DURIP: A Low-Light Photon-Calibrated High-Resolution Digital Camera Imaging System

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LONG-TERM GOALS

Bioluminescence represents an operational threat to U.S. Navy nighttime operations because of the risk due to flow-stimulated light emission from naturally occurring plankton. Conversely, bioluminescence presents additional capabilities for detecting moving objects at night, particularly in the littoral zone where conventional acoustic surveillance is severely challenged. We are interested in the hydrodynamic conditions that stimulate bioluminescence, the resulting bioluminescence signatures, and how to estimate signatures based on levels of bioluminescence potential. Studies of bioluminescence require the application of low-light detection technology for the measurement and imaging of dim light sources.

OBJECTIVES

Low light imaging for applications such as bioluminescence is challenged by the need for high gain, low sensor noise, and high speed. Bioluminescence imaging is typically done with low-light camera systems using 2^{nd} or 3^{rd} generation image intensifiers coupled to a charge-coupled device (CCD) detector. Intensified camera systems show high detector sensitivity because photons are multiplied by the intensifier before being detected by the CCD. However, these systems are limited in spatial resolution, suffer from high background noise, and have insufficient stability for radiometric calibration. Recently developed electron multiplication CCD's exhibit low light capability without the need for image intensifiers. These new detectors use an on-chip multiplication gain technology to multiply photon-generated charge above the read noise. They contain a special extended serial register, known as a multiplication register, for change amplification after photons have been detected in the device's active area. Electrons are accelerated from pixel to pixel in the multiplication register and secondary electrons produced via an impact-ionization process. The result is high sensitivity and greatly improved signal to noise ratio. Electron multiplication CCD's also offer high spatial resolution, because in intensified CCD cameras the image intensifier limits spatial resolution.

Unlike image intensifiers, electron multiplication cameras do not carry the risk of potential damage from high light exposure and their performance does not degrade with time. They are also more reliable, with a fail rate of only 2-3% compared to 15% for intensified cameras. Because of their combination of high sensitivity, low noise, stability, high frame rate capability, and suitability for radiometric calibration, electron multiplication cameras are expected to eventually replace intensified cameras for most low light applications. For example, new camera technology for multispectral aerial

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surveillance of bioluminescence is based on the electron multiplication technology rather than image intensification.

The objective of this project is to develop a photon-calibrated bioluminescence imaging system based on a Photometrics Cascade:512B digital camera with on-chip multiplication gain. The back-illuminated pixel array has a quantum efficiency > 90%, contributing to its high sensitivity. The wide dynamic range of 16 bits per pixel (2^{16} = 65,536 levels per pixel) is the highest available. The exacting specifications of the Cascade:512B make it suitable for high precision photometry, where pixel levels are calibrated in photon units. This is a new capability in low light high speed imaging, because intensified cameras, which have traditionally dominated these applications, are not sufficiently stable for photon calibration. During this no-cost extension, the camera underwent calibration with a final calibration report to be received soon.

APPROACH

The Photometrics Cascade:512B digital imaging system offers very high sensitivity through the use of on-chip multiplication gain. Electron multiplication is a new technology for charge coupled device (CCD) cameras available since 2002. The Cascade:512B camera is a second generation implementation of this technology, showing increased sensitivity and lower noise than first generation cameras. High sensitivity is enhanced by the use of a back-illuminated CCD, so that rather than passing through the electronic circuitry covering the CCD, light enters from below through thinned silicon. The result is > 90% quantum efficiency, the highest commercially available, resulting in almost complete capture of all available photons of light. The 512 x 512 pixel array yields a pixel size of 16 x 16 µm, larger than the 7.4 µm pixels in first generation cameras and thus contributing to high sensitivity while providing good spatial resolution. The wide dynamic range of 16 bits per pixel is the highest commercially available. It results in 2^{16} = 65,536 gray scale levels per pixel, allowing simultaneous detection of bright and dim signals. For comparison, the highest bit depth in other digital cameras is only 12 bits (2^{12} = 4096 levels per pixel) while analog cameras are capable of only 8 bits (2^8 = 256 levels per pixel) when digitized. The camera is thermoelectrically cooled to –30˚C to reduce noise and enhance the signal to noise ratio. The camera is controlled through a Microsoft Windows compatible PC through a PCI interface with high bandwidth data transfer.

The Cascade:512B is directly controlled by Metamorph image processing software, an extremely powerful integrated package capable of full control of camera function, image acquisition, and image processing. The camera is fitted with a Schneider Optics 17 mm f/0.95 C-mount lens, chosen because of its high resolution, robust mechanical construction, flat response over the entire visible range, and fully documented specifications that are important for radiometric calibration.

Radiometric calibration of the Cascade:512B camera will be carried out by the Atmospheric Optics Group (AOG) of the Marine Physical Laboratory at Scripps. The AOG calibration facility is set up for calibrating low noise 16 bit CCD cameras used for whole sky imaging. It has calibrated many Photometrics Series 300 16 bit CCD cameras, as well as two other visible CCD camera types, a short wave IR imager, and a variety of photomultiplier devices. The Cascade:512B has the appropriate specifications for absolute radiometric calibration: low noise, thermoelectric cooling for thermal stability, wide 16 bit dynamic range, and fixed gain. Multiple calibrations are performed as part of the determination of the absolute radiance calibration. These typically include system linearity, absolute radiance, rolloff, and flat field tests. Because the sensitivity of the Cascade:512B is very non-linear as a function of gain, the camera will be photon calibrated at multiple gain settings for two lenses (17 and 25 mm).

WORK COMPLETED

The imaging system, including camera, computer, image processing software, and lens as described above, has been acquired and tested. Evaluation tests last year included imaging of dinoflagellate bioluminescence stimulated by a turbulent jet.

Since then the camera system has been successfully used in several projects: (1) a DARPA seedling project through Science Applications International Corporation (SAIC) examining flow stimulation of bioluminescence, (2) a DARPA project through the CEROS program to Oceanit developing a self-assessment tool for bioluminescence stimulated by underwater vehicles or other moving platforms, and (3) an NSF-funded project at Scripps using bioluminescence as a quantitative tool in measuring shear stress and dissipation within breaking wave crests.

Radiometric calibration of the camera was recently performed by the Atmospheric Optics Group (AOG) of the Marine Physical Laboratory at Scripps. The calibration report is pending.

RESULTS

Last year we reported that evaluation tests using a turbulent jet demonstrated that the Cascade:512B, which implements 2nd generation technology in electron multiplication, achieves superior imaging compared to the 1st generation electron multiplication Cascade:650 camera. With its higher sensitivity, it is better able to image low light events; with its lower noise, it yields higher signal to noise ratios. These results indicate that the Cascade:512B is a viable alternative to conventional camera systems using image intensification.

During the past year the camera was used in several DOD-funded and other projects. A DARPA project through SAIC examined flow stimulation of bioluminescence in the context of boundary layer hydrodynamics. The Cascade:512B was used to obtain images used for quantitative analysis of fluid shear stress.

The goal of a DARPA project as part of the CEROS program was to develop a self-assessment tool for wake-stimulated bioluminescence of underwater vehicles or other moving platforms. A field test in San Diego Bay during summer 2006 verified that the chosen detector system had sufficient sensitivity to measure bioluminescence stimulated by a propeller. The Cascade:512B was used to obtain images of the propeller-stimulated bioluminescence (Figure 1) and other types of flow stimulation. Quantitative analysis of these images determined that the region of maximum light intensity was at, and immediately behind, the propeller.

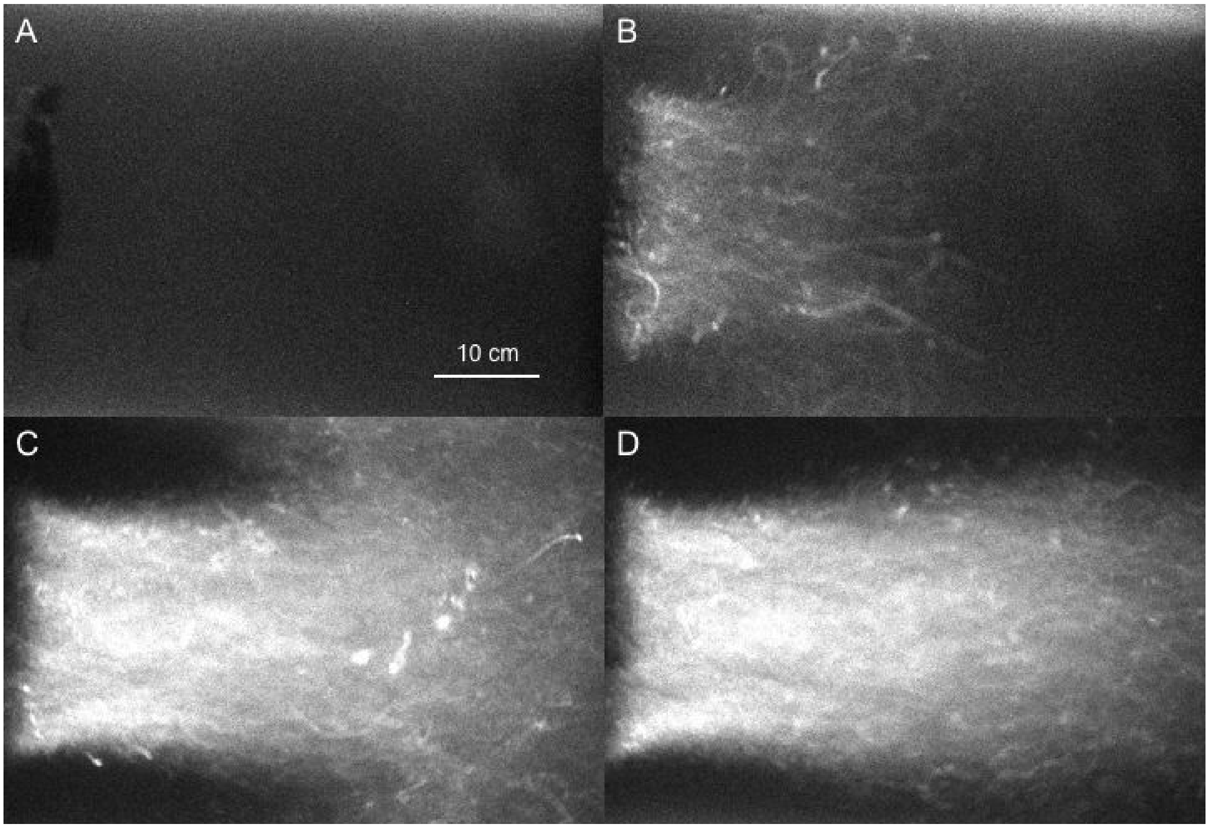

Figure 1. Bioluminescence from the natural plankton assemblage in San Diego Bay during summer 2006 imaged using the Cascade:512B. Images show 2 sec integrations as a propeller is turned on.

The Cascade:512B is critical to an NSF funded project using bioluminescence as a quantitative tool in measuring shear stress and dissipation within breaking wave crests. This work, in collaboration with Grant Deane and Dale Stokes of Scripps Institution of Oceanography, involves seeding dinoflagellates into the test volume of a laboratory wave tank and imaging the stimulated bioluminescence using the camera. The approach is to apply a flow stimulation model recently developed by Deane and Stokes (2005) to convert gray scale levels in the images to levels of shear stress.

IMPACT/APPLICATIONS

There is strong interest in the electron multiplication CCD camera technology because of its high gain, low noise, wide dynamic range, high speed, and indefinite life span. The most exciting new capability is that these cameras have the specifications and stability for radiometric calibration. This opens new opportunities for low light / high speed imaging with a photon calibrated digital camera. This capability has not previously been available in intensified cameras because of the lack of stability for calibration purposes. Thus the Cascade:512B, considered one of the best commercially available electron multiplication cameras, shows excellent promise for spearheading a new era in digital imaging that will benefit many disciplines.

The camera already is contributing to several recent research projects and will be of great benefit to future projects. The camera will also be used by Scripps graduate students as part of their dissertation research, and by student interns who assist in our research projects. Thus the next generation of scientists will be introduced to the latest technology in low light digital imaging.

REFERENCES

Deane, G. B. and M. D. Stokes. 2005. A quantitative model for flow-induced bioluminescence in dinoflagellates. Journal Of Theoretical Biology 237: 147-169.