A Submersible Holographic Camera for the Undisturbed Characterization of Optically Relevant Particles in Water (HOLOCAM).

James M. Sullivan
WET Labs, Inc.
70 Dean Knauss Drive
Narragansett, RI 02882
Phone: (401) 783-1787 fax: (401) 783-0309 e-mail: jims@wetlabs.com

Award Number: N0001410C0041
http://www.wetlabs.com

LONG-TERM GOALS

Our long-term goal is to develop novel oceanographic instrumentation to address fundamental questions in ocean optics. The primary goal of this project is to develop a holographic instrument capable of imaging and characterizing natural (i.e. undisturbed) particle fields in the ocean. The long-term science goal is to understand the link between suspended particles and the bulk scattering properties of natural waters. We believe in-situ digital holographic microscopy, recently developed and employed for both fluid dynamics and biological studies, has the capability to obtain critical data relevant to this goal.

OBJECTIVES

Our overall objective is to develop an in-situ profiling digital holographic microscopy system (HOLOCAM) capable of characterizing the properties of optically relevant particles within a size range of < 1 to 1000 µm. Our team will design, fabricate and characterize the HOLOCAM with the goal of commercialization. The HOLOCAM will be compact, submersible, capable of vertical profiling of undisturbed volumes of water, and with real-time visualization. It will quantify particle number, size and shape (e.g. cross-sectional area, surface area, aspect ratio, sphericity) and the 3-D spatial structure of the particle field (e.g. nearest neighbor distances). Identification of particles with unique shape characteristics (e.g. bubbles) and orientation should be achievable. The proposed HOLOCAM will extend the size range of particles currently resolvable by an existing system from a minimum of ~10 µm down into the sub-micron range (thus capturing the full range of optically relevant particles).

APPROACH

We have assembled a team of established experts from the oceanographic community to help achieve our objectives, including investigators from a business and two academic entities: J. Sullivan and M. Twardowski from WET Labs Inc., J. Katz from the Johns Hopkins University (JHU) and P. Donaghay from the University of Rhode Island (URI). In addition to HOLOCAM design and fabrication, this research team will evaluate the sensor's performance in the laboratory, assess absolute resolution and uncertainties, deploy it in the field, and develop custom software to analyze particle characteristics.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **A Submersible Holographic Camera for the Undisturbed Characterization of Optically Relevant Particles in Water (HOLOCAM).**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **WET Labs, Inc,70 Dean Knauss Drive,Narragansett,RI,02882**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Our work plan for the final year of the project was to complete assembly of two HOLOCAMs and conduct rigorous field testing.

WORK COMPLETED

1. Project design and status meetings.
Project investigators and lead engineers have met numerous times each project year to discuss the evolution of the HOLOCAM system design and control electronics. The primary focus of meetings have included overall mechanical design of the HOLOCAM, designing and improving control systems for synchronous firing of laser and cameras, redesign and repackaging of laser power electronics, building flexibility into the optical layout of the holography system, and data acquisition and storage system requirements.

2. Control electronics and modifications.
Custom DC based power supplies (350 V) and electronic trigger circuits of the cameras and laser were designed, built and tested with both HOLOCAM systems. It was determined during testing that modifications to the control electronics were required for accurate firing of the laser and synchronization to the dual camera system. This required several iterations of design modification and testing. The pulsed lasers used in the HOLOCAMs were also found to be non-functional (would not reliably fire) in environments with temperatures below ~ 13° C. Thermal isolation and internal heaters for the lasers were required to be built into the HOLOCAM design.

3. Acquired components for design improvements.
While the bulk of components required to build the systems were acquired during the first two years, additional components were needed and acquired. Several modifications were determined to be needed during the build and testing of the first and second systems and the additional required parts (neutral density filters, mounting hardware, lenses, etc.) were obtained. Some components (one of the lasers) were also found to be defective during the build/testing and required warranty repairs. This was a substantial effort during this year. (Figure 1).

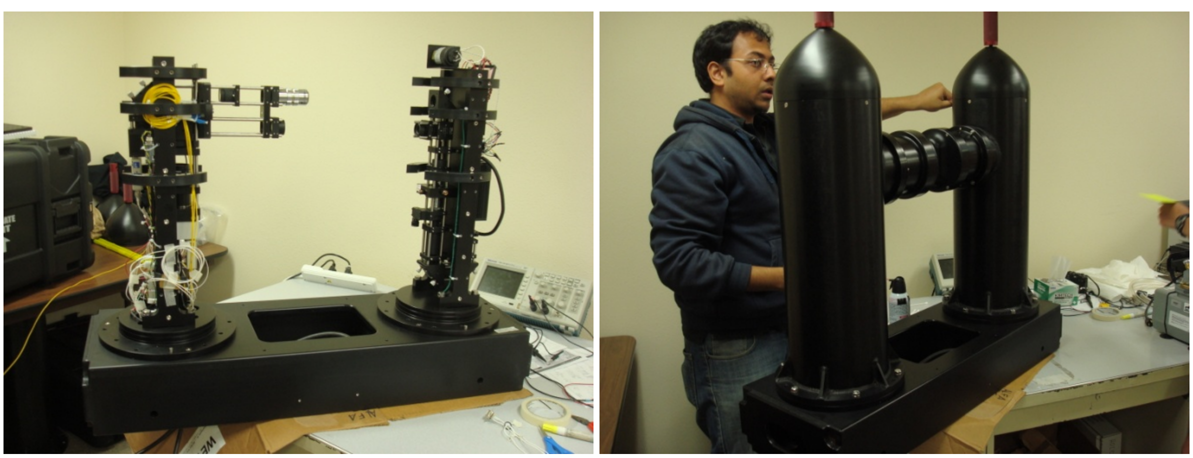

Figure 1. Internal electro-optical structure of the in-situ HOLOCAM (left panel). Pressure housings being assembled onto the first HOLOCAM (right panel).

4. HOLOCAM construction.
The full mechanical builds of both in-situ HOLOCAMs was completed at WET Labs. They have both been pressure and submersion tested (Figure 2).

Figure 2. Submersion and system testing of the first HOLOCAM at WET Labs.

5. HOLOCAM system testing.
It was discovered during testing of the lasers acquired for the two HOLOCAM systems that one of the lasers did not meet the firing frequency specification of the other. This required sending the laser back to the manufacturer for modification to make it identical to the other laser. The build of the second HOLOCAM system was on hold until this laser is returned from service. The laser was returned from service and additional problems were discovered (cold solder joint on board, non-reliable firing, etc.). This laser has been sent back three times to the manufacturer (and is currently being warranty serviced again). Given the issues with this laser, a new, third laser was purchased and integrated in the second HOLOCAM build. If the malfunctioning laser can ever be satisfactorily fixed by the manufacturer, it will serve as a spare for the two systems.

6. Software development/refinement for reconstructing digital holograms and particle analysis.
The first generation software for hologram numerical reconstruction and analysis of particle characteristics is complete. Improvements to these programs from both JHU and WET Labs software programmers were addressed during HOLOCAM testing. Refinements to these programs will evolve with the continued use of the systems. For example, our JHU partner has accelerated the speed of hologram reconstruction substantially using Graphics Processing Unit boards (GPUs). Reconstructing one plane of a 4kx4k hologram (four times the area of the HOLOCAM) takes a total of 0.26 s, but most of this time is initial CPU activities (0.22s), and the actual reconstruction on the GPU takes 40 msec. This means that reconstruction of ~1000 planes to get an entire volume, including transfer to the CPU, will takes ~ 2 sec. Having 3-D particle fields reconstructed shortly after acquiring data is now a reality.

7. Deliverables. Per contract requirements, a full HOLOCAM system (system 001) was delivered to our academic partner at JHU. They have conducted extensive laboratory testing and are currently field testing the system in Norway. The second HOLOCAM system (002) is being used in laboratory and field tests by WET Labs.

8. Continued diagnostic lab testing with bench-top HOLOCAM test-bed.
The small bench-top HOLOCAMs built to provide working holographic images used in the analytical software development have continually been used in comparisons to data collected by the in-situ HOLOCAM system, as well as a portable shipboard system used on projects that could not support deployment of the larger submersible system (see section 9 below).

9. Continued laboratory and field measurements.
Two in-situ HOLOCAM systems (and two bench-top systems) were built, and laboratory and field testing has been conducted by both JHU and WET Labs. We have recently (Sept. 2013) conducted a joint field test of the HOLOCAM in East Sound, WA in conjunction with instrument testing (LIDAR, LISST-HOLO, CytoSense, etc.) being conducted by Alan Weidemann's NRL group at Stennis Space Center, MS (Figure 3). As part of an ONR MURI project on the biological response to the dynamic spectral-polarized underwater light field (Sullivan, Co-PI), two field exercizes were conducted to measure and model (among other goals) the underwater spectral-polarized light field in distinct water types (oligotrophic and eutrophic). As part of this effort, water samples were taken from all environments sampled and the bench-top HOLOCAM was used to quantify the particle fields in these samples. The results will be used to help augment other in-situ optical data for the project. A final MURI field experiment is planned in 2014 and it is hoped that the in-situ HOLOCAM will be deployed as part of this experiment. The bench-top HOLOCAM has also recently been used in support of two projects: a U.S. Coast Guard sponsored project to develop new technologies to quantify and characterize oil emmulsions in seawater (Twardowski, PI) and a NSF-NIH sponsored project to better understand the environmental factors that impact toxic algal blooms in the Great Lakes, including their initiation, development, and senescence. The project is integrated with existing harmful algal bloom monitoring and observational activities through the NOAA Great Lakes Environmental Research Laboratory (GLERL). Particle characterization from the HOLOCAM was used to support both of these projects.

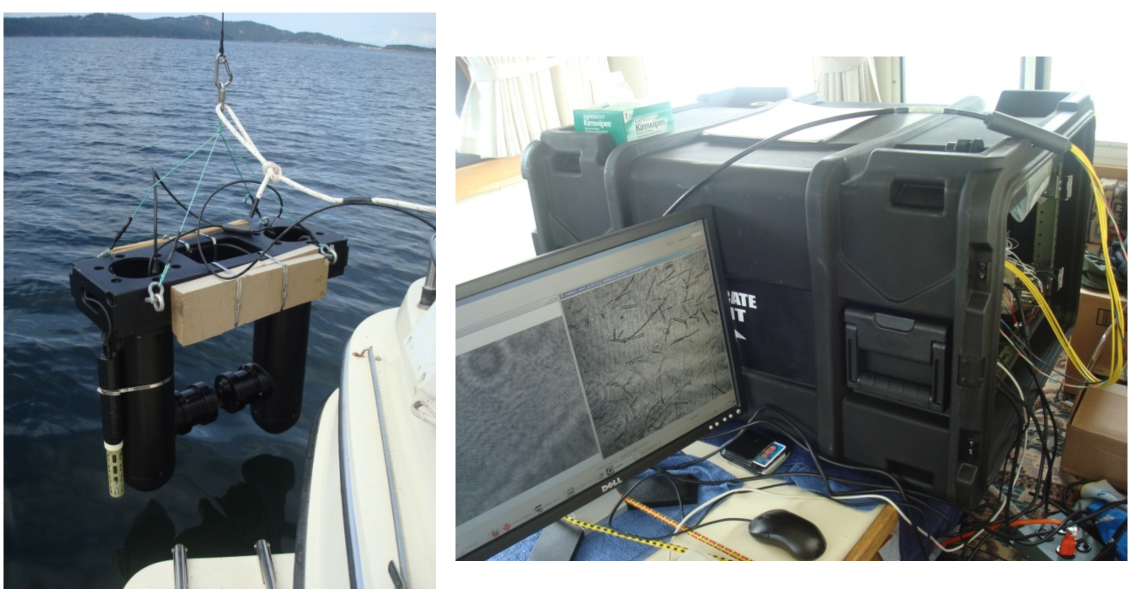

Figure 3. HOLOCAM system being deployed in East Sound, WA in Sept. 2013 (left panel). The HOLOCAM DVR real-time data acquisition system in use on the research vessel (right panel).

RESULTS

1. After extensive design and build meetings throughout the project, the research group finalized the design of the submersible HOLOCAM and completed the builds of two systems (e.g. Figure 1). The system is very similar to that outlined in the original proposal. This design still allows for future velocity measurements using the low magnification system, and the highest possible particle resolution for the high magnification system. A complete HOLOCAM system was shipped to our academic partner at JHU during April 2013 in fulfillment of contract deliverables.

2. Research into hardware based GPU hologram reconstruction has continued and appears to nearing a final stage of development (see section 6. above). This technology will be critical to making the HOLOCAM a viable, near-real time research tool.

3. Two bench-top HOLOCAM test beds have been continually used in both laboratory validation experiments and field testing and will be used alongside the submersible system during future deployments.

4. Transitioning of the expertise required for reconstruction and analysis of holograms to WET Labs from JHU has continued. WET Labs has taken holographic processing techniques outlined by our academic partners at JHU and adapted them all into a single programming language that is both widely used in the community and easily modified by end users (i.e. Matlab). Along with image analysis techniques, our JHU partners have developed software for detecting and measuring the size and spatial distribution of bubbles in reconstructed holograms utilizing edge detection and the unique shape of bubbles, and software to calculate in-situ velocity fields and gradients, as well as turbulence dissipation rates from pulsed time series of holograms. This software has been used successfully to process East Sound field data (Talapatra et al., see publications) and we will seek to transition these additional processing techniques into the core system software. We will continually assess how to improve both reconstruction and analytical software during future use of the submersible system and hope to integrate GPU reconstruction abilities in the near future as part of our ongoing partnership with JHU.

5. The recent field test in East Sound, WA during Sept. 2013 has already yielded intriguing results. During this cruise there was a strong phytoplankton bloom of the diatom *Ditylum*. This large, chain forming species formed thin layers throughout the Sound. The HOLOCAM captured the dramatic difference in the characteristics of the natural particle field inside and outside of these thin layers (Figure 4). Outside of the thin layer, aggregates, detritus and smaller particles dominated the particle field, however within the thin layers, very long chains of *Ditylum*, which averaged ~ 2 - 3 mm in length, dominated the particle field. It was also very common within the thin layers to find that the majority of these large chains had preferential orientation in the flow (Figure 5). This has very large repercussions to in-situ optics (see Related Projects).

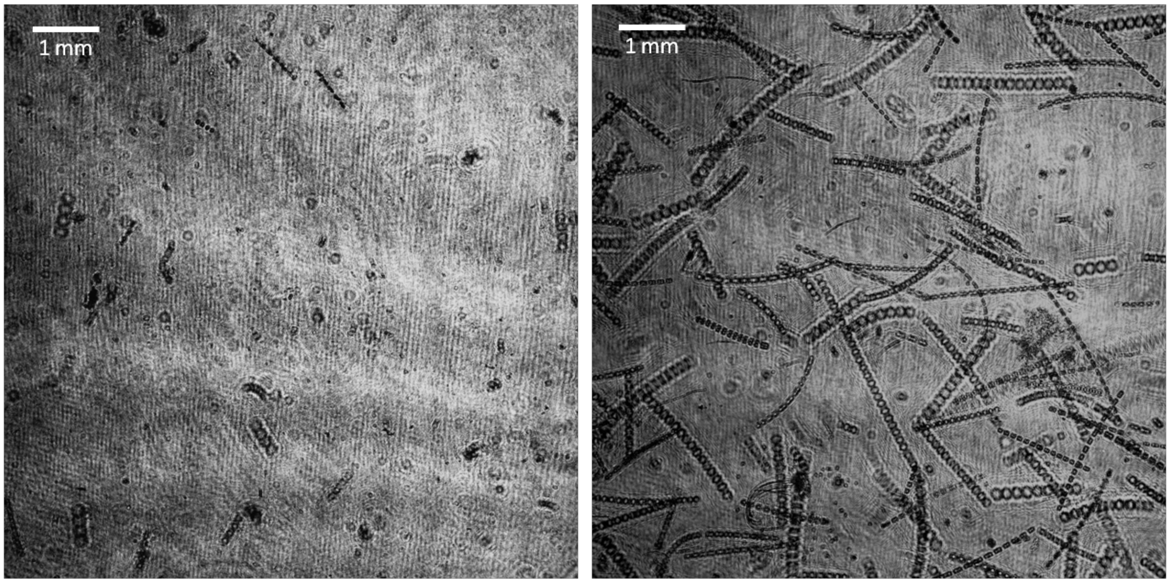

Figure 4. Raw holograms of the particle field inside (right panel) and outside (left panel) a thin layer of phytoplankton. The large chain forming diatoms observed in the thin layers (right panel) were from the genus Ditylum.

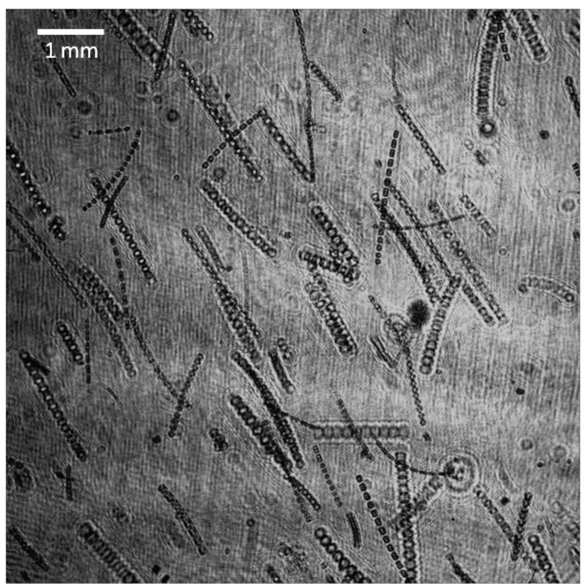

Figure 5. Raw holograms showing the orientation of Ditylum chains within a phytoplankton thin layer in East Sound, WA, 2013.

IMPACT/APPLICATIONS

The HOLOCAM could be used in a number of applications relating to ecosystem health and coastal resource management. For example, it could be used to monitor and detect oil droplets in the water column and in fact, the bench-top HOLOCAM was used for this application in a recent Coast Guard project (see related projects below). It could also be used for sediment load monitoring and assesment. Holographic images of undisturbed, optically significant particles will not only facilitate an improved understanding of the variability of inherent optical properties (IOPs, e.g. volume scattering), apparent optical properties (e.g. remote sensing reflectance, diffuse attenuation) and the performance of operational systems (e.g. LIDAR, laser line scanners), but could also provide critical data to any science question that requires an understanding of particle size, shape, fine-scale distribution, and/or short time-scale dynamics.

TRANSITIONS

The HOLOCAM is being developed as a new commercial product for WET Labs, Inc. The design of the HOLOCAM requires WET Labs to integrate new engineering and manufacturing capabilities in the use of lasers, high-speed fiber optic data transfers, GPU programming and image analysis techniques.

RELATED PROJECTS

WET Labs and our partners on this project have several on-going ONR sponsored research projects that will both benefit, and be benefited by, the HOLOCAM project. Upon successful development and laboratory validation/characterization of the HOLOCAM, the sensor will be deployed in the field as part of an integrated HOLOCAM - optics profiler. Field deployments of the HOLOCAM – optics profiler will be used to further evaluate and validate the HOLOCAM while also providing data (in addition to that from laboratory experiments) to investigate science objectives relevant to these related projects.

For example, we were encouraged by ONR in 2012 to submit a full proposal to characterize the degree to which natural, undisturbed particle populations are preferentially oriented in coastal waters using several optical sensors including the HOLOCAM. If this proposal is funded (it is currently on hold due to budget issues at ONR), the HOLOCAM will be extensively used during a planned field effort to support this research. This research is critical because in virtually all optical measurements and models, the VSF is assumed to have no dependency on the direction of illumination or the azimuthal plane of scattered radiance. For this assumption to be true, all particles suspended in the water column must be randomly oriented. From simple physics of hydrodynamic flows for the nonspherical particles that comprise virtually all the particles in the ocean, this is not a reasonable assumption. Furthermore, direct evidence from the field is confirming ubiquitous preferential particle alignment in coastal waters, particularly within density gradients (e.g. HOLOCAM field data from Talapatra et al., and recent results from East Sound, WA). Consequently, it appears that our understanding of the geometry-dependent VSF, and thus light transmission through coastal waters is significantly biased, with errors expected to be > 20% and often possibly > 50% in particle layers found within density gradients with low turbulence.

In addition, phase-I work for a recent U.S. Coast Guard contract (Twardowski, PI) evaluating the feasibility of developing a compact, inexpensive, multi-angle scattering instrument to quantify the size distribution and abundance of emulsified oil droplets in water, and determine the refractive index of the oil to readily derive density and viscosity, has used the bench-top HOLOCAM to determine the accuracies in size distributions and concentrations determined with the scattering instrument. The HOLOCAM will be used again in phase II work of this contract during large tank testing at the OHMSET facility.

PUBLICATIONS

Talapatra, S., Hong, J., McFarland, M., Nayak, A.R., Zhang, C., Katz, J., Sullivan, J. M., Twardowski, M. S., Rines, J., & P. Donaghay (2013). Characterization of biophysical interactions in the water column using *in situ* holography. *Mar. Ecol. Prog. Ser.*, Vol. 473: 29-51., doi: 10.3354/meps10049.