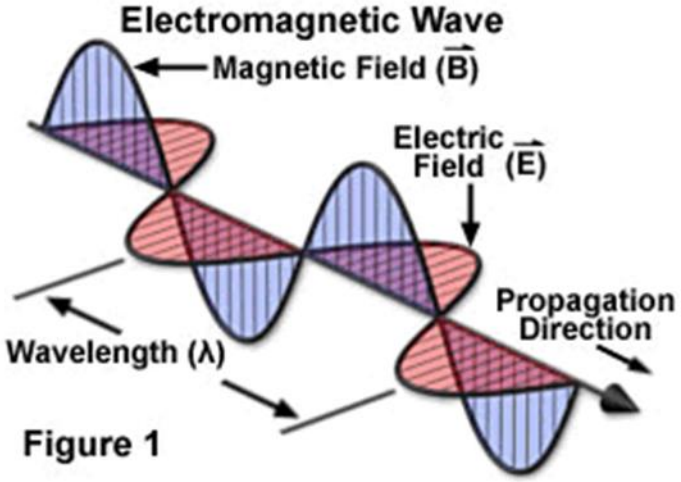
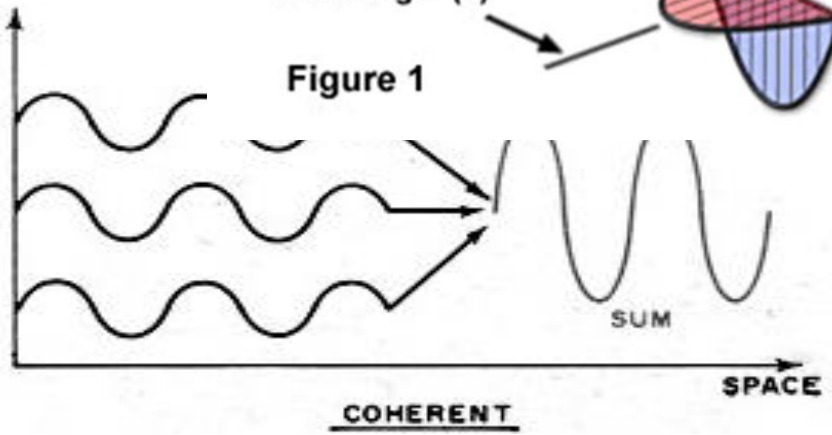



Figure 1