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We present preliminary results from recent test of the LUCIE 2 (Laser Underwater Camera Image Enhancer) conducted in Halifax Harbour, Nova Scotia, Canada. LUCIE 2 is a near compact laser range gated camera (25 cm in diameter, 70 cm in length, and neutrally buoyant in water) originally designed to decrease search and recovery operations under eye sage restrictions. The second generation LUCIE makes it a potential tool for MIW operations when divers are in the water identifying bottom objects. Coincident in-situ optical properties of absorption and scattering were taken to help resolve the environmental information contained in the LUCIE image. We present preliminary analysis on the performance of the system and a comparison with diver and camera identification.

15. SUBJECT TERMS
range gating, absorption, scattering , laser imaging, underwater optics

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Using a Laser Underwater Camera Image Enhancer for Mine Warfare Applications: What is Gained?

A. D. Weidemann, G. R. Fournier, J. L. Forand, P. Mathieu and S. Mclean

[1]*Abstract*-- **We present preliminary results from recent tests of the LUCIE 2 (Laser Underwater Camera Image Enhancer) conducted in Halifax Harbour, Nova Scotia, Canada. LUCIE 2 is a new compact laser range gated camera (25 cm in diameter, 70 cm in length, and neutrally buoyant in water) originally designed to decrease search and recovery operations under eye safe restrictions. The second generation LUCIE makes it a potential tool for MIW operations when divers are in the water identifying bottom objects. Coincident in-situ optical properties of absorption and scattering were taken to help resolve the environmental information contained in the LUCIE image. We present preliminary analysis on the performance of the system and a comparison with diver and camera identification.**

Index Terms--**range gating, absorption, scattering, laser imaging, underwater optics.**

I. INTRODUCTION

THE idea of using the combination of a short green laser pulse with a time gated image intensifier in order to enhance the range of visibility underwater occurred almost as soon as components were available more than a quarter of a century ago. In such a system, a laser pulse is sent out and after a suitable delay the camera gate is turned on. This means that the intense backscatter from the water column lying between the target of interest and the camera can be prevented from being recorded on the image since the camera is shut precisely during the time it would enter the optics.

In 1990 DREV began designing a first generation system of this type, the Laser Underwater Camera Image Enhancer (LUCIE). This system [1] used the then new technology of compact high efficiency laser diode pumped Nd-YAG doubled into the green by a new generation of reliable crystals(BBO, KTP).

Over the course of the next few years, two versions of the system underwent an exhausting series of trials in various environments (from harbor to open ocean). Both versions were mounted on a Remotely Operated Vehicle (ROV) and for the long dwell times required for reliability testing, on a bottom-resting platform with pan and tilt capability. During all the various trials, simultaneous measurements were taken of both the absorption and scattering coefficients along with the near forward phase function. These measurements were carried out using a near forward nephelometer cum transmissometer (NEARSCAT). These simultaneous measurements [2] allowed us to both model and extrapolate performance data to waters with different properties.

Both versions of the camera proved to be extremely reliable. In cases were there was no or little natural illumination and one had to rely on onboard lighting systems, the range gated system allowed one to extend the useful imaging range from a factor of three to five when compared to a normal camera with 500 watt quartz-iodine lamps.

We found that in many circumstances, typical survey and identification missions could be carried out approximately 10 times faster than with standard imaging equipment. Part of this speed increase is due to the larger coverage due to the extended range. Another significant contributor to the efficiency of survey is the capability of the ROV to now hover and image at a sufficient distance from sandy or muddy bottoms that its own motors do not raise significant amounts of scattering material in the water column. We did not foresee this highly nonlinear effect on identification mission effectiveness before the trial results were analyzed.

Our original versions of LUCIE were built to allow a great deal of experimental flexibility and were fitted on a large ROV (Hysub 5000 from ISL). They were contained in a set of 3 joined cylinders 30 cm in diameter and 1 meter long. The system weighed 300 kilos and required 750 watts of inrush power and 500 watts of continuous power. This large size made the system difficult and expensive to operate. We therefore decided to see if a significant miniaturization that did not sacrifice performance and increased significantly the ease of use could be carried out.

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II. BASIC CAMERA DESIGN

After a detailed analysis of an extensive set of calibrated measurements from a first generation underwater range-gated camera (LUCIE), we therefore carried out the design and build of a second generation camera (LUCIE2) which incorporates the most significant improvements from the lessons learned during those first sea trials.

One of the success stories of those trials was the obvious high reliability of high repetition rate diode pumped doubled Neodymium laser. Our first camera was in several instances immersed and operated underwater for several days. After being in storage for over a year, the camera was also brought back to full functionality and readiness in less than 24 hours. The delay was due to a small leak that had developed in a seal of the liquid cooling system of the laser.

The second important successful part of the original design was the inherent eye safety of the high repetition rate diode pumped lasers. Because of the high repetition rate, the eye damage threshold for the pulsed laser becomes identical to the CW damage limit. This much higher wattage figure means that even in clear waters the system is eyesafe at a maximum distance of 1.5 meters from the aperture. This allowed divers to operate around the camera while it was in operation. We therefore decided to keep this approach in our second-generation system. We decided, however, to use an air and conduction cooled laser to both alleviate weight and ensure against potential system leaks. Our new camera is therefore a completely dry system, a feature which we believe will considerably enhance its long term reliability. The high repetition rate also implies that the in-water speckle is averaged out over each frame, in itself a significant benefit if we wish to apply modern image enhancement techniques to the results. As stated above, the camera uses an air cooled Neodymium Vanadate laser with a BBO doubling crystal. The doubled output at 532 nm is 300 milliwatt average in water at a repetition rate of 22 kHz with a pulse length of 5 ns. The average power is sensitive to the diode temperature. A reduction of 3 degrees centigrade from a nominal setpoint of 27 degrees will reduce the power by 50%. The overall system cooling is controlled by an array of Peltier coolers placed underneath the laser enclosure. To make the system more rugged, we are currently working on ways to reduce this undesirable temperature sensitivity of the laser.

The most desirable improvements that were identified from an analysis of our original results were:

- Smaller size, weight and power
- Flat-field initial laser illumination matched to camera FOV
- Predictable illumination degradation
- Fixed beehive pattern removal (removal of minifier)
- Higher resolution
- Larger FOV
- Programmable AGC
- Optimized signal processing (Poisson noise dominance)
- Improved user interface

In our second-generation camera, the size has been reduced from 3 cylinders 30X 100 cm weighting 300 kilos to one cylinder 25X70 cm, weighting 45 kilos. The power consumption has also been reduced by more than a factor of 3 to an average 175 watts. The illumination system is controlled by a holographic beam shaper that produces a flat illumination field with a 4/3 aspect ratio. This aspect ratio matches the field of view (FOV) of a standard video camera. The intensity varies by less than 5% over 90% of the FOV.

Given an initial intensity distribution of this type it is relatively easy to compute its transition to a Gaussian shape illumination as the beam propagates through natural waters with their typical forward peaked scattering phase functions. The spatial degradation of the illuminating field is predictable at all zoom settings and ranges [3]-[4]. This allows numerical intensity compensation algorithms to be applied.

One extremely annoying feature of intensified cameras is the appearance of a beehive pattern superimposed on the image. This beehive pattern is due to the varying transmission through the fiber bundles (minifiers) used to collect the light output of the phosphor on the back plate of the image intensifier and reduce it to a size appropriate to the CCD array of the video camera. In order to eliminate this effect our camera uses a high aperture (f=0.8) lens to image the phosphor directly on the CCD. The light collection efficiency is less by a factor of two but this is irrelevant since we use a gated tube in chevron configuration with a luminous gain of 1,000,000 that can count individual photons if required. It can still count photons even with the reduced efficiency of the lens over the fiber bundle. We have found that the image is more pleasing to the operator and more importantly much easier to apply image enhancement algorithms to.

A slightly higher resolution is obtained by using a 25mm diameter photo-cathode intensifier tube rather than the usual 18 mm type. The photo-cathode has a low noise (500 counts s^{-1} cm^{-2}) T type S20 coating with a 10% quantum efficiency at 532 nm. We have found that our new camera is able to easily resolve 160 line pairs across the width of the screen.

The lens system is 10 cm in diameter with a zoom range of 16 mm to 160 mm at an f=1.8. The lens has an auto-iris control and a fully motorized focus and zoom. Both camera and illuminator can be zoomed from 80 to 800 mr in water. The laser divergence and lens system can be slaved together to ensure maximum uniform illumination over the entire range of field of views. This larger field of view is achieved at the same sensitivity level as in our first generation system because of the larger diameter photo-cathode. The intensifier gate delay can be varied from 0 to 500 ns and the gate width can be increased from 3 ns to 500 ns.

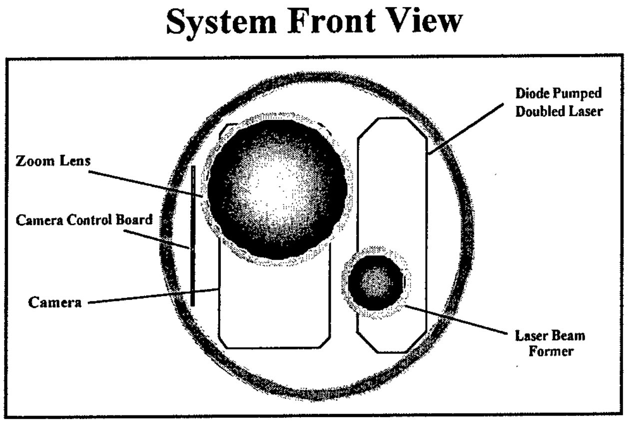

Fig. 1. Schematic of the front view of the LUCIE2 range gated imager. The zoom lens is 10 cm in diameter and the laser beam exit port is 2.5 cm in diameter. The ports are separate to avoid back scattering of the laser beam in the receiving optics.

The video output is digitized at full resolution 640 pixel by 480 pixels at 30 frames per second by a Matrox Orion frame grabber. This allows us to apply a substantial amount of real time processing to the camera such as frame averaging, smoothing by convolution, histogram equalization and other enhancement techniques. This approach as also allowed us to test several automatic gain control (AGC) algorithms that operate over the full range of gain of the camera i.e. from photon counting mode to full illumination.

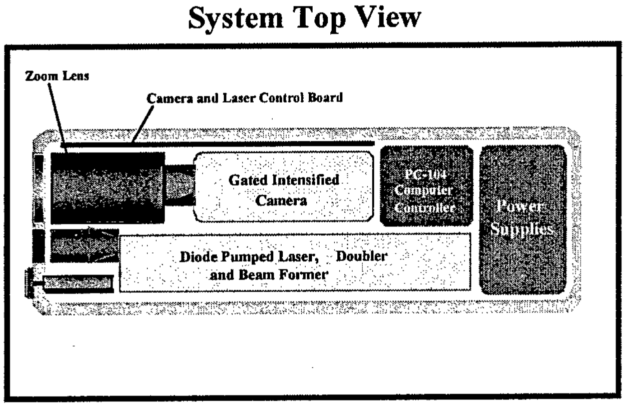

Fig. 2. Schematic of the top view of the LUCIE2 range gated imager showing a block diagram of the components.

This numerical approach has also allowed us to develop a fairly sophisticated user interface where virtually all the controls for the camera operation, orientation and choice of image processing methods are situated on one joystick control (Logitech Wingman Extreme Digital 3D).

Figure 1 is a schematic front view of this new system. Figure 2 is a side view of the same LUCIE2 system showing a block diagram of the components. Figure 3 is a picture of the actual camera system.

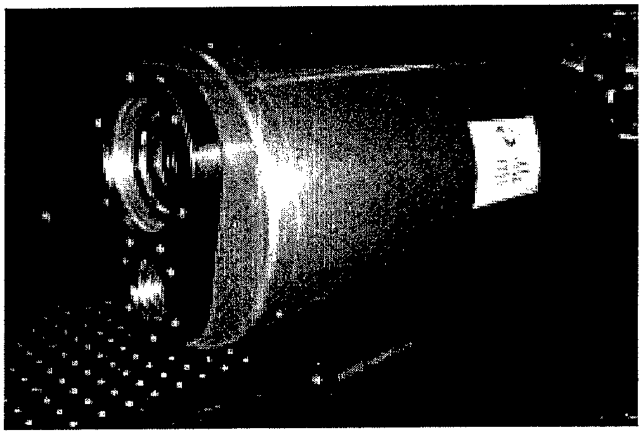

Fig. 3. Picture of the LUCIE2 camera. The system is 25 cm in diameter by 70 cm in length. The receiving optics are 10 cm in diameter.

III. In Situ Optical Measurements

As mentioned above, in previous trials we carried out simultaneous measurements of the relevant optical properties of the waters in which we were operating. This data when combined with simple models, gave us considerable insight into the potential system performance in varied conditions. In this new set of trials, a team from NRL Stennis carried out the simultaneous environmental measurements. The measurements included absorption and attenuation at nine wavelengths (WetLabs Inc., ac-9 plus), backscattering at 140 degrees and radiance attenuation (HobiLabs Inc., a-beta at 532 nm), scattering at 100, 125 and 150 degrees (Wetlabs ECOVSF), and CTD.

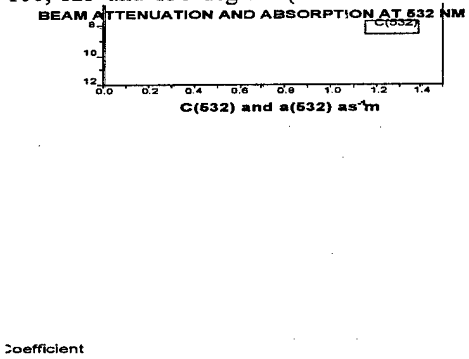

Fig. 4. Depth profile of absorption and beam attenuation at 532 nm showing increase from 0.9 to 1.2 m^{-1} near the bottom for c (532).

The optical properties as a function of depth changed with the tidal cycle, sewage discharge, and wind direction. These layers were found at both the surface and at depth depending on the tidal cycle, wind, and discharge. Figure 4 is a profile of beam attenuation and absorption collected at the time of the LUCIE profile.

The measurements of the optical properties of the water column are generally of good quality. In some cases we noted the presence of large quantities of extremely big particles (centimeter size and bigger). As these particles can substantially or completely block the optical paths of the instruments, their effects on absorption, scattering and the phase function, are not properly accounted for by the instrumentation used. In the case of the very particular waters we were operating in, the results are therefore a lower limit on the values of these parameters. We have not yet found a reliable method to properly compensate this effect.

We should also note that the simultaneous measurement of the total scattering coefficient at several wavelengths allows one to approximate the near forward angle behavior of the phase function and to determine the precise inverse power dependence of the particle size distribution. Armed with this information, it is then possible by using a few large angle scattering measurements at one wavelength to fit the complete experimental data by a phase function model [5]-[6]. This model depends only on the inverse power as a function of size of the particle size distribution and on the average relative index of refraction of the particles. The current set of measurements is thus sufficient for us to ultimately determine to a satisfactory accuracy all the relevant parameters necessary to build a complete theoretical model of the experiment. This model will be a considerable help in the further analysis and generalization of our trial results.

IV. TRIAL DESCRIPTION

The trials were carried out between February 13 2002 and February 21 2002 along side pier 9 and the Satlantic facilities in Halifax harbor. The mean water throughout the trial period was 1 degree centigrade. The test site was located less than a hundred yards from a main untreated sewer outlet, a situation that created a serious challenge to the imaging system. The water depth at the test site was 10 meters and the level of natural light at the bottom was high. The LUCIE2 underwater enclosure was first mounted on a large pan and tilt mount that could rest on the bottom and was hydraulically powered. A small aperture large depth of field Fischers diver camera with two 150 watts quartz-iodine lamps was also attached to the mount. This camera provided both the standard source of illumination for normal camera use and served as a second reference for performance comparison. The first reference is the camera in LUCIE2 itself, which can of course be used in un-gated mode as a standard high sensitivity video camera.

Several sets of targets were used during the trial. The first set of diver visibility targets we used was the set developed by W Mcbride and T. Bowers of Planning Systems Incorporated. These consisted of calibrated sets of black line pairs on a white background. The line widths ranged from 1 mm to 128 mm on two different panels. The line spacing in millimeters, which is double the line width, is indicated on the side of each line pair set. At different times during the trial we also used other target types. We used a line set (white lines on black background), which had served in all our previous experiments. The line widths range from 1.5 mm to 48 mm. Each subsequent line pair set is the double in size of the previous set. We also put together a small target that used very low contrast objects to see if we could estimate the effect of low contrast and the effect shape difference for objects with the same albedo. The three types of targets are shown in figure 5.

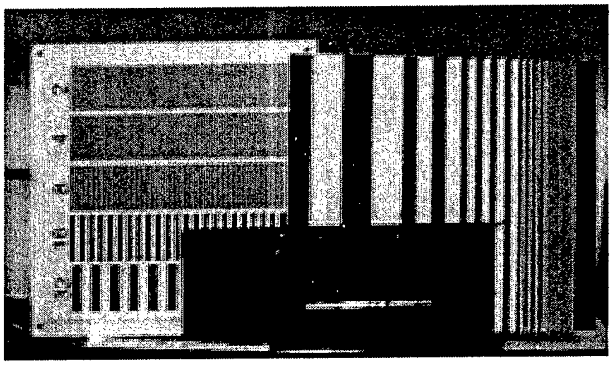

Fig. 5. Digital camera picture of part of the 3 target sets used in the trials of LUCIE2. The leftmost set was used in the evaluation of the diver target visibility. The rightmost set is our standard line target used in all our previous studies. The central target is our low contrast montage.

Following the procedures we had established during our previous trials with the first generation of active imager. The various targets were imaged at many different ranges under as many different conditions as possible. Coincident measurements of the optical properties of the water column were carried out. We are currently proceeding with a detailed analysis and theoretical modeling.

V. SAMPLE RESULTS

Our preliminary analysis indicates that the performance of the LUCIE2 imaging system is comparable to our previous version. During this trial we had the opportunity to measure the performance of the camera against that of divers at shallow depths using natural illumination conditions. As mentioned before, the water depth at the test site was 10 meters and the level of natural light at the bottom was high.

To carry out the comparison, we used the black line against white background targets. A measuring tape was attached to the target and the divers moved back from the target noting at what distance they stopped distinguishing that the discrete lines in a target set were indistinguishable.

The conditions were particularly challenging on the day this test was carried out The measured absorption coefficient was 0.2 m^{-1} and the scattering coefficient was 0.8 to 1.0 m^{-1}. On that day we were in the middle of a sewer plume and a nearby ship's bilge was adding significantly to the turbidity. It should be noted that large pieces of debris were abundant and our measurement equipment would not have tallied their contribution to extinction and absorption. In these particularly difficult conditions, the divers reported a visibility range of approximately 3 meters (10 feet). After this they could still distinguish the presence of a white diffuse target but they could not make out any details.

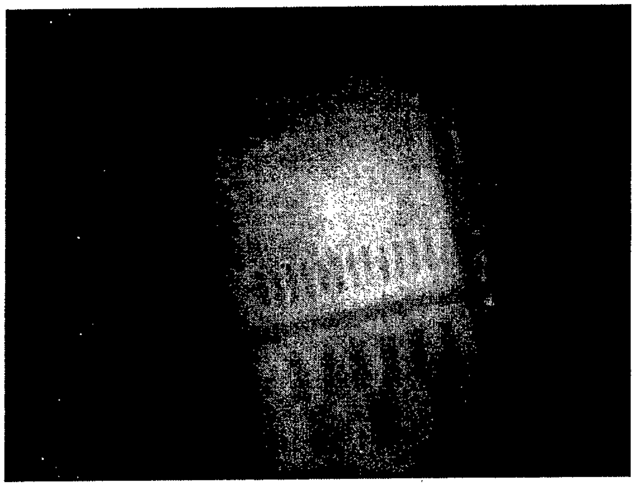

Fig. 6. Picture taken by LUCIE2 at a range of 5 meters under conditions in which divers reported a visibility of 3 meters. The diagonal field of view is 20°. Note that the 16mm lines are clearly distinguishable (4th row from the top).

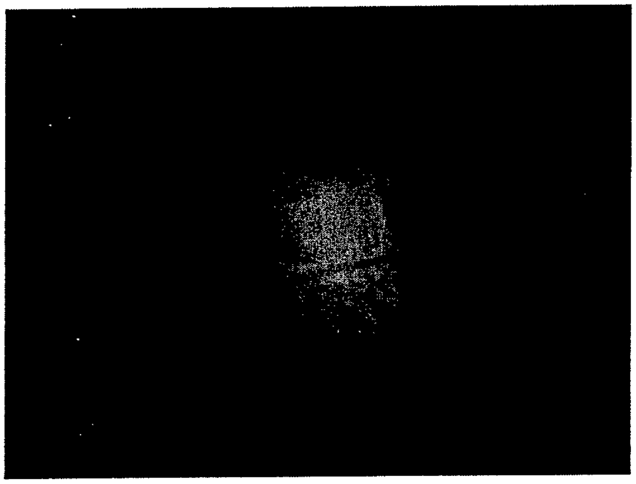

Fig. 7. Picture taken by LUCIE2 at a range of 5 meters, with diver visibility noted to be 3 meters, but with a diagonal field of view of 40°. Here the bottom row (32mm lines), on the top panel, are distinguishable.

Figures 6 and 7 are the images taken by LUCIE2 under the same conditions at a distance of 5 meters from the same target. Figure 6 is a narrow field of view picture (20° along the diagonal) while figure 7 is a wider field of view under the same conditions (40° along the diagonal). In the first picture the 16 mm spacing line pairs are easily distinguishable while the 8 mm spacing are a blur. In the second picture it is the 32 mm spacing which is the smallest visible. This behavior is as expected from the combination of the camera modulation transfer function and the excess blur due to in water scattering. This preliminary data allows us to estimate that, under the particularly difficult conditions outlined above, the range performance of the LUCIE2 system is about twice that of divers. A more detailed analysis will have to be carried out if we wish to reliably generalize this estimate to other relevant operational conditions.

VI. SUMMARY AND FUTURE WORK

The preliminary analysis of the results of the latest trial generally confirms our previous experience with the first generation of gated camera. The LUCIE2 system extends the range by a factor of 3 to 5 over conventional cameras when there is no natural illumination. In this latest trial, we established also that the range of increase over diver visibility in the case of strong natural illumination is at least a factor of 2 as illustrated above. This range increase contributes in two different ways to the efficiency of search and identification missions. The increased range allows a larger swath to be scanned in the same time. More importantly however, the increased range permits a larger vehicle standoff distance from muddy or sandy bottoms. This larger distance means that the vehicle motion and maneuvering will not disturb this bottom material and therefore increase itself significantly the level of turbidity. The elimination of this nonlinear feedback effect has in our experience contributed to an overall reduction by a factor of 10 to typical search and identification missions.

We believe that we have gathered enough data that we will be able by further modeling and analysis to extend our results to other water types and to better understand the detailed relationship between contrast, resolution and range.

In the near future we plan to first add a complete geo-positioning capability to the system that will allow easy co-ordination and target handoff between diver teams and ROV operations. One of the other lessons learned during this trial is that almost complete automation of the system would substantially increase its effectiveness. In the short term, we plan to address part of this issue by better image processing and control algorithms that fully exploit the auto ranging capability of the camera. In the longer term we are considering including a small short-range medium resolution sonar to automatically detect and range on targets.

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