FINAL REPORT

N000141612779

Optical Wavefront Processing for Hybrid Lidar-Radar

N000141612779 : Optical Wavefront Processing for Hybrid Lidar-Radar

Reporting Period: JUN 16, 2017 to JUN 15, 2018

Date Received: 2018-06-15 21:06:54.0

Submitter: William Jemison

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Major Goals

The major project goal is to experimentally demonstrate optical wavefront processing (OWP) to improve the ranging performance of underwater lidar by manipulating the optical wavefront of the lidar beam before it illuminates the lidar receiver. Range enhancements exceeding 25% are desired. Three types of OWP are being investigated: 1. Optical wavefront shaping 2. Optical wavefront sensing 3. Optical wavefront encoding

OWP has been used in a variety of applications including medical imaging and astronomy to correct for wavefront distortions caused by the propagation medium (i.e. human tissue in medical imaging, and the atmosphere in astronomy). We are, to the best of our knowledge, the first group to use SLMs for wavefront processing in underwater lidar to compensate for the effects of optical propagation in turbid water. This compensation is expected to improve the signal to noise ratio of the optical signal prior to the lidar detector to enable temporal digital signal processing techniquies, developed under previous ONR support, to work better in high turbidity conditions.

Accomplishments Under Goals

Two major efforts were undertaken in this reporting period. The first related to optical wavefront shaping, and the second to optical wavefront sensing.

The first effort was to investigate the possibility of achieving improvements in underwater lidar systems by transmitting orbital angular momentum (OAM) laser beams instead of conventional Gaussian beams. The scientific literature suggests that when OAM beams scatter off particles, there is less light scattered directly forward and also less light scattered directly backward compared to Gaussian beams. The literature suggests that this could lead to higher signal-to-interference-and-noise (SINR) ratios in lidar systems. The possibility of achieving SINR improvements in turbid water lidar was investigated analytically, numerically, and experimentally during this reporting period. New mathematical and computational tools were developed to assist in this investigation. The investigation concluded that for typical coastal and harbor water turbidities, there is not likely to be an SINR gain when OAM beams are used instead of Gaussian.

The second effort also investigated using OAM beams to improve lidar performance, but in this case, the OAM beams were generated at the receiver rather than at the transmitter. Here, OAM optics were used to separate coherent target light from forward scattered target light. This proved to be an effective way of improving range measurement accuracy. Typical range measurement errors in turbid water were reduced by as much as 90% relative to using conventional receiving optics. (Please see supplementary document for more details.)

Plans Next Period

In the next reporting period, development work will build on the success of using optics to separate unscattered target light from forward scattered target light, by looking to separate unscattered target light from backscattered light. If successful, this would allow backscatter to be removed from the lidar measurement before it reaches the opto-electronic receiver, rather than relying on digital filtering to remove the backscatter after it reaches the receiver. System analysis performed on Clarkson University's chaotic lidar ONR project suggests that this would result in a significant improvement in SINR relative to using digital filtering only. This would in turn increase the probability of detection (PD) for the lidar, or alternatively allow a reduction in transmitter signal energy. For example, in one case study it was estimated that if 90% of the backscatter could be removed, the PD would increase from 22% to 99.9%, or alternatively the transmitter energy could be reduced by 5x.

Preliminary work on this idea has suggested the feasibility of backscatter removal using either OAM optics or grating optics. A patent disclosure is in progress.

Results Dissemination

An in-person status briefing was given to the program manager at the ONR offices in Washington DC in August 2017.

An in-person program review as held at NUWC Newport in June 2018, at which a briefing was given to an audience of ONR staff, a program review committee, and graduate students and faculty.

A paper on enhanced underwater lidar performance using OAM phase plates was published in Optics Express in February 2018.

A paper on the propagation of OAM beams underwater was presented at the SPIE Defense and Commercial Sensing conference in April 2018.

A lecture on underwater beam propagation was given to Clarkson's digital signal processing class in November 2017, to an audience of about 25 students.

A seminar on enhanced underwater lidar performance using OAM phase plates was given to Clarkson's physics department in November 2017, to an audience of about 30 graduate students and faculty.

Honors and Awards

Austin Jantzi's paper on underwater propagation of OAM beams was recognized with an Honorable Mention award at SPIE DCS 2018.

Training Opportunities

Austin Jantzi attended the SPIE Defense and Commercial Sensing conference in April 2018.

Mr. Jantzi took graduate courses at Clarkson University, earning 30 credits towards his doctorate.

Austin Jantzi participated in a 10-week summer internship at NAWCAD from June-August 2017, supported by the Naval Research Enterprise Internship Program.

Technology Transfer

This project benefits from close collaboration with NAWCAD Patuxent River. Technical discussions about the project are regularly held by phone. Status update presentations are given every 1-2 months to NAWCAD staff.

This project's program review was held at NUWC Newport in June 2018.

Participants

Name	Role	Person Months
Rumbaugh, Luke	Co PD/PI	1
Jantzi, Austin	Graduate Student (research assistant)	12
Jemison, William	PD/PI	1

ONR Research Performance Progress Report

Project: Optical Wavefront Processing for Hybrid Lidar-Radar
(Grant # N000141612779)

Reporting Period: 16 June 2017 to 15 June 2018

Reporting PI: Dr. William Jemison, Clarkson University, Potsdam, NY

The following materials supplement the "Accomplishments" section of the ONR RPPR submitted to ARO Extranet.

What was accomplished towards achieving this project's goals?

Text from Extranet: The first effort was to investigate the possibility of achieving improvements in underwater lidar systems by transmitting orbital angular momentum (OAM) laser beams instead of conventional Gaussian beams.

The scientific literature suggests that when OAM beams scatter off particles, there is less light scattered directly forward and also less light scattered directly backward compared to Gaussian beams. The literature suggests that this could lead to higher signal-to-interference-and-noise (SINR) ratios in lidar systems. The possibility of achieving SINR improvements in turbid water lidar was investigated analytically, numerically, and experimentally during this reporting period. New mathematical and computational tools were developed to assist in this investigation.

The investigation concluded that for typical coastal and harbor water turbidities, there is not likely to be an SINR gain when OAM beams are used instead of Gaussian. While this null result was disappointing on one level, it represented a major contribution to the knowledge base of the underwater lidar community, which had developed an interest in the possibilities of OAM beam propagation.

Supplementary details: The hypothesis from literature is shown in Figure 1. An OAM beam scattering off a single particle is known to experience less direct backscatter and direct forward scatter than a Gaussian beam.

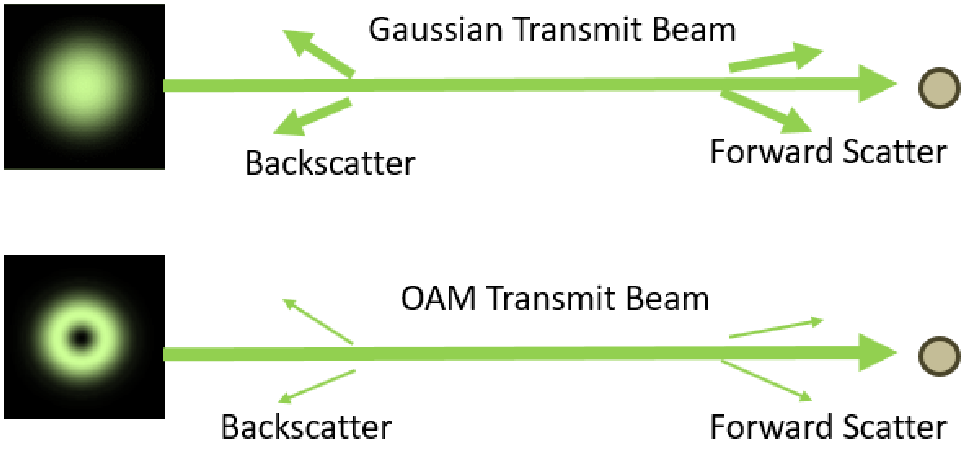


Figure 1. Hypothesis from scientific literature: OAM beam transmission will lead to less direct backscatter and less direct forward scatter.

Using numerical electromagnetic solvers, it was found that this was indeed true for a single particle, and in particular it was true for single particle of interest in underwater environments. However, using a new combination of analytical and numerical tools, it was found that there is little difference between the aggregate backscattering and forward scattering patterns generated using OAM and Gaussian beams. Figure 2 shows the difference – or, lack of a significant difference – in forward scatter between the two beam types for realistic water conditions.

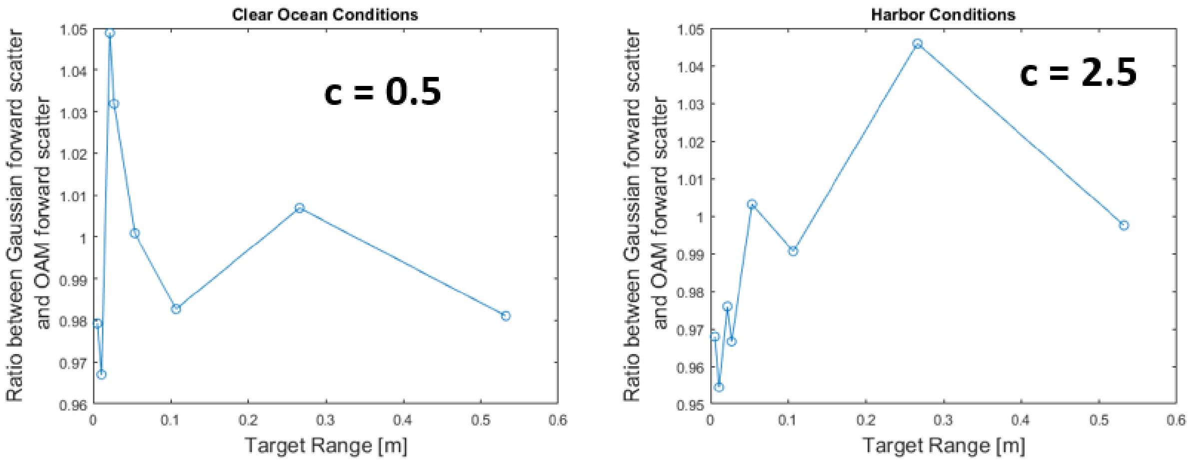


Figure 2. Comparison of total forward scattered light hitting an object when using a Gaussian laser beam and an OAM laser beam in turbid water. The x-axis is the distance to the object illuminated by the forward scattered beam. The y-axis would be 1 if there were no difference, and would be far from 1 if there were significant difference. *Left:* In coastal ocean conditions, there is little difference; the curve is nearly 1 after 0.1 m. *Right:* In turbid harbor conditions, there is little difference; the curve is nearly 1 after 0.4 m.

Text from Extranet: The second effort also investigated using OAM beams to improve lidar performance, but in this case, the OAM beams were generated at the receiver rather than at the transmitter. Here, OAM optics were used to separate coherent target light from forward scattered target light. This proved to be an effective way of improving range measurement accuracy. Typical range measurement errors in turbid water were reduced by as much as 90% relative to using conventional receiving optics. (Please see supplementary document for more details.)

Supplementary details: Figure 3 shows the approach taken to allow separation of unscattered, coherent light and forward scattered, incoherent light reflected from the target. An OAM spiral phase plate was placed in the receiver's optical train. This changed the amplitude profile of any spatially coherent light (i.e., light with a flat wavefront) into an annulus shape. Any *incoherent* light was not affected. After the phase plate, a streak camera was used to observe the light. The streak camera took a rapid sequence of slices from the middle of the received beam. Unscattered, spatially coherent light reflected from the target fell onto the streak camera in two discrete locations away from the center of the camera. Forward scattered, spatially incoherent light from the target fell across the entire active width of the camera.

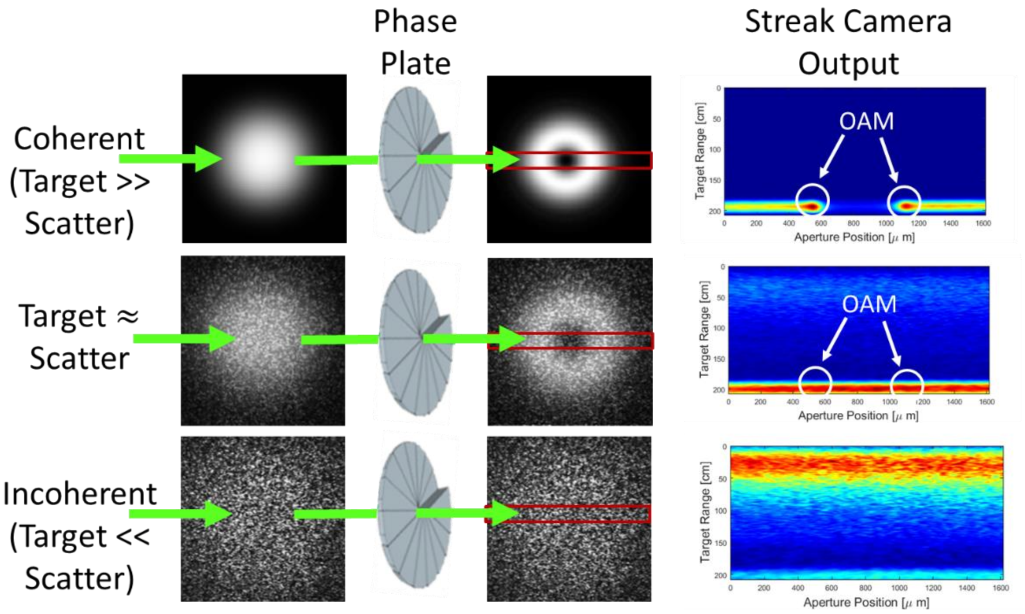
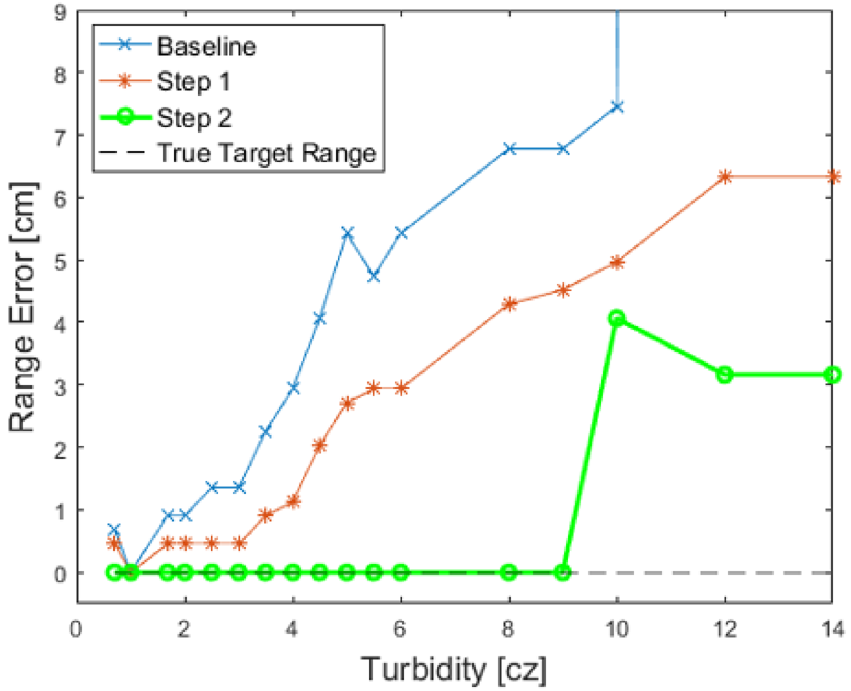


Figure 3. Using a spiral phase plate and a streak camera to separate unscattered (coherent) light from scattered (incoherent) light in a lidar measurement. *Left:* Amplitude profiles of the beams reflected by the targets and entering the receiver. *Center:* Beams after passing through the phase plate. The red slice shows the region imaged by the streak camera. *Right:* Streak camera image taken from a sequence of beams. The "OAM" spots show where coherent light falls. Scattered light falls across the entire width of the camera.

Digital image processing allowed separation of the coherent from incoherent light, with the result that the coherent light could be isolated. This allowed the range to be more accurately estimated. Figure 4 shows the effective improvement in range measurements. The range error using the phase plate and streak camera (green trace) is significantly less than with the streak camera alone (blue trace), especially at high turbidities.



Significantly reduced range error and extended operating range!

Figure 4. Reduction in range error using the OAM phase plate technique. The range error using a streak camera with no phase plate is shown in blue. The error increases nearly linearly until a turbidity of 10 cz, at which point the error jumps as the sensor tracks the backscatter. The range error using a phase plate and streak camera is shown in green. The error is nearly zero until 10 cz, after which it is nonzero but still much lower than the baseline.

N000141612779 : Optical Wavefront Processing for Hybrid Lidar-Radar

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Major Goals

The major project goal is to experimentally demonstrate optical wavefront processing (OWP) to improve the ranging performance of underwater lidar by manipulating the optical wavefront of the lidar beam before it illuminates the lidar receiver. Range enhancements exceeding 25% are desired. Three types of OWP are being investigated: 1. Optical wavefront shaping 2. Optical wavefront sensing 3. Optical wavefront encoding OWP has been used in a variety of applications including medical imaging and astronomy to correct for wavefront distortions caused by the propagation medium (i.e. human tissue in medical imaging, and the atmosphere in astronomy). We are, to the best of our knowledge, the first group to use SLMs for wavefront processing in underwater lidar to compensate for the effects of optical propagation in turbid water. This compensation is expected to improve the signal to noise ratio of the optical signal prior to the lidar detector to enable temporal digital signal processing techniquies, developed under previous ONR support, to work better in high turbidity conditions.

Accomplishments Under Goals

Overview of Work Performed: In the first year of this project we investigated the use of spatial light modulators (SLMs) for optical wavefront shaping. This approach leverages emerging commercial-off-the-shelf (COTs) SLMs to shape the underwater lidar beam to compensate for scattering thus allowing more target light to be collected by the system. SLM devices have matured significantly over the last decade and they now support millions of pixels that can be individually programmed over several pi of phase shift. This allows the SLM to be used as a programmable optical lens or wavefront shaper. We explored two optical wavefront shaping approaches. In the first approach, the SLM was used as a programmable lens to compensate for the forward scattering of light in turbid water. This forward scattering effectively acts as a diverging lens. By modifying the focal length and curvature function of an SLM placed at the lidar transmitter the divergence due to scattering can be reduced which will allow more light to hit the target and to be collected by the receiver for a given turbidity. In the second approach, the SLM was used to autofocus through turbid water. An adaptive algorithm was used to correct for scattering effects allowing more light to be focused at a desired location.

Progress towards each approach is described later in this report.

Plans Next Period

The plans for the next reporting period are consistent with the agency-approved application:

We will continue to improve our optical wavefront shaping results. Specifically, we will continue to improve the adaptive algorithms used for autofocusing the lidar beam to compensate for the distortion introduced by turbid water. We will seek improvments in convergence time and autofocusing performance. To date we have conducted the optical wavefront shaping experiments in benchtop experiments using only small volumes of water with limited ranges of turbidity. Experiements will be repeated in Clarkson's 28 foot lidar test tank under a range of turbidities.

We will begin to investigate optical wavefront encoding to improve underwater lidar performance. Specifically, we will investigate the performance of orbital angular momentum (OAM) beams for underwater lidar. This investigation will build on initial experiments conducted by the Navy that indicate that OAM beams may improve the discrimination of target signals in low light environments by leveraging the optical coherence properties of OAM beams. Mr. Austin Jantzi, the graduate student supported by this program, will conduct experiements at NAWC-AD in Patuxent River during the summer of 2017 under the Naval Research Enterprise Internship Program (NREIP). He will continue these experiments at Clarkson Univeristy after completing the NREIP.

Results Dissemination

Mr. Jantzi presented a progress report at the 2017 ONR Navy Undersea Research Program Review held June 6-8th in Arlington, VA.

Honors and Awards

Nothing to Report

Training Opportunities

Mr. Austin Jantzi, the graduate student supported by this program, advanced his professional skills in setting up optics experiments, developing signal processing algorithrms, and analyzing data. Mr. Jantzi also presented a progress report at the 2017 ONR Navy Undersea Research Program Review held June 6-8th in Arlington, VA.

Technology Transfer

Nothing to Report

Participants

Name	Role	Person Months
Crouse, David	Co PD/PI	1
Rumbaugh, Luke	Co PD/PI	1
Jantzi, Austin	Graduate Student (research assistant)	12
Jemison, William	PD/PI	1

Accomplished Under Goals Summary:

Project Goal: This project investigates the use of optical wavefront processing (OWP) to improve the performance of underwater lidar by manipulating the optical wavefront of the lidar beam before it illuminates the lidar receiver. Three types of OWP are being investigated:

1. Optical wavefront shaping
2. Optical wavefront sensing
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Optical Wavefront Shaping Approach #1 - Programmable Lens

The experimental setup for this optical wavefront shaping experiment is shown in Figure 1. The laser source illuminates an SLM that is programmed as a lens with a variable focal length and curvature function. The output of the SLM illuminates a volume of turbid water. An optical trap was used to block ballistic or non-scattered light to isolate the forwards scattered light. In this preliminary set of experiments a small beaker of water was used with Maalox added as a scattering agent. Hundreds of combinations of focal length and curvature functions were used while monitoring for a maximum intensity distribution. The best results indicated an intensity enhancement factor ranging from 6x to 10x. This is an encouraging results using a straightforward technique. As discussed in the plans for future work, in the coming period of performance this experiment will be repeated in Clarkson’s 28 foot lidar tank under a variety of turbidites.

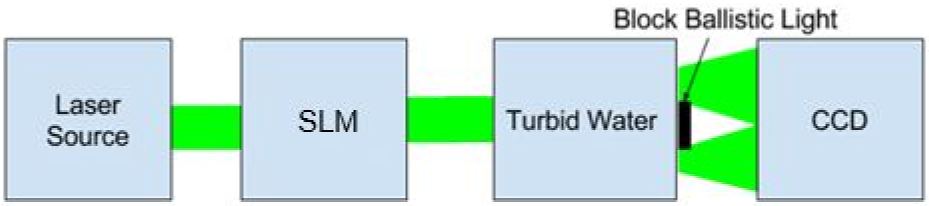


Figure 1. Experimental setup for the programmable lens experiment

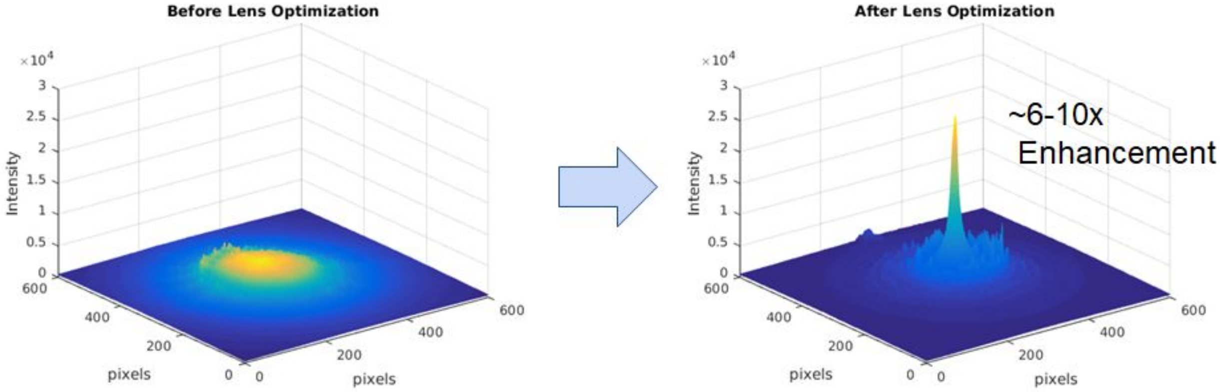


Figure 2. Experimental result - the best results showed a 6-10x enhancement in the peak intensity.

Optical Wavefront Shaping Approach #2 - Autofocusing

Autofocusing through turbid water is anticipated to be challenging since the particulate in the water that causes scattering is constantly moving, producing a dynamic scattering environment. Therefore, we initially implemented our autofocusing algorithms using paper as a static optical scattering medium. Paper is a diffuse scatterer, mimicking the diffuse scattering of underwater targets. This static case allowed us to test our algorithms in a controlled environment. Figures 3 and 4 show the experimental setup used to focus a laser through a piece of paper. The SLM first focused the laser beam onto a piece of paper. The paper then scattered the laser beam in an arbitrary pattern, which was imaged onto the sCMOS camera using a microscope objective. The SLM's phase pattern was then adaptively changed to focus the paper-scattered light onto the camera. The SLM phase pattern was chosen using feedback from the camera's observation of the arbitrary scattering pattern.

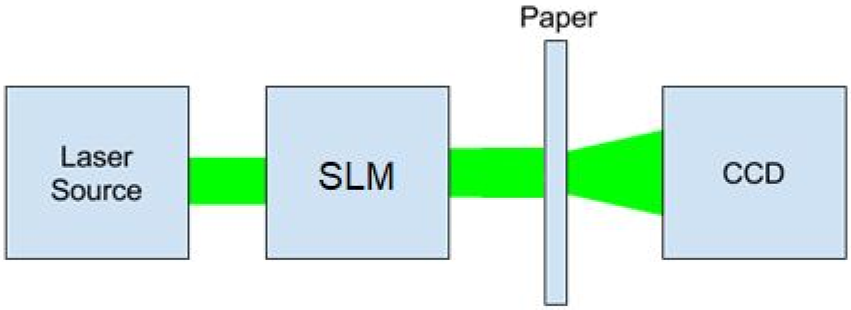


Figure 3. The experimental setup for focusing through a thin scatterer.

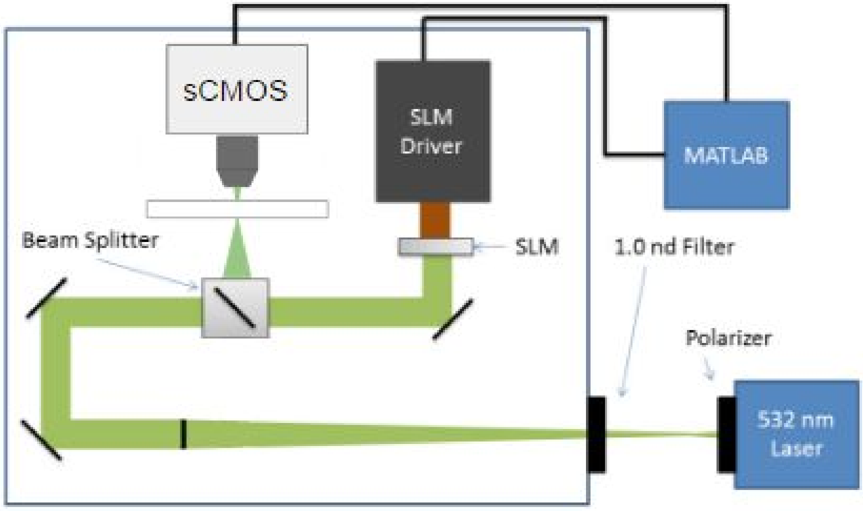
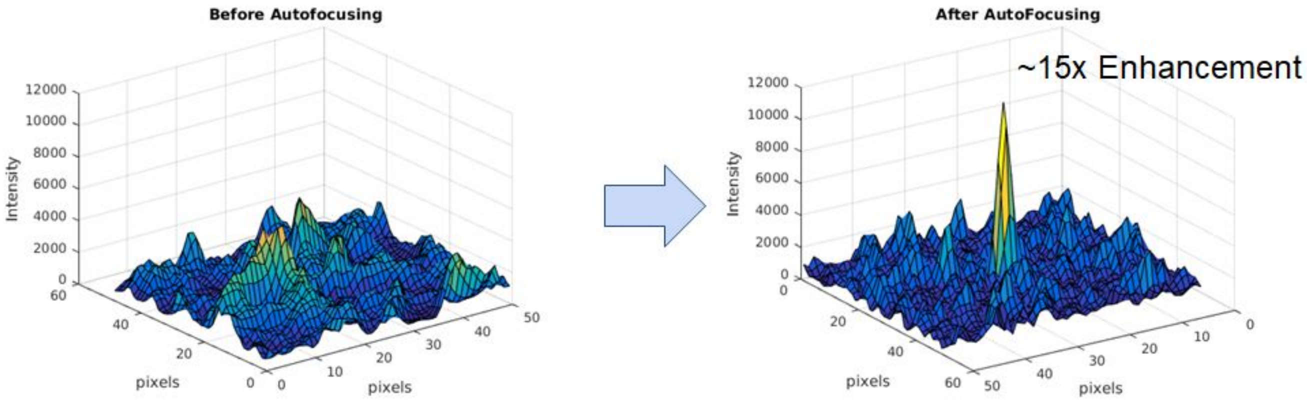


Figure 4. The experimental setup for focusing through a thin scatterer. A piece of paper was placed in the beam path to scatter the laser beam. The SLM initially focused the beam onto the paper, and a microscope objective collimated the scattered light onto the camera.

As shown in Figure 5, the intensity of the light was enhanced by approximately 15 time after autofocusing. Also, when focusing through paper, the focus was significantly sharper than focusing through air. This was actually *because* of the arbitrary scattering pattern created by the paper. The scattering pattern was so arbitrary that, when the SLM was used to constructively interfere different parts of the pattern at the focus point, no other points experienced constructive interference.



Before Autofocusing

After AutoFocusing

Figure 5. By observing the intensity at a desired focal point, varying the phase, and selecting the phase that gives maximum constructive interference, a laser beam can be focused through a piece of paper. *Left:* Image of scattered laser beam at the camera, before any optimization. *Right:* Image of laser beam focused through the piece of paper

The next step was to replace the paper with a volume of turbid water. In this preliminary experiment a small beaker of water was used with Maalox added as a scattering agent. A block diagram of the experimental approach is shown in Figure 6 and a typical experimental result is shown in Figure 7. A 2.5 times enhancement was achieved in this proof-of-concept experiment. As discussed in the plans for future work, in the coming period of performance this experiment will be repeated in Clarkson's 28 foot lidar tank under a variety of turbidites.

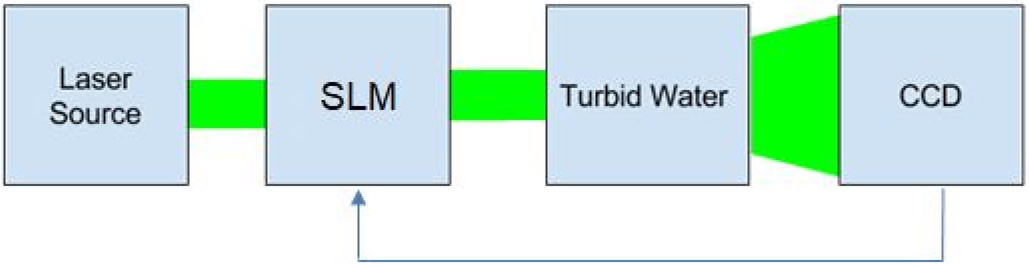


Figure 6. Block diagram of experimental approach of autofocusing through turbid water.

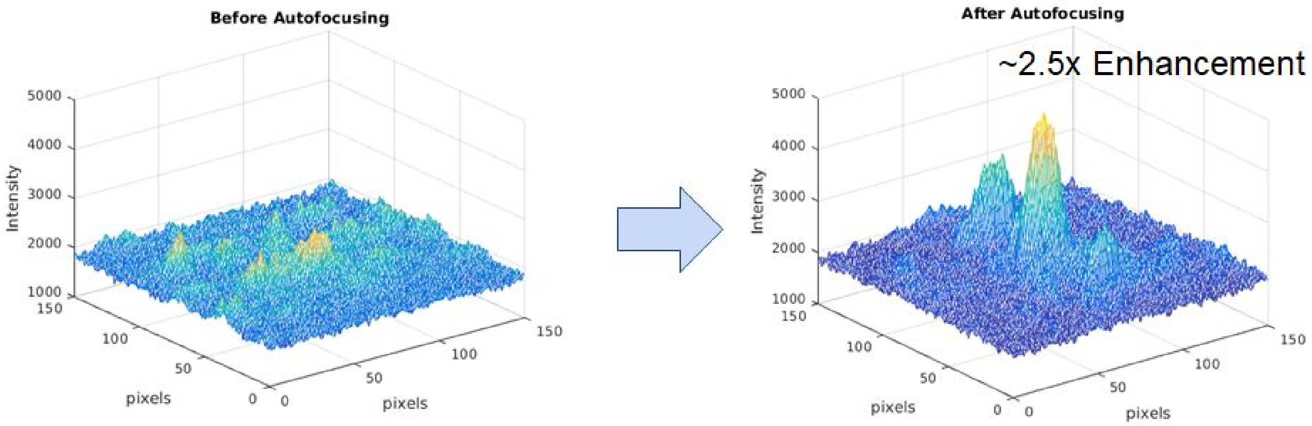


Figure 7. Experimental result of autofocusing through turbid water showing a 2.5 times enhancement in peak intensity.

A high-level summary of the experiments performed are shown below.

Experiments	Result	Takaway	Enhancement
1. Collimating Scattered Light in Turbid Water	✓	Simple; Promising	~6-10x
2. Autofocusing through Paper	✓	Worked Well	~15x
2. Autofocusing through Turbid Water	?	Further Investigation Ongoing	~2.5x

Future Plans

We plan to continue investigating autofocusing in turbid water, transitioning the benchtop experiments to the more realistic conditions in the large lidar test tanks at both Clarkson University and the Naval Air Warfare Center Aircraft Division (NAWC-AD), seeking to achieve enhancements in intensity closer to the enhancements observed in the case of a static scatterer. In the summer of 2017, experiments will be conducted to test the performance of optical wavefront sensing, another type of OWP. This initial investigation of using optical techniques to discriminate between scattered and unscattered light will be conducted at NAWC-AD.

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Submitter: William Jemison

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Major Goals

The major project goal is to experimentally demonstrate optical wavefront processing (OWP) to improve the ranging performance of underwater lidar by manipulating the optical wavefront of the lidar beam before it illuminates the lidar receiver. Range enhancements exceeding 25% are desired. Three types of OWP are being investigated:

1. Optical wavefront shaping 2. Optical wavefront sensing 3. Optical wavefront encoding

OWP has been used in a variety of applications including medical imaging and astronomy to correct for wavefront distortions caused by the propagation medium (i.e. human tissue in medical imaging, and the atmosphere in astronomy). We are, to the best of our knowledge, the first group to use SLMs for wavefront processing in underwater lidar to compensate for the effects of optical propagation in turbid water. This compensation is expected to improve the signal to noise ratio of the optical signal prior to the lidar detector to enable temporal digital signal processing technique, developed under previous ONR support, to work better in high turbidity conditions.

Accomplishments Under Goals

Two major efforts were undertaken in this reporting period. The first related to optical wavefront shaping, and the second to optical wavefront sensing.

The first effort was to investigate the possibility of achieving improvements in underwater lidar systems by transmitting orbital angular momentum (OAM) laser beams instead of conventional Gaussian beams. The scientific literature suggests that when OAM beams scatter off particles, there is less light scattered directly forward and also less light scattered directly backward compared to Gaussian beams. The literature suggests that this could lead to higher signal-to-interference-and-noise (SINR) ratios in lidar systems. The possibility of achieving SINR improvements in turbid water lidar was investigated analytically, numerically, and experimentally during this reporting period. Models for beam propagation in underwater environments were developed using numerical and analytic methods and show excellent agreement with experimental results. The investigation concluded that for typical coastal and harbor water turbidities, there is not likely to be an SINR gain or improved beam propagation when OAM beams are used instead of Gaussian.

The second effort investigated using receiver optics that rely on spatial optical coherence to improve lidar performance. These devices, such as diffraction gratings and axicons, shape the spatially coherent light in a well-defined way, while leaving the incoherent light unchanged. This is used to spatially separate coherent target light from forward scattered target light and from backscattered light. This spatial separation allows scattered light to be removed from the lidar measurement before it reaches the opto-electronic receiver, rather than relying on digital filtering to remove the backscatter after it reaches the receiver. This method was demonstrated to spatially separate target light from scattered light, and reduce the effects of scattering on beam transmission relative to conventional receiving optics. A provisional patent disclosure has been filed.

Plans Next Period

In the next reporting period, development work will focus on axicon receiver optics as the filtering method used to spatially separate target and scattered light and remove the scatted light from the system before opto-electronic detection. System analysis performed on Clarkson University’s chaotic lidar ONR project suggests that this would result in a significant improvement in SINR relative to using digital filtering only. This would in turn increase the probability of detection (PD) for the lidar, or alternatively allow a reduction in transmitter signal energy. For example, in one case study it was estimated that if 90% of the backscatter could be removed, the PD would increase from 22% to 99.9%, or alternatively the transmitter energy could be reduced by 5x. Initial results show that spatial optical coherence filtering with axicons reduces the intensity of light collected. Temporally resolved measurements will show the effect of the spatial optical coherence filtering on backscatter light and target light, and how this effect evolves with increasing turbidity. A patent disclosure is in progress.

Results Dissemination

An in-person status briefing was given to the program manager at the ONR offices in Washington DC in August 2018.

An in-person program review as held at NUWC Division Keyport in June 2019, at which a briefing was given to an audience of ONR staff, a program review committee, and graduate students and faculty.

A seminar on enhanced underwater lidar performance using OAM phase plates was given at the RAD-Lidar conference in November 2018, to an audience of about 30 researchers.

A paper on a mixed numerical and analytical method for investigating OAM beam scattering in turbid water using OAM phase plates was published in Optics Engineering in April 2019.

A paper on spatial coherence filtering for scatter rejection in underwater laser systems was presented at the SPIE Defense and Commercial Sensing conference in April 2019.

Honors and Awards

Austin Jantzi's paper on spatial coherence filtering for scatter rejection in underwater laser systems was recognized with an Honorable Mention award at SPIE DCS 2019.

Training Opportunities

Austin Jantzi attended the FAU RAD-Lidar conference in November 2018.

Austin Jantzi attended the SPIE Defense and Commercial Sensing conference in April 2019.

Austin Jantzi took graduate courses at Clarkson University, earning 30 credits towards his doctorate.

Austin Jantzi attended the Hacking for Defense Summit in May 2019.

Austin Jantzi participated in a 10-week summer internship at NAWCAD from June-August 2018, supported by the Naval Research Enterprise Internship Program.

Technology Transfer

One provisional patent disclosure was filed.

Participants

Name	Role	Person Months
Rumbaugh, Luke	Co PD/PI	1
Jantzi, Austin	Graduate Student (research assistant)	12
Jemison, William	PD/PI	1

Optical Wavefront Processing for Underwater Lidar

Austin Jantzi, Ph.D. Candidate
Dr. William Jemison
Clarkson University

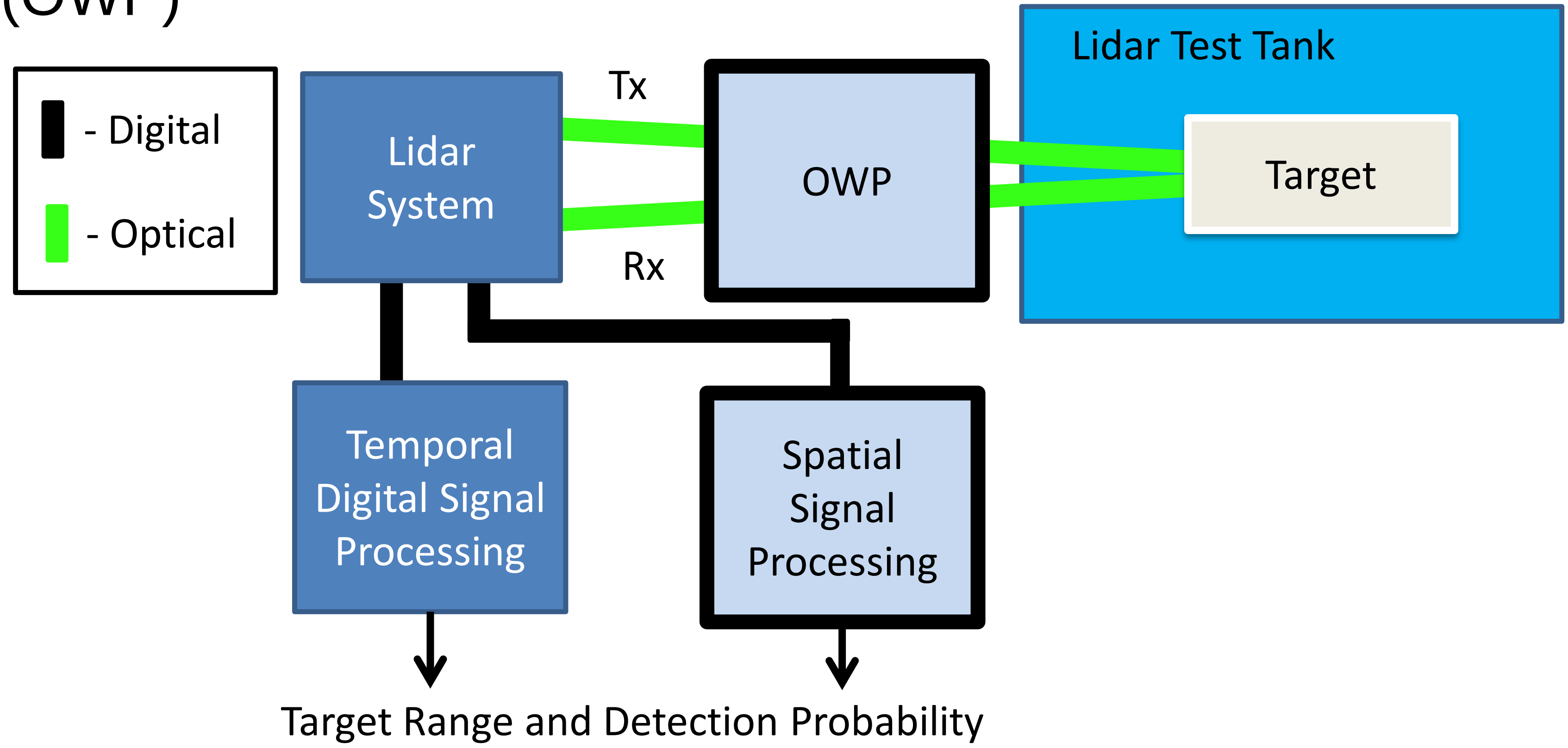
Dr. Linda Mullen
NAWC-AD

NURP Program Review

June 4, 2019

OBJECTIVE

Extend the range and increase the range accuracy of underwater lidar systems using optical wavefront processing (OWP)

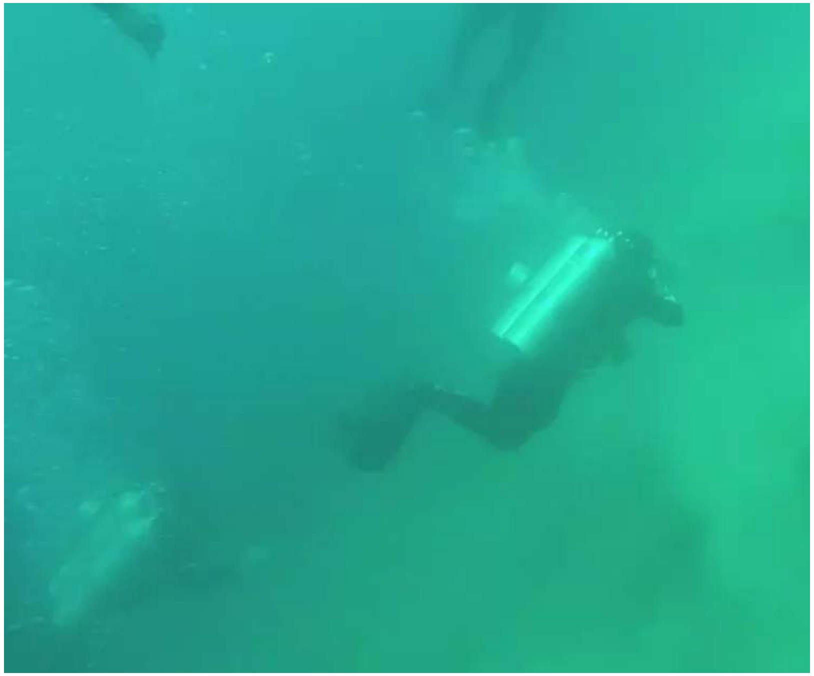


OPW operates in the optical domain

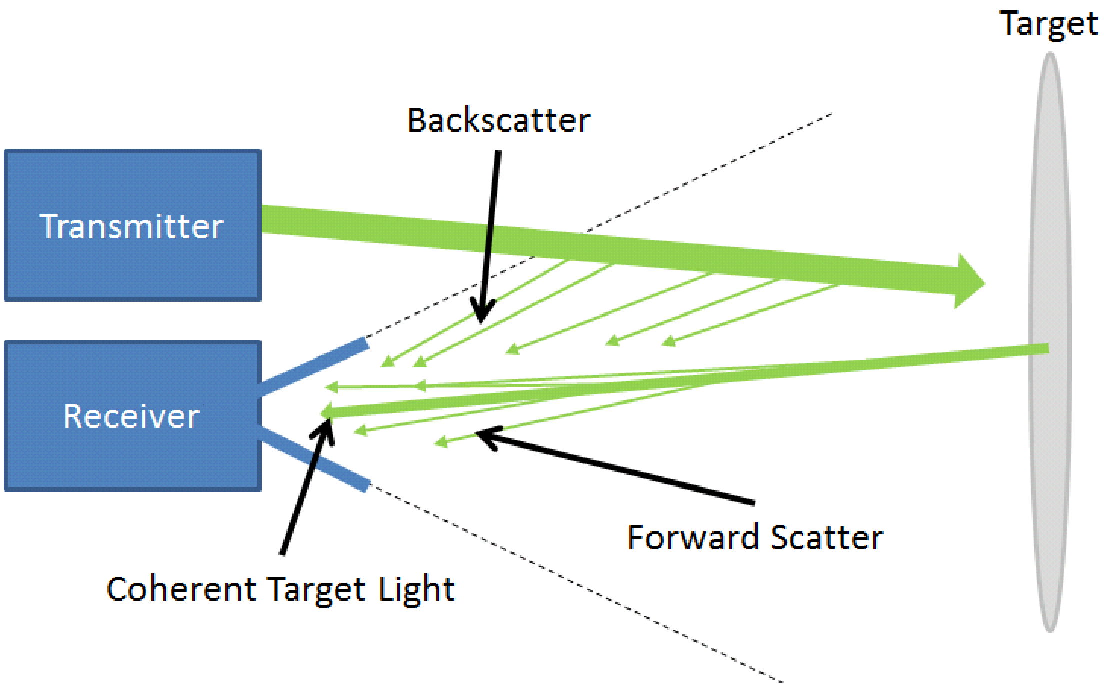
RELEVANCE TO NAVY

Extend Lidar System Performance:

- The Navy is interested in detecting underwater objects
- Turbid environments limit the performance of underwater optical systems
- Optical Wavefront Processing has the potential to improve the Navy's ability to detect and accurately locate targets of interest in turbid underwater environments



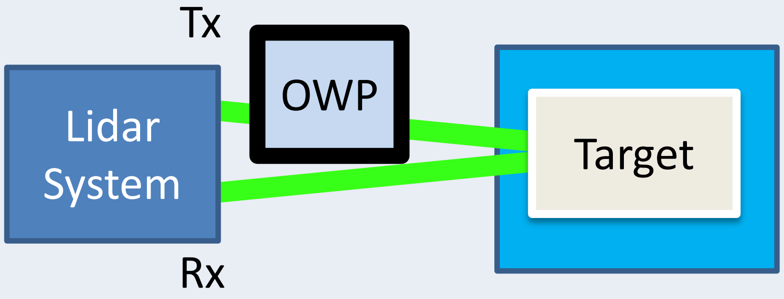
LIGHT PROPAGATION UNDERWATER: EFFECTS OF SCATTERING



- **Forward scattered light** – causes range error due to delayed arrival time
- **Backscattered light** – never reaches the target; adds clutter, making it more difficult to find the target

Can we use OWP to mitigate the effects of scattering?

TECHNICAL APPROACHS

<table>
<tr>
<td>1.</td>
<td>Optical Wavefront Encoding:
Encode the <i>transmit</i> beam with spatial modes - does it change the inherent scattering properties?</td>
<td>


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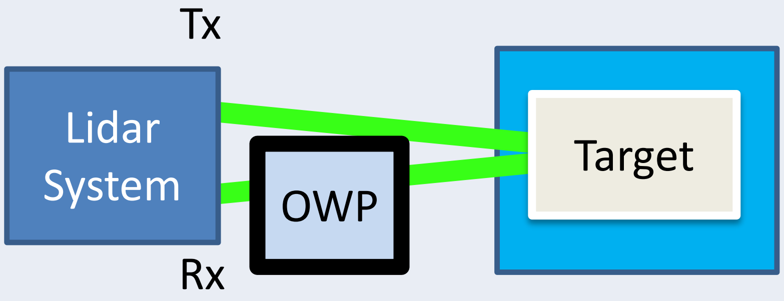
<td>2.</td>
<td>Optical Wavefront Sensing:
Sense the difference in coherence between scattered and unscattered light using spatial modes at the <i>receiver</i></td>
<td>


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TECHNICAL APPROACH 1: OPTICAL WAVEFRONT ENCODING

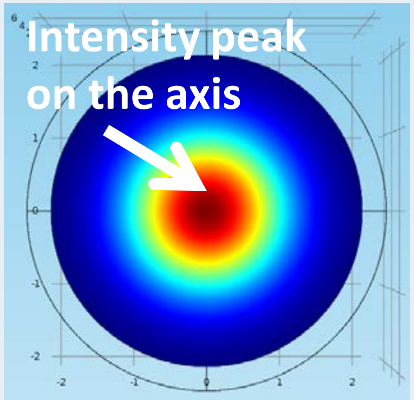
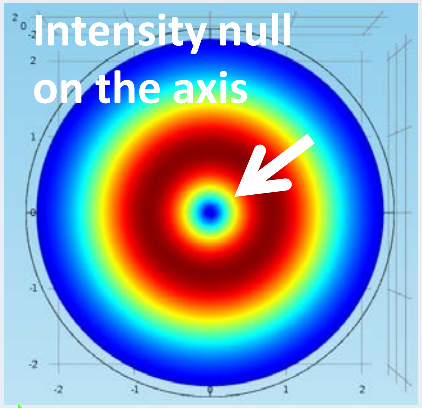
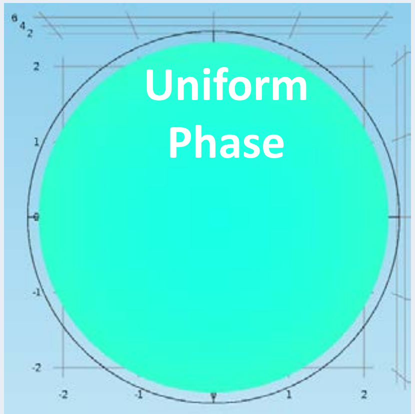
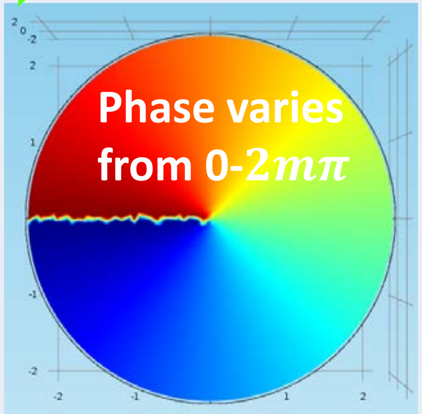
Approach	Hypothesis	Potential Impact	Method
Encode the lidar transmitter beam with orbital angular momentum (OAM)	Several recent papers suggest that OAM beams propagate with less forward scatter and backscatter.	Less scattered light collected at the lidar receiver increasing performance	Developed a mixed-method simulation to predict the scattering behavior of a beam encoded with OAM to test the hypothesis

- FY18 developed the mixed analytical and numerical method
- FY19 extended the results of the mixed method to simulate OAM beam propagation

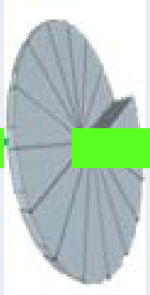
BLUF: no inherent advantages to OAM beam propagation with respect to scattering in practical underwater environments.

Austin Jantzi, Melanie Cockrell, Luke Rumbaugh, William Jemison, “Mixed numeric and analytic method for investigating OAM beam scattering in turbid water,” (2019) published in *Optical Engineering*.

ORBITAL ANGULAR MOMENTUM (OAM) BEAM PROPERTIES

	Gaussian Beam	OAM Beam
Beam Amplitude	 Intensity peak on the axis	 Intensity null on the axis
Beam Phase	 Uniform Phase	 Phase varies from 0-2$m\pi$

OWP



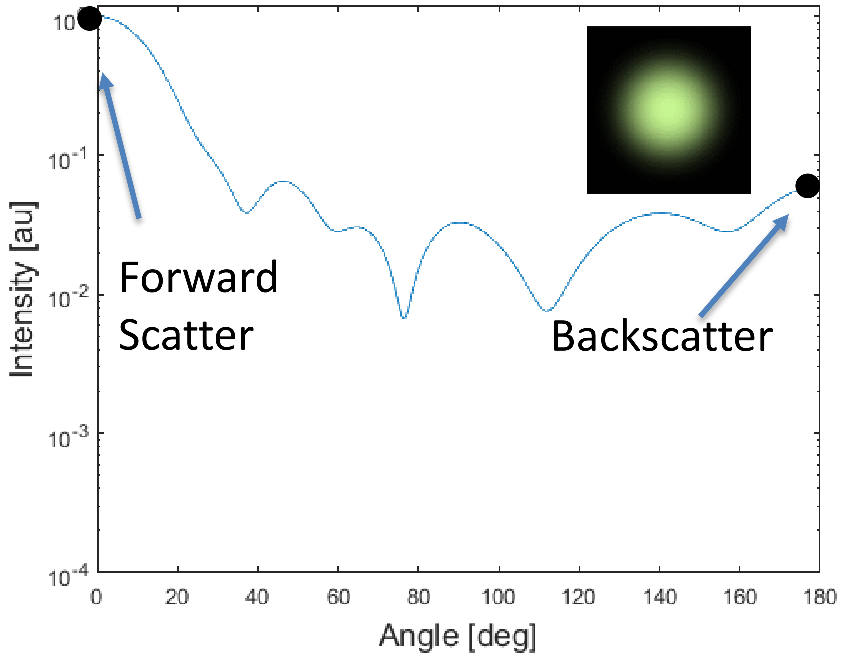
Spiral phase plate

OWP converts a coherent Gaussian Beam to a coherent OAM Beam

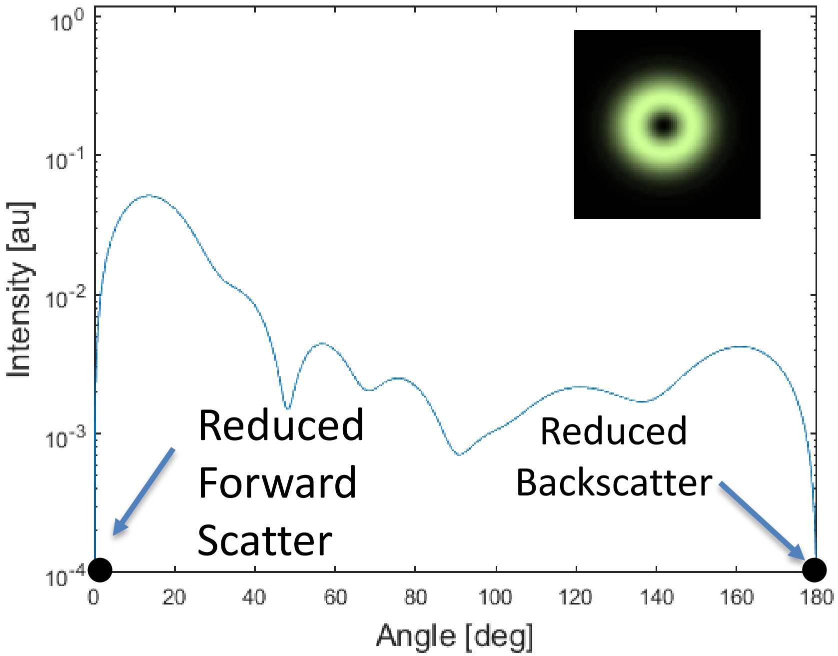
SINGLE PARTICLE SCATTERING SIMULATIONS

- Single particle scattering simulations can be generated with commercially available software- COMSOL
- There is reduced scattering for on-axis single particle scatter when using an OAM beam

Gaussian Beam: Single Particle Scattering

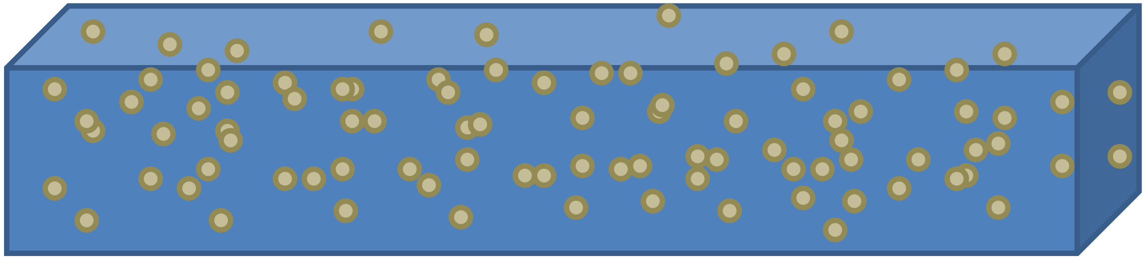


OAM Beam: Single Particle Scattering



Does this scale to multiple scattering, turbid underwater environments?

MULTIPLE PARTICLE SCATTERING APPROACH



- Large simulation spaces have very high computational costs
- COMSOL cannot be used, need to develop a new method

Far Field Intensity from N Particles

Interference term determined by geometry

$$\overbrace{I(k_x,k_y,k_z)} = \sum_{j=1}^{N}[\underbrace{\mathscr{F}\{A_j\}^2} + \sum_{k=j+1}^{N} \underbrace{\mathscr{F}\{A_j\} * \mathscr{F}\{A_k\}}\,\overbrace{\cos((k_X\Delta x + k_Y\Delta y + k_Z\Delta z + \underbrace{\Delta\delta))]}}$$

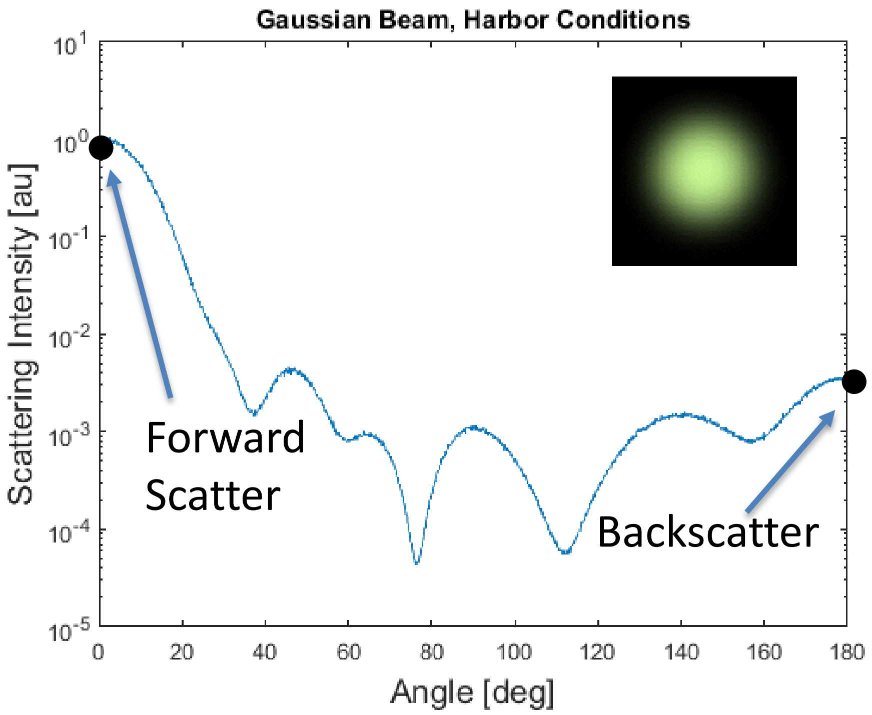
Single scattering functions generated by COMSOL

Phase term changed for OAM

Numerical simulations combined with analytical methods can scale scattering simulation to many particles

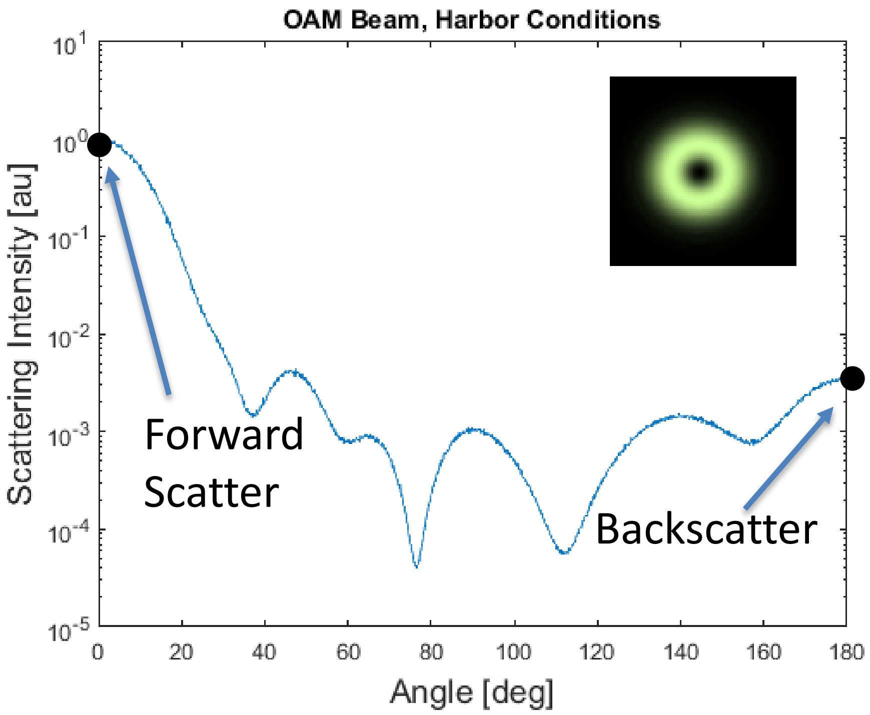
MULTIPLE PARTICLE SCATTERING SIMULATIONS

Scattering from 500 particles similar to an underwater environment


Gaussian Beam, Harbor Conditions

Forward Scatter

Backscatter


OAM Beam, Harbor Conditions

Forward Scatter

Backscatter

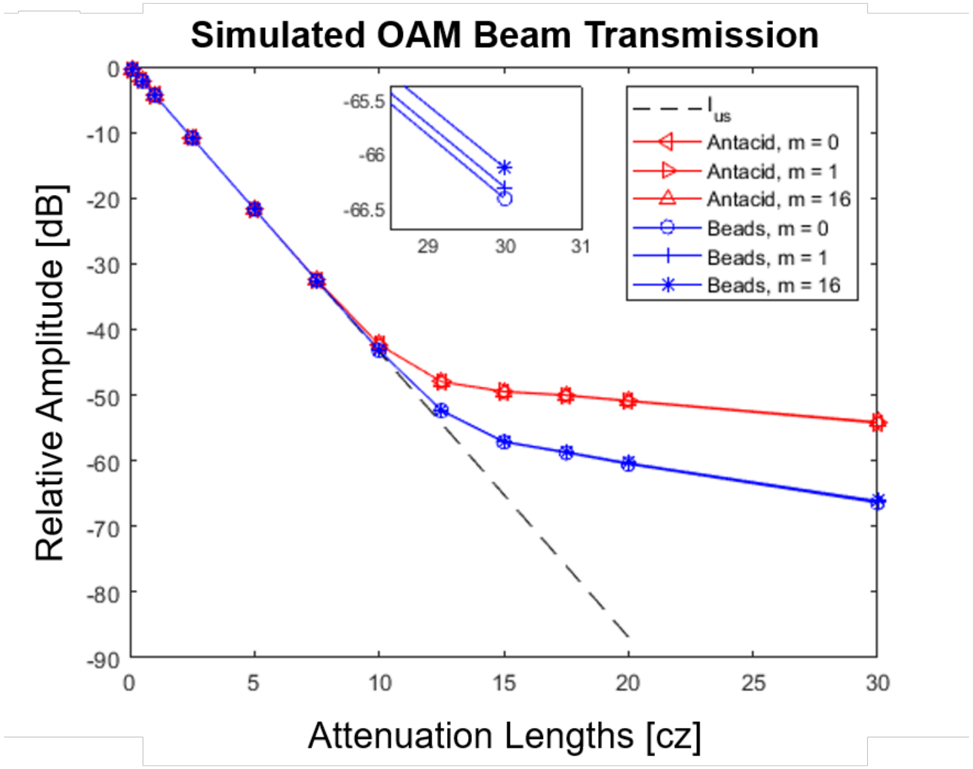
__Conclusion__: In multiple scattering, turbid underwater conditions, the advantageous forward scattering and backscattering null observed for single scatters is no longer present

SIMULATED OAM BEAM TRANSMISSION

OAM beam transmission is simulated using radiative transfer equation:

- Inputs:
  - Scattering albedo
  - System field of view
  - **Volume scattering function**

Simulated results agree well with experimental results



<u>Conclusion:</u> no inherent advantages to OAM beam propagation with respect to scattering in practical underwater environments.

Austin Jantzi, Melanie Cockrell, Luke Rumbaugh, William Jemison, “Mixed numeric and analytic method for investigating OAM beam scattering in turbid water,” (2019) published in *Optical Engineering*.

TECHNICAL APPROACH 2: OPTICAL WAVEFRONT SENSING

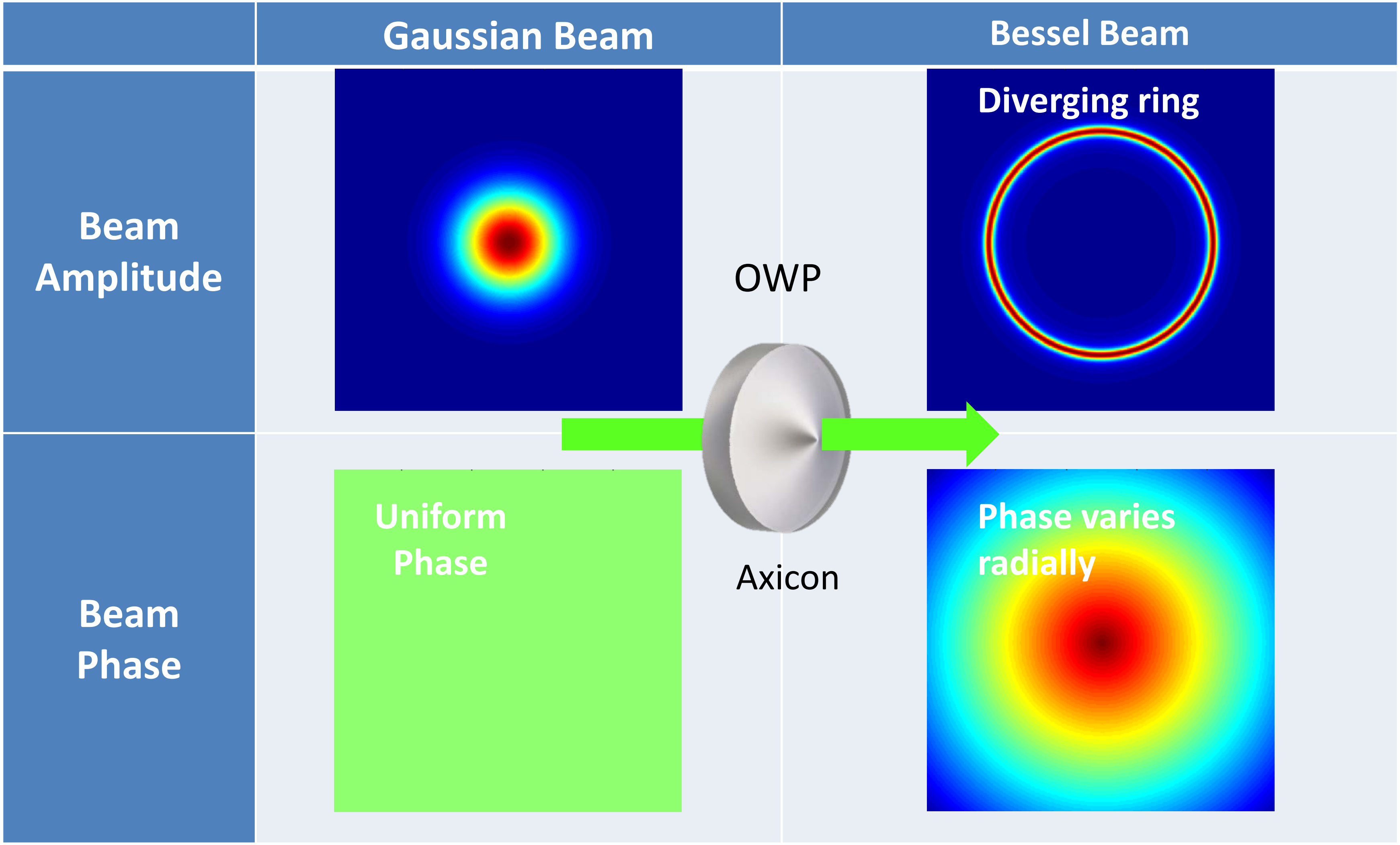
Approach	Hypothesis	Method	Potential Impact
Use an spatial phase element at the lidar receiver (Optical Wavefront Sensing)	Coherent light from targets will be transformed by the spatial phase element; incoherent light from scatter will not be transformed	Experimentally compare the performance of underwater laser systems with and without Optical Wavefront Sensing	Allows for discrimination between coherent light and scattered light

BLUF: *Approach 1: FY18 extended range and improved accuracy using streak camera/OAM filtering (reported last year)*
Approach 2: FY19 used all optical/axicon filtering to reject unwanted photons (reported this year)

Austin Jantzi, William Jemison, Alan Laux, Linda Mullen, & Brandon Cochenour (2018). Enhanced underwater ranging using an optical vortex. *Optics express*, *26*(3), 2668-2674.

Austin Jantzi, Luke Rumbaugh, and William Jemison. "Spatial coherence filtering for scatter rejection in underwater laser systems." *Ocean Sensing and Monitoring XI*. Vol. 11014. SPIE, 2019.

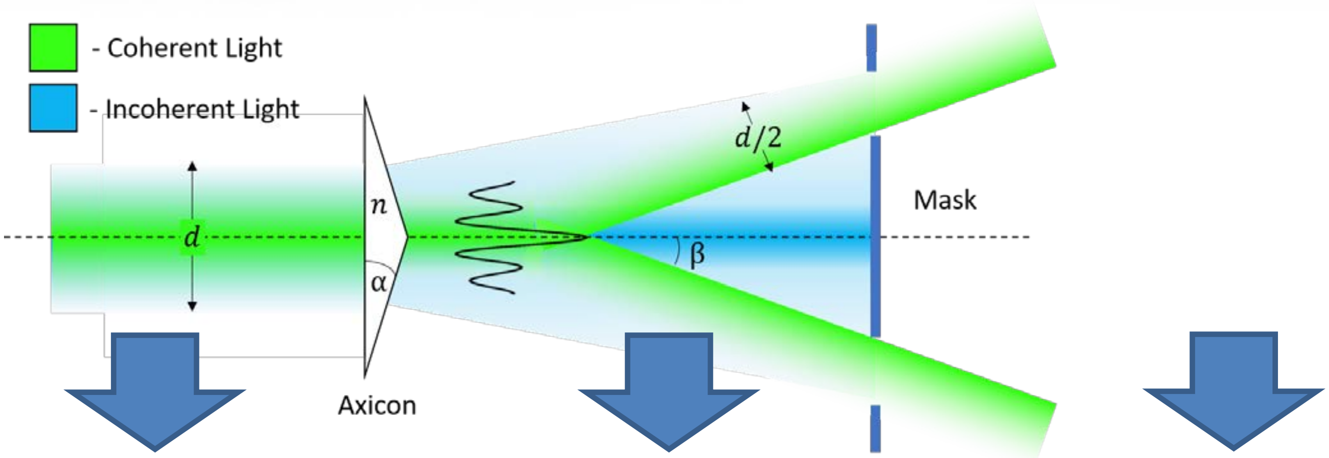
SPATIAL PHASE ELEMENT: AXICON
Converts Gaussian to Ring

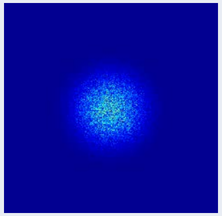
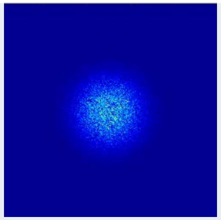
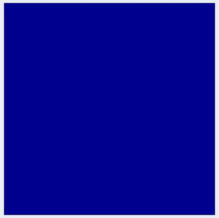
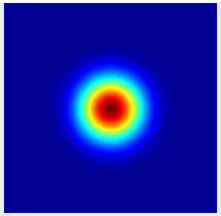
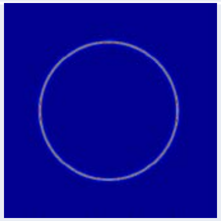
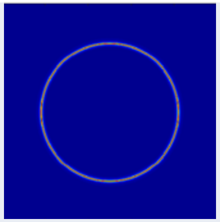
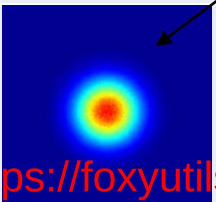
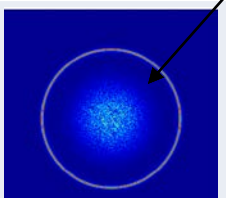
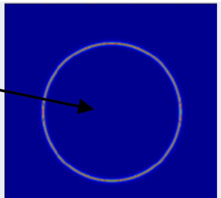


	Gaussian Beam	Bessel Beam
Beam Amplitude		Diverging ring
Beam Phase	Uniform Phase	Phase varies radially

OWP converts a coherent Gaussian Beam to a Bessel Beam

USING AXICON TO DISCRIMINATE BETWEEN COHERENT AND INCOHERENT LIGHT



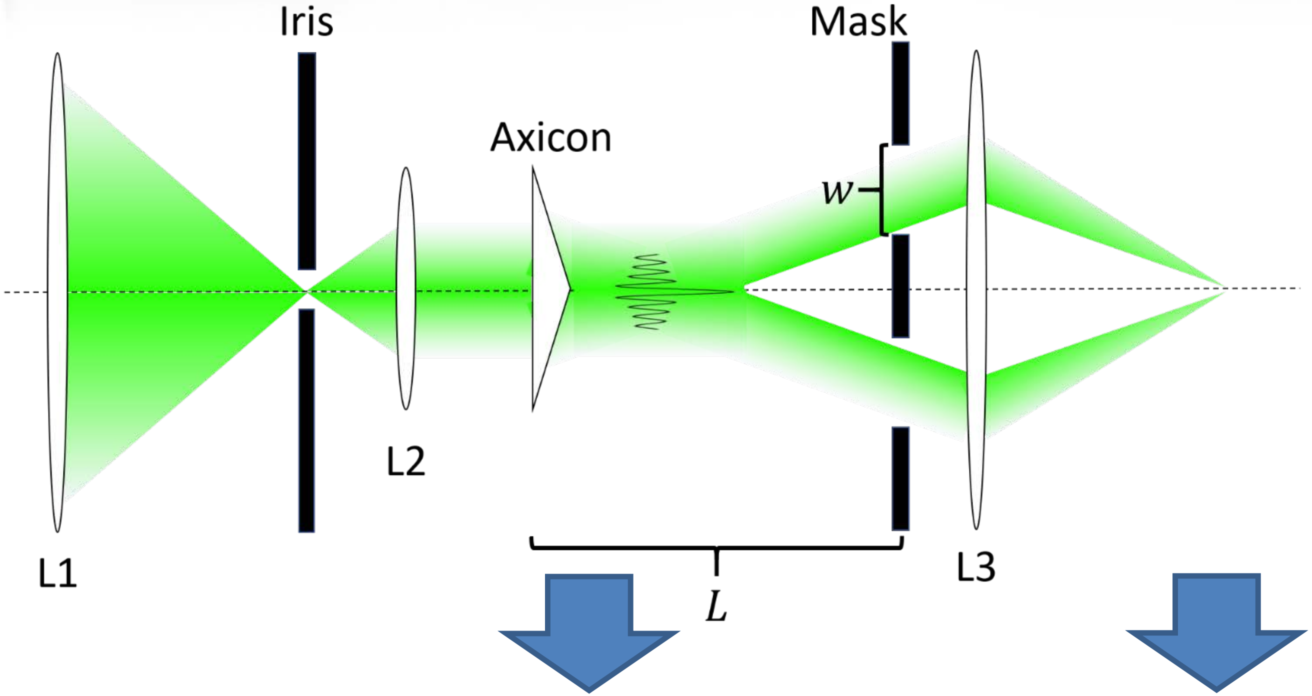
	Before Axicon	After Axicon	After Mask
Incoherent Light			
Coherent Light			
Sum			

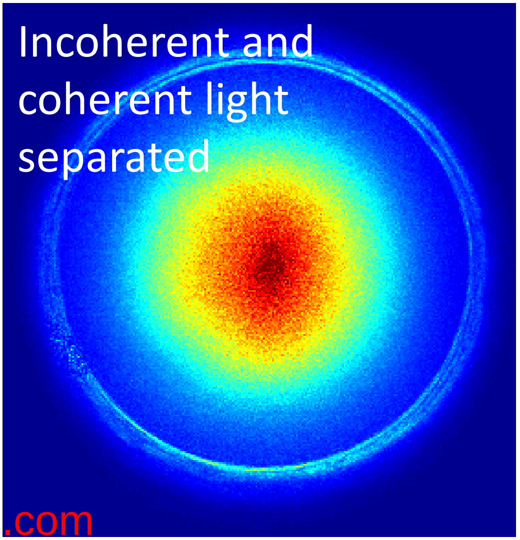
Coherent and incoherent overlap

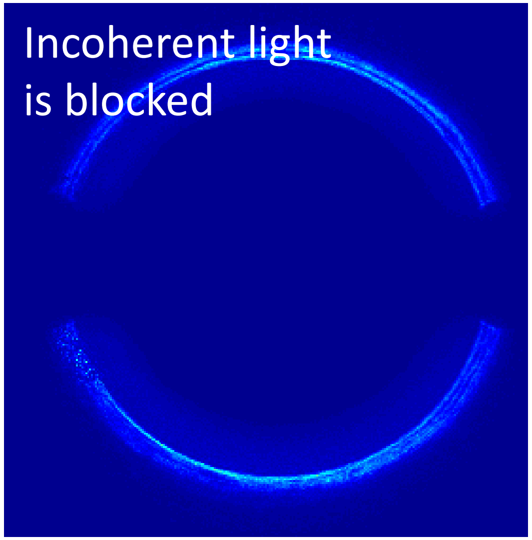
Coherent and incoherent separated

Incoherent light blocked

AXICON FILTER DESIGN AND EXPERIMENTAL RESULTS

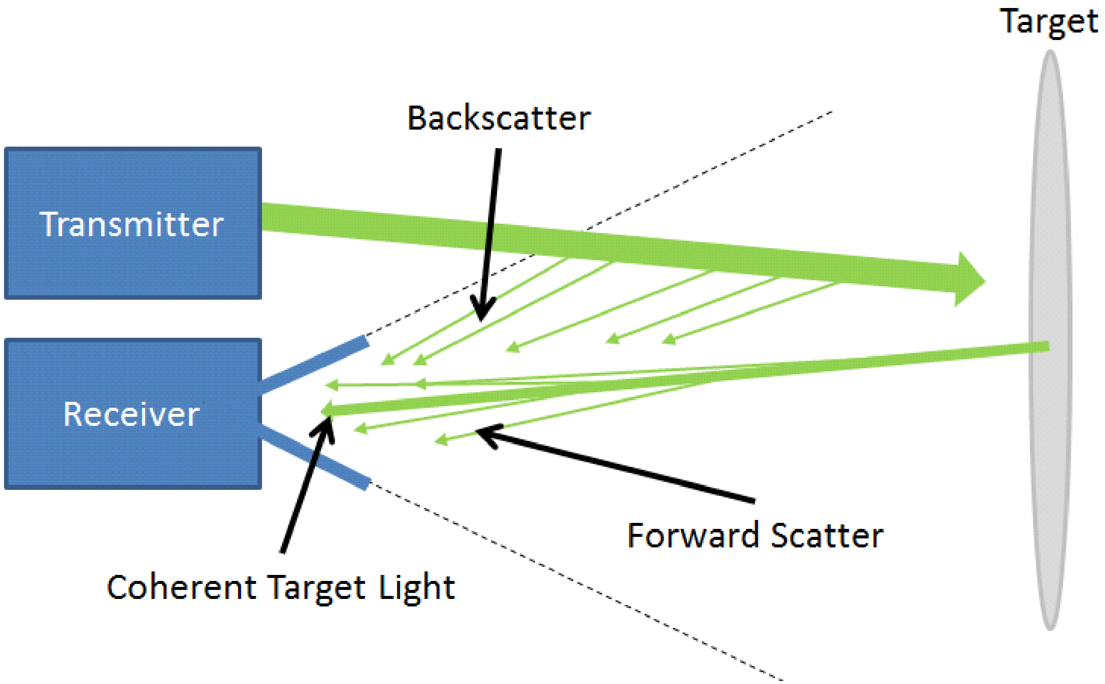



Incoherent and coherent light separated


Incoherent light is blocked

Axicon filter spatially separates scattered and unscattered light, and removes scattered light from the system using all optical methods

NEXT STEPS



- Investigate the coherence of scattered and target light
- Perform experiments that integrate spatial coherence filtering with existing lidar systems and digital signal processing techniques

MISSION MODEL CANVAS

Key Partners

Partnership with asphericon may be necessary to provide custom axicons.

Key Activities

Complete system performance experiments integrating OWP and existing lidar systems

Development of integrated filters allows Optical Wavefront Processing to be added to existing lidar systems.

Key Resources

Key resources are available at Clarkson University and NAWC-AD for integrated system performance experiments.

Value Proposition

Optical Wavefront Processing can extend the range and improve the range accuracy of underwater lidar systems, proving greater situational awareness and actional information for MIW/EOD mission operators.

Buy-In/Support

No additional by-in/support is needed to complete system performance experiments.

Deployment

Widespread deployment would require the development of a low cost, all optical filter.

Beneficiaries

The beneficiaries are ONR program managers and MIW/EOD mission operators. They need more extended range and more accurate range measurements to take action in turbid underwater conditions.

Mission Budget/Costs

The key elements driving the cost would be the potential development of custom optical devices for an integrated system.

Mission Achievement

Achievement is measured as increased maximum range and improved range accuracy compared to existing lidar systems.

CONCLUSIONS

Optical Wavefront Encoding:

- Investigation indicates that the scattering of OAM beams is very similar to scattering from Gaussian beams – no inherent advantages to OAM beam propagation with respect to scattering in practical underwater environments.

Optical Wavefront Sensing:

- Coherence detection can discriminate between coherent target returns and incoherent scatter returns.
- This can be exploited in post processing to improve underwater lidar systems
- Unwanted scattered light can be removed from the system through all optical processing

CURRENT AND FUTURE WORK

Further exploring coherence detection:

- Investigate the coherence properties of scattered and target light
- Integrate axicon filter into conventional lidar systems
- Measure the effect of the axicon filter in a time resolved, bi-static geometry
- Measure system performance for OWP integrated with existing lidar systems

RECENT PUBLICATIONS, PATENTS, AWARDS

Optical Wavefront Encoding

1. Jantzi, A. W., Cockrell, M. G., Rumbaugh, L. K., & Jemison, W. D. (2018, May). A mixed numeric and analytic method for investigating OAM beam scattering in turbid water. In *Cyber Sensing 2018* (Vol. 10630, p. 106300J). International Society for Optics and Photonics.
    i. Honorable mention in Ocean Monitoring and Sensing
2. Jantzi, A. W., Cockrell, M. G., Rumbaugh, L. K., & Jemison, W. D. (2019). Mixed numerical and analytical method for investigating orbital angular momentum beam scattering in turbid water. *Optical Engineering*, *58*(4), 043104.

Optical Wavefront Sensing

1. Jantzi, A., Jemison, W., Laux, A., Mullen, L., & Cochenour, B. (2018). Enhanced underwater ranging using an optical vortex. *Optics express*, *26*(3), 2668-2674.
2. Jantzi, Austin, Luke Rumbaugh, and William Jemison. "Spatial coherence filtering for scatter rejection in underwater laser systems." *Ocean Sensing and Monitoring XI*. Vol. 11014. International Society for Optics and Photonics, 2019.
    i. Honorable mention in Ocean Monitoring and Sensing

Patent Disclosure:

William Jemison, Austin Jantzi, Luke Rumbaugh, “Spatial separation of coherent and incoherent lidar returns using an optical grating approach”