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An autonomous vehicle approach for quantifying bioluminescence in ports and harbors

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ABSTRACT

Bioluminescence emitted from marine organisms upon mechanical stimulation is an obvious military interest, as it provides a low-tech method of identifying surface and subsurface vehicles and swimmer tracks. Clearly, the development of a passive method of identifying hostile ships, submarines, and swimmers, as well as the development of strategies to reduce the risk of detection by hostile forces is relevant to Naval operations and homeland security. The measurement of bioluminescence in coastal waters has only recently received attention as the platforms and sensors were not scaled for the inherent small-scale nature of nearshore environments. In addition to marine forcing, many ports and harbors are influenced by freshwater inputs, differential density layering and higher turbidity. The spatial and temporal fluctuations of these optical water types overlaid on changes in the bioluminescence potential make these areas uniquely complex. The development of an autonomous underwater vehicle with a bioluminescence capability allows measurements on sub-centimeter horizontal and vertical scales in shallow waters and provides the means to map the potential for detection of moving surface or subsurface objects. A deployment in San Diego Bay shows the influence of tides on the distribution of optical water types and the distribution of bioluminescent organisms. Here, these data are combined to comment on the potential for threat reduction in ports and harbors.

Keywords: autonomous underwater vehicles, bioluminescence, marine, ports, security

1. INTRODUCTION

1.1 Bioluminescence

Bioluminescence in the ocean is the result of biologically-generated photons from a chemiluminescent reaction. It is produced by over 700 genera representing 16 phyla, spanning the range of small single cell bacteria to large vertebrates[1]. A ubiquitous feature of most of these organisms is that mechanical stimulation will cause these organisms to generate light, which often leads to brilliant displays in the wakes of ships, in breaking waves, or even around the bodies of rapidly moving dolphins[2]. Early research on this phenomenon was driven primarily by the desire to understand the physiological mechanisms for bioluminescence, as well as the ecological advantage that bioluminescent abilities provides to these luminous organisms[3]. Aside from the basic desire to understand the organism-specific bioluminescence potential and ecological advantage, the fact that these organisms produce light upon mechanical stimulation is an obvious military and homeland security concern. Light production as a function of mechanical stimulation provides a low-tech method of identifying surface and subsurface vehicles and swimmers. The development of a passive method of identifying potential hostile forces, as well as the development of

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strategies to reduce the risk of detection is a relevant goal for naval operations[4] and is reflected in the support of marine bioluminescence research over the last 40 years[5].

1.2 Relevance of Bioluminescence for Harbors and Ports

In addition to being both offensive and defensive concern for military operations, bioluminescence may also be relevant to homeland security. Specifically, harbors and ports have been listed as potential targets. In June 2002 the Coast Guard concluded that "based on information received across the U.S. Government, there is a credible threat to maritime interests from swimmers and divers[6]." The FBI also issued a warning that "various terrorist elements have sought to develop an offensive scuba diver capability[7]." In fact an Underwater Port Security System (UPSS) and Integrated Anti-Swimmer system are being developed and tested[8]. Unnoticed divers would potentially have direct access to both military and civilian ships, refineries, docks, and major population centers. Although the likelihood of hostile action during the daylight hours would be minimized by both harbor/port traffic and increased visibility, the threat would be expected to increase during the night. The fact that swimmers would cause sufficient mechanical stimulation of the surrounding water to cause maximal bioluminescence makes bioluminescence a potential method for detection to prevent access to these targets.

1.3 Measurement of Marine Bioluminescence

The measurement of bioluminescence is routinely made by closed instrument systems known as bathyphotometers, which were first developed in the 1960's[9,10,11]. Bathyphotometers use a pumping system that creates a defined rate of flow through the detector chamber (Fig. 1A). Pumping at a defined rate of flow was motivated by the need to maintain consistent stimulation of a known volume and to consider the flash intensities and duration of particular groups of bioluminescent organisms[12]. The detection chambers have an integrated photomultiplier tube for detection of the low light signals. This general design has been the basis for the suite of bathyphotometers presently in use.

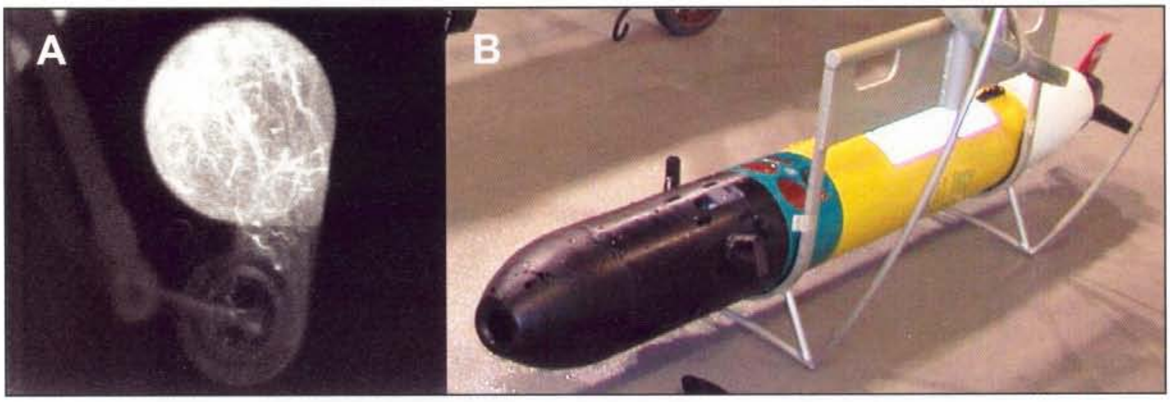

Figure 1: A) Visual tracking of cell paths through a bathyphotometer detection chamber. Here, dinoflagellates are stimulated at the impeller pump where they first enter the chamber. The chamber has an integrated photomultiplier tube that records the flashes in photons per second. B) The bioluminescence autonomous underwater vehicle used in this study. The bathyphotometer is integrated into the nose of the vehicle (black section) with a fluorometer and optical backscatter sensor aft of the detection chamber. Further aft is a CTD and upward and downward looking ADCPs (green) for quantifying the physical dynamics. The vehicle is 40kg and 1.8 meters long.

The ability to measure parameters in the ocean has changed significantly in the past 10 years. Both miniaturization of sensors and the development of sophisticated platforms have allowed for sampling on small spatial and temporal scales not previously possible. This has also enabled improved sampling coverage of the near-shore coastal environment where the time and space variability in physical and biological dynamics (including bioluminescence) is orders of magnitude higher. Bathyphotometers have followed this pattern with time and have reduced in size with lower power requirements to integrate in the various platforms. Current platforms include, undulating tow packages, fixed moorings, profiling moorings, ROVs and autonomous underwater vehicles (AUVs; Fig. 1B).

In order to fully characterize the potential of bioluminescence as a means for detection from the surface, the measurement of bioluminescence potential needs to be combined with the optical properties of the water. There have been significant advances in the development of optical sensors during the same period of bathyphotometer development. This development has been fueled, in part, by the need for in-water validation of ocean color satellites, as well as the Naval need to define the inherent optical properties (absorption and scattering) for visibility and performance prediction modeling[13,14]. Concurrent measurement of these properties is critical for reasonable quantification of bioluminescence water-leaving radiance in coastal regions.

2. APPLICATION

Here we use an AUV outfitted with a bathyphotometer module (Fig. 1B) to examine the fluctuations of bioluminescence in relation to the physical dynamics in a working harbor and port. San Diego harbor was chosen as the site for this demonstration as there are numerous potential military and civilian targets (Fig. 3). After notifying the U.S. Coast Guard, the AUV was deployed from Shelter Island and was programmed to repeat a one kilometer track on the south side of the harbor channel. The vehicle undulated between the surface and 2 meters off the bottom. Every three passes the vehicle made a horizontal pass at 5 meters in order to obtain current flow data above and below the vehicle from the ADCPs. The deployment took place on November, 17th and 18th, 2004 from 23:40 to 03:26 LT. This time was chosen for the large tidal variation to quantify the maximum variation in physical, biological and optical parameters. Thirty-four passes of the transect line were taken over the deployment. After the mission, the vehicle returned to the deployment location off of Shelter Island and was retrieved. In addition to bioluminescence, the vehicle collected temperature, salinity, chlorophyll fluorescence, optical backscatter and 3D current flow above and below the vehicle.

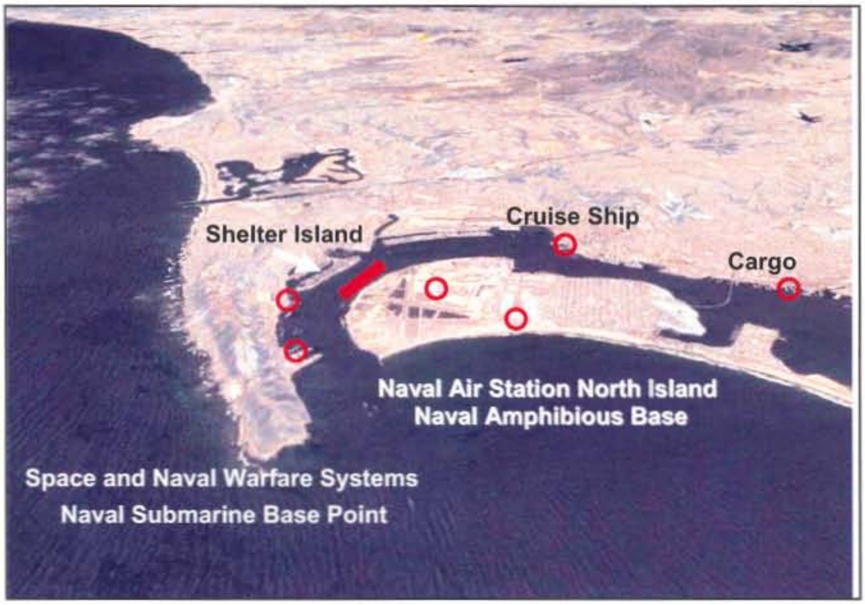

Figure 3: Aerial view of San Diego Harbor and surroundings. This active harbor was chosen for demonstration as there are many sites of military and homeland security interest (red circles). These include the Naval Submarine Base Point Loma, the Space and Naval Warfare Systems Center, the Naval Air Station North Island, the Naval Amphibious Base Coronado, the cruise ship terminal and the ports cargo terminal. The deployment location for the AUV in this study is marked by the red line in the harbor channel. Deployment of the vehicle was from Shelter Island.

3. RESULTS AND DISCUSSION

On November 17th and 18th during the deployment, the tide was an incoming neap tide with a maximal height of 1.3 meters above mean low water (MLLW; Fig. 4). The deployment began just prior to the maximum transition at 01:15 LT. The integrated along path currents measured from the AUV's ADCPs show that the maximal mean currents of 26 cm/sec occurred during this period. ADCP data also shows little cross path flow in the channel. Along path flow was minimal during the slack tide at the end of the deployment.

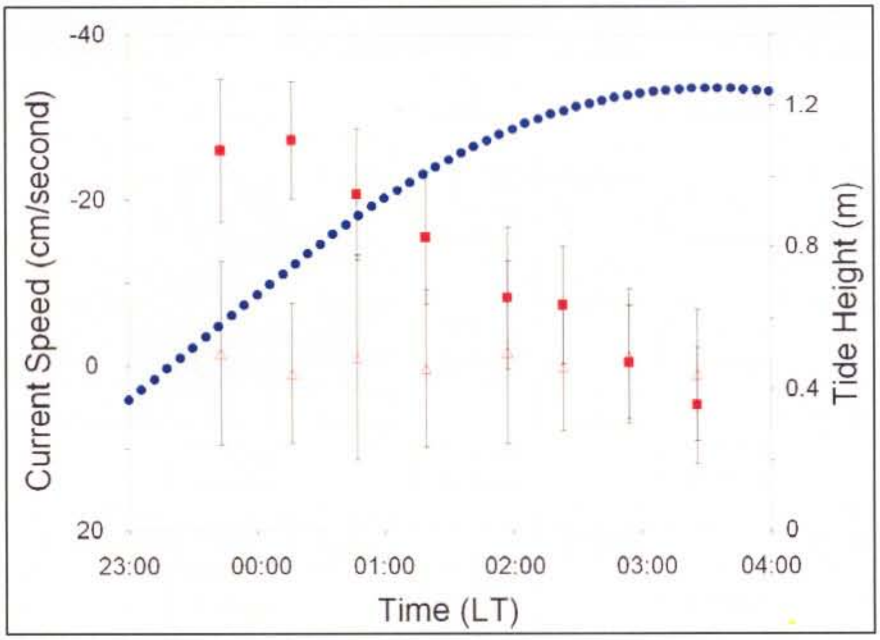

Figure 4: Mean current speeds in both the along path direction (filled red squares) and the cross path direction (open red triangles) measured from the AUV's upward and downward looking ADCPs. The standard deviations are shown for each pass from 23:40 until 03:26 LT between the 17th and 18th of November, 2004. The along path and cross path data are relative to the direction of the vehicle and transect line which has a heading of 223°. Tide height data taken from the NOAA tide gauge station in San Diego Harbor is also shown for the study period (filled blue circles).

Data from the AUV shows that warmer harbor waters were associated with lower salinities and were dominant in the channel early during the deployment (Fig. 5A&B). As the mission progressed, the harbor water transitioned to colder, clearer and more saline oceanic water reaching a maximum influence at slack tide. The diagonal patterns in each parameter suggest that material moving from one side of the 1 kilometer transect to another took ~ 1 ½ hours, indicating mean currents of ~ 15 cm/sec and is consistent with the on board AUV current data (Fig. 4). High fluorescence characterized transition zones and maximum gradients between the oceanic and harbor waters (Fig. 5C). The concentration of autotrophic plankton along fronts and gradients such as the one in this study is a common feature in biology[15]. Although phytoplankton contributed to the optical backscatter as measured by the AUV, the dominant scattering component was non-living material, evidenced in that the highest backscattering was associated with the warmer harbor water and not the highest fluorescence (Fig. 5D). As the region became more influenced by oceanic waters, water clarity increased. Unlike fluorescence patterns, high bioluminescence potential was not linked with the gradients between the water types, but exclusively associated with the oceanic waters. The highest bioluminescence potential was measured toward the end of the experiment, associated with the parcel of cold, clear saline oceanic water that transitioned through the study area (Fig. 5E). Bioluminescence potential has been shown to have a diel rhythm with little bioluminescence expressed during the daylight hours and the highest bioluminescence expressed at night. Previous work has shown that the levels of bioluminescence do not change significantly in the 6-hour period around midnight[16], therefore the patterns measured in this study do not include significant variability due to a diel pattern.

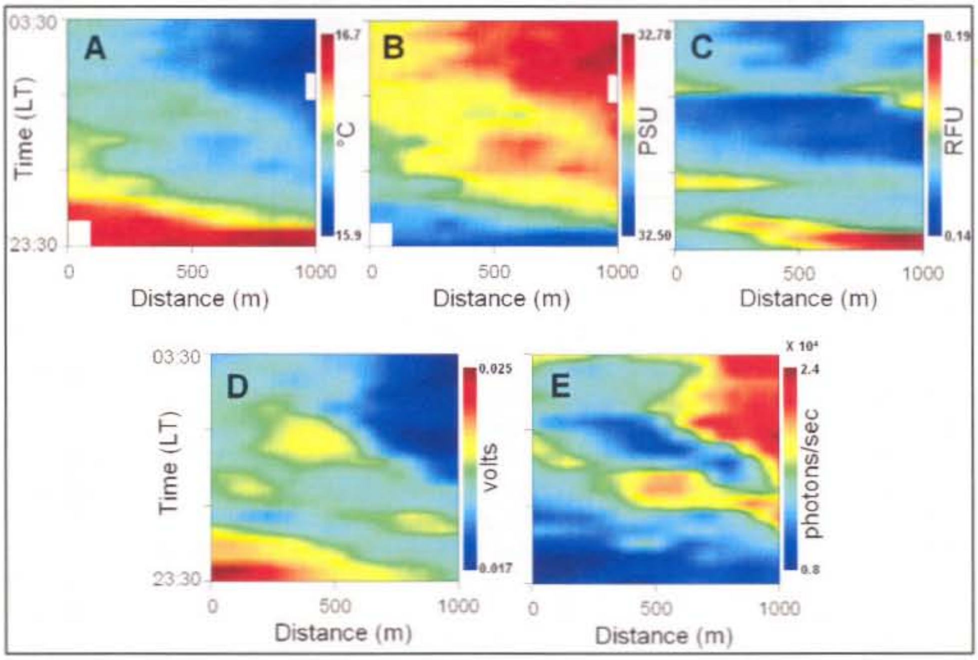

Figure 5: Depth averaged A) temperature, B) salinity, C) fluorescence, D) optical backscatter and E) Bioluminescence Potential as a function of distance over the vehicle deployment period. The data represent 26 time points. The distance axis is relative to the point furthest inside the bay with the furthest distance being toward the harbor entrance.

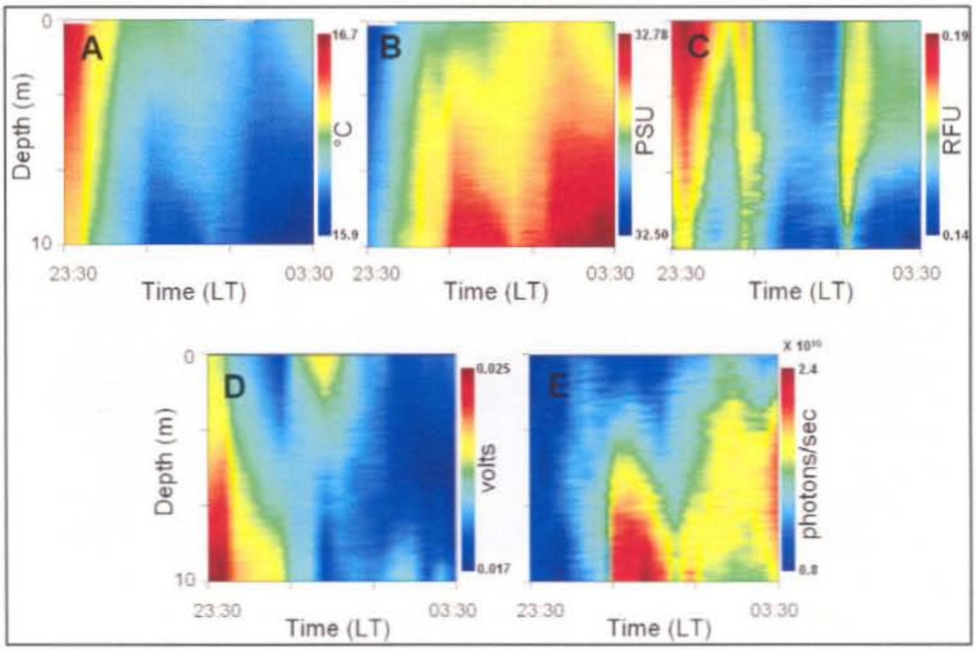

Figure 6: Depth distributions of A) temperature, B) salinity, C) fluorescence, D) optical backscatter and E) bioluminescence potential over the vehicle deployment period. Data are averaged across the transect line to represent the changes in the depth distributions during the study.

The distribution of the five parameters measured by the AUV with depth showed a similar transition from harbor water to ocean water (Fig. 6). The patterns in temperature, salinity, optical backscatter and bioluminescence potential were consistent, showing the highest bioluminescence potential in clear oceanic water. The influx of oceanic water midway through the deployment seen and described in Figure 5 is clearly from an incursion along the bottom. Again, the distribution of fluorescence illustrates that the autotrophic community was dominant in sharp gradients between harbor and oceanic water. The lack of correlation between bioluminescence potential and fluorescence suggests that the organisms responsible for the bioluminescent signal were predominantly heterotrophic. Another interesting pattern in all of the measured parameters was a stronger vertical separation in signal approaching the slack tide. Examination of the depth distribution of each parameter during the slack tide suggests that the water column is re-stratifying, with the buoyant harbor water moving over the denser oceanic water (Fig.7). Current patterns show the harbor water exiting and oceanic water entering San Diego Bay. Even though this movement is occurring, a vertical front of clear high bioluminescent potential water is maintained.

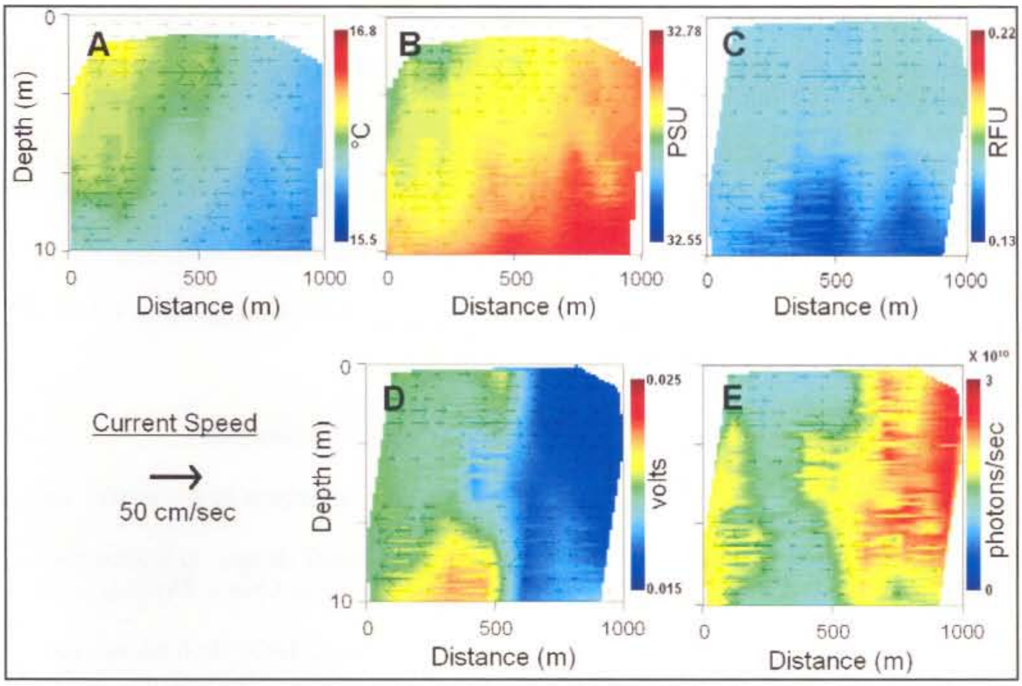

Figure 7: Transect data of A) temperature, B) salinity, C) fluorescence, D) optical backscatter and E) bioluminescence potential as a function of depth and distance for one pass taken at 03:06 LT. Overlaid are the along path current speeds taken at 02:55 LT from the horizontal path at 5 meters (see text).

4. CONCLUSIONS

The multi-instrument approach performed here helps to elucidate the complex dynamics occurring in harbor entrances that are enhanced during periods of large tidal range and demonstrates circumstances during which the possibility of passive threat detection by bioluminescence stimulation might be most feasible. Bioluminescence potential in the oceanic influenced waters was sufficiently high for detection and was dominated by heterotrophic organisms, which maintained their coherence with the clear oceanic waters throughout the deployment. This has implications for port and harbor security and may provide low-cost means of detection. Detection of subsurface vehicles and/or swimmers would be most feasible in the harbor mouth where there is the greatest influence of clear oceanic water. The greatest threat would be at low tide, when the turbid harbor water is dominant and it is less likely that bioluminescence stimulated below the surface would propagate to the surface at detectable levels. Although this study is not an exhaustive assessment of the complex coastal dynamics, it has demonstrated the utility of AUVs in measuring bioluminescence potential and other parameters in ports and harbors to define conditions when bioluminescence could best be used as a means of passive threat detection. Further studies are needed to examine additional environmental conditions, i.e. when the bioluminescent community is autotrophic and when the tidal currents are reversed, in order to fully evaluate the use of bioluminescence detection as a means of enhancing harbor and port security.

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