A new multispectral imaging instrument for *in-situ* characterization of flocs & colloidal aggregates in natural waters

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ABSTRACT

In-situ sampling, characterization and quantification of colloidal aggregates and flocs in ambient water is complex but needed in order to understand their role in development and maintenance of moving fluid muds, muck, bottom boundary lutocline layers and nephelometric interfaces in aquatic systems. These bottom boundary interfaces and associated processes contribute to sedimentation, particle deposition and resuspension of total particulate matter and associated nutrients. Increasing the scientific understanding of the above requires advances in environmental sensing instrumentation (passive and active) to successfully understand these aquatic interfaces. Standalone *in-situ* sensors that automatically perform multiple steps including sampling, separation, and detection have the potential to greatly advance analytical science. A new *in-situ* multispectral optical camera system for environmental monitoring and surveillance of delicate flocs and related aggregate structures is described. Results of the system show that flocs - 0.1 mm –10.2 mm diameter (mean diameter of 2.77 mm), with a variance of 5.952 mm and a *median* effective cross-section area of 30 mm^2 can be measured using the passive multispectral optical imaging system. The system is lightweight, compact and suitable for shallow or deep water deployment. When combined with fixed station acoustic echogram instruments, nephelometric (turbidity) waves can be easily observed. Time sequential analysis of imagery allows the system to be used as an optical particle velocimetry system (OPVS). Initial shallow water testing resulted in Lagrangian particle velocities of 0.3 to 3 cm sec^{-1} to be measured. Similar results were obtained from an acoustic velocity current meter (MAVS3) and a Marsh McBirney 201D electromagnetic current meters. When combined with results from direct methods using sondes for estimating sediment mass fluxes, the combined systems provide data necessary for sediment and water quality modeling. The new optical sensor system will help address analytical needs reported in past studies and provides a new standard method and protocol for measuring the movement of sediment and particulates in the aquatic bottom boundary layers.

Key Words: flocs, colloidal aggregates, multispectral, sondes, subsurface sensing, acoustic imaging, optical imaging, hyperspectral, lagoons, estuaries, water quality, water monitoring, coastal ocean, environmental surveillance, optical monitoring, shallow water, particle velocimetry, turbidity, video imaging, remote sensing, dredging, fluid mud, muck, noncontact sensing, video analysis, subsurface probes.

1. INTRODUCTION & BACKGROUND

Background

Marine flocs and colloidal aggregates has been previously studied by Gibbs, 1983 where he demonstrated flocs and coagulation of minerals begin at salinities as low as 0.5 to 1 practical salinity units (psu) or ppt in natural waters. In 1970 Gibbs published his paper concerning world water chemistry and demonstrated the important role of how salts and minerals in water from different origins can be described. His basic model and research demonstrated the importance of natural occurring flocs and colloidal aggregates in not only marine but freshwater systems, where salts and minerals in rainwater contribute to the coagulation (flocculation) process that begins in near surface waters after rainfall events. *In-situ* sampling of flocs cannot be accomplished with traditional sampling techniques such as Niskin bottles[3] or pumped samples. These fragile aggregates are best considered to be similar to “snowflakes”. They break under the influence of rapid pressure changes and water movement that accompanies Niskin water samplers and the pumping of water.

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Thus, those interested in studying these naturally occurring precursors to the buildup of fine grain mud and muck in rivers and estuaries have resorted to various imaging or optical methods and associated image processing techniques that make use of multichannel camera systems[4,5]. An advantage of imaging systems includes the ability to characterize the size and shapes of the marine snow - colloidal particle aggregates[5]. Flocs imaged in water from water environments have been shown to have size ranges from ~ 0.1 mm to over 2 mm[5]. In many cases micro flocs coagulate, consolidate, and interact in a flocculation process that produces larger flocs and colloidal aggregates (several loosely combined flocs). The result is the creation of mixed sediment flocs and suspensions - a combination of organic matter and small inorganic particulates. These aggregates can remain in suspension until they settle to the bottom boundary lutocline. These settled mud particles in aquatic systems can be easily resuspended and entrained back into the water column before natural dewatering of the surface muds occurs. Once natural dewatering occurs, the individual flocs and aggregates can no longer be distinguished and become a major component of cohesive bottom sediments. The dewatering or consolidation rates of the flocs, their deposition, and erosion can depend upon the electrostatic charges, biogenic coatings, salinity, minerals (in rain and freshwater), turbulent shear stresses, velocity gradients in the bottom water, and differential settling[6,7,8]. Sediments remobilized from the bed and "*algae*" flocculate and form biotic-abiotic aggregates[9]. These aggregate characteristics change with algae type and environmental conditions such as turbidity, the type of sediment (anoxic or oxic), minerals, and the structure of the fine sediment particles *and* algal species. The resulting flocculation and aggregates in turn affects the underwater light climatology and light obscuration in the bottom boundary layer[9] within submerged vegetation canopies. The spectrum of this underwater light field is critical to the functioning of ecologically important submerged vascular plants. Verspagen, et al., 2006 showed aggregation with clay particles caused sedimentation of Microcystis spp. cyanobacteria species, thus demonstrating the interplay between these sediment particle movements and population dynamics of Microcystis strains[10] with varying "stickiness".

In-situ collections of colloidal aggregates and flocs can be made using different sediment traps and passive sondes[11,12]. In fact, they are the only means that allow researchers to collect *direct in-situ fluxes* (g m^2 day^{-1}) of the horizontal and vertical (sinking or resuspended) aquatic snow[13,14,15,16] that makes fluid mud and muck. Laboratory floc motion (stirrers) and movement observations and recirculating annular flume experiments provide valuable flocculation process data[5]. The new *in-situ* multispectral imaging system described in detail below also provides *in-situ* particle motion in terms of their horizontal floc movement in the bottom boundary layer. In essence, it is also an "optical particle velocimetry system" (POVS) that also provides individual size information concerning micro flocs and colloidal aggregates.

2. TECHNIQUES & METHODS

2.1 Study areas for testing the floc & particle velocimetry system (OPVS)

Figure 1 shows a satellite image of the study for testing. The locations are in Indian River Lagoon, Florida where four transects and stations for *in-situ* data and imagery (surface & subsurface) was collected near Sebastian Inlet (middle image). Transects across the Intracoastal Waterway (ICW) were selected based upon a monitoring project related to a recent maintenance dredging project funded by the Florida Inland Navigation District (FIND). Data from transect 2 are reported in this paper. The second area is in Palm Bay (right image). Three stations located within the highlighted box were sampled for flocs and measurements of muck depths using a sludge judge. The Palm Bay area is shown using a recent multispectral (R,G,B) Pleiades satellite image with 2 m spatial resolution that was acquired on June 22, 2015.

2.2 Design characteristics of the new multispectral optical particle velocimetry system (OPVS)

The *in-situ* camera system can be oriented in a vertical or horizontal position with a digital multispectral camera that views an encased glass optical waveguide. The waveguide is approximately 20 cm in dimeter with approximately 100 light emitting diodes (LEDs) secured to the edge of the glass plate as depicted in Figure 2. The light from the LEDs enter the glass light guide and produce a uniform "upwelling" light field that is viewed by a digital multispectral camera. The glass surface can be coated with a white antireflective material in order to obtain a desired spectral response. A multispectral digital camera or a hyperspectral imaging camera is mounted in a manner to view the glass plate as depicted in Figure 3. The cameras are carefully focused to view particles passing across (but very close) to the glass plate. Figure 3 shows the internal components for the subsurface illumination system located within a watertight case.

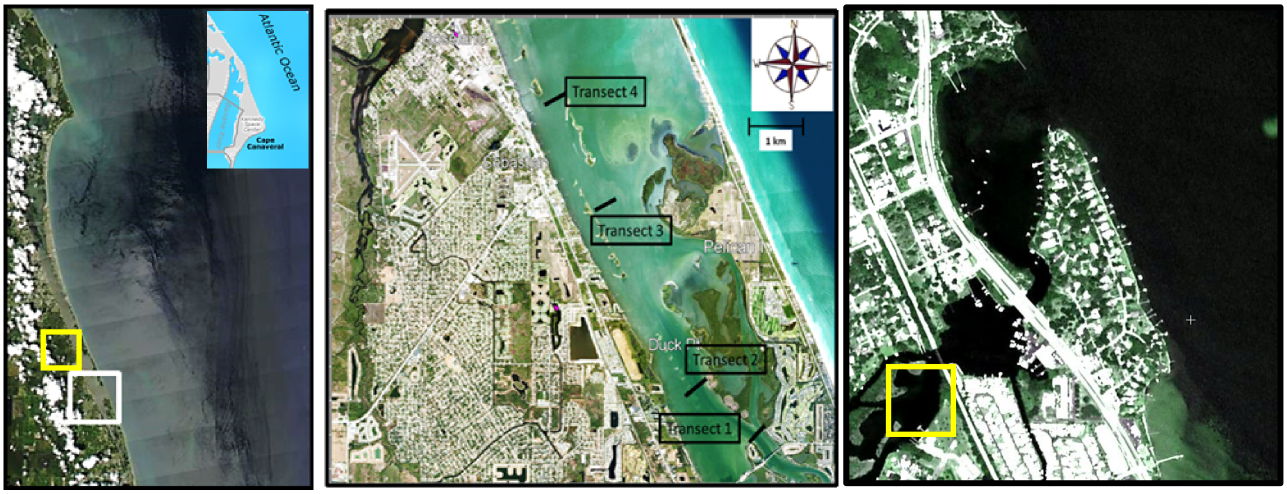


Figure 1. MODIS Aqua image (left) of Space Coast Florida near Cape Canaveral (August 24, 2015). The southern study area is outlined in white box within the left image. The southern study area is shown (center) with a multispectral satellite image (courtesy Digital Globe) and transects where *in-situ*, subsurface, and surface data were collected from February through August, 2015. The study area is along the Atlantic coast of Florida, south of the Sebastian Inlet and north of the Wabasso Florida causeway shown south of transect 1. The second study area (outlined in yellow) is within Palm Bay, Florida (right image) outlined within a Pleiades satellite image acquired June 22, 20115.

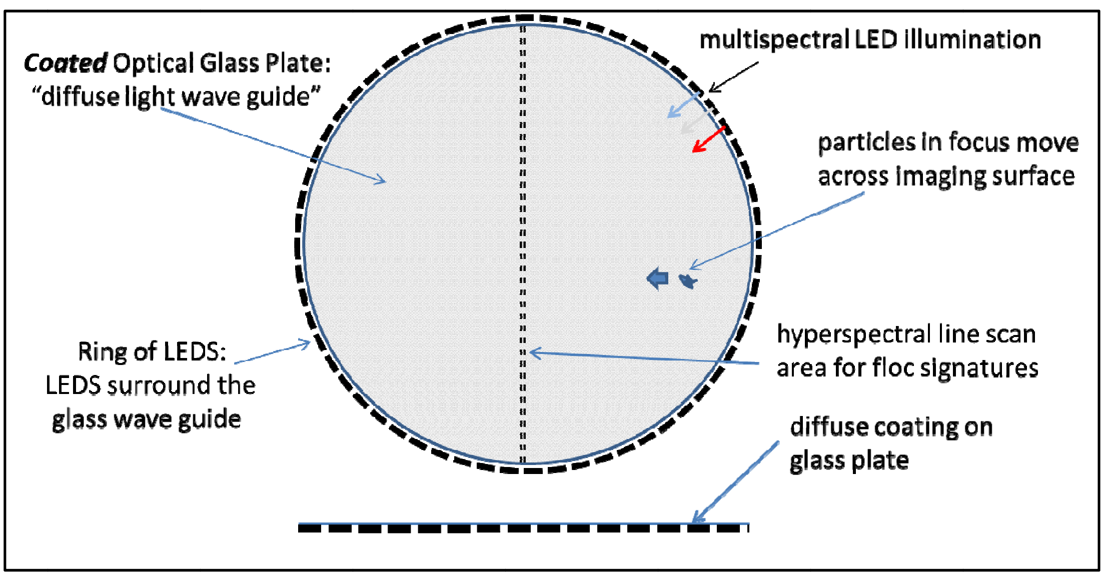
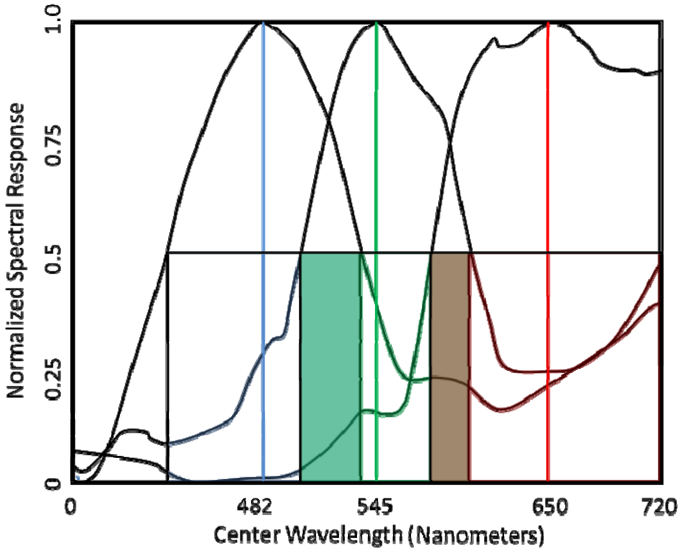


Figure 2. Schematic depicting the circular LED light guide as an illumination source for imaging flocs and colloidal aggregates. A white anti-reflection coated glass plate is imaged as flocs move across the multispectral camera's field of view. A hyperspectral line-camera can is used to perform spectral imaging of the flocs and colloidal particles as they move across a 1-D hyperspectral sensor array within the field of view of a Peltier cooled hyperspectral line camera (indicated by the vertical line). LEDs can be selected with specific spectral features along with the glass coating in order to provide a desired spectral illumination field for spectral imaging.

Spectral response curves of the digital multispectral bands are shown system in Figure 3 (left). The current system consists of a high definition video camera system with low light level sensitivity. Using precise focal plane focusing - flocs and particles are tracked as they move across the illuminated light guide. The video sequences can be individually analyzed in order to calculate individual floc sizes, particle velocities and directional movements (x,y,z) in a moving lutocline, or nephelometric layer in the water.



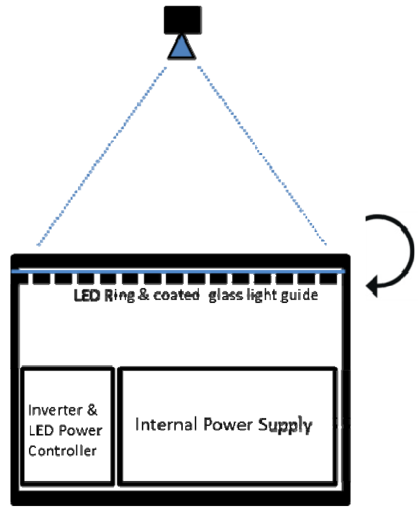


Figure 3. Normalized spectral response curves (left) of the multispectral camera used to test the *in-situ* subsurface spectral imaging of flocs. The submersible floc camera system is depicted (right) showing the components contained within a watertight submersible case for deployment up to 3.8 atmospheres (39 m). The system can image vertically or horizontally when deployed at the water bottom.

The subsurface active-passive sensing system can be oriented to view horizontal *or* vertical movements (speed and direction) of particles and colloidal assemblages as indicated in Figure 3 (right). The frame rate (30-120 Hz) can be increased or decreased according to flow conditions. Because of the possible turbid conditions in lutoclines and the mobile fluid mud layer, the active light source intensity can be adjusted as necessary. Instead of using backscattered light, the particle assemblages are viewed using the forward light level illumination system. This reduces the backscattering effects used in existing submerged imaging systems. Thus the forward scattering portion of the volume scattering phase function of water is used to illuminate particles. This reduces light scattering effects that typically degrade subsurface particle detection. Figure 4 is a spectral (normalized) response curve of the illumination field using the LEDS and light guide. Viewing the illumination area without the source switched on, allows one to measure the spectral intensity of the downwelling light field and can be used to calculate a *reflectance of the natural floc particles*.

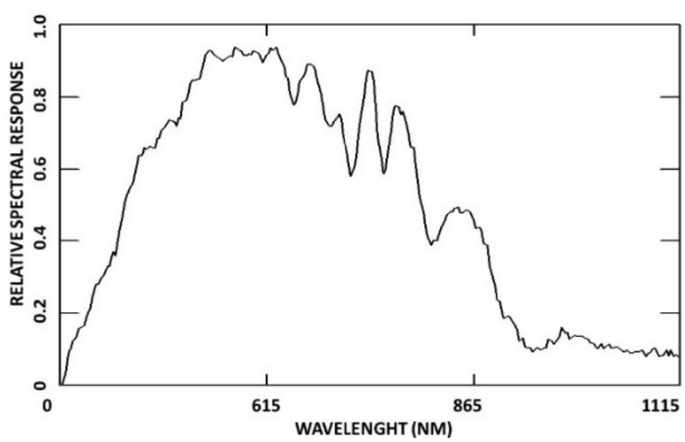


Figure 4. The spectral response curve of the LED light guide after the active light passes through the anti-reflective coated wave guide within the underwater housing. The measured signature was obtained with a SE590 high radiometric sensitivity and narrow band solid state spectrograph at the height above the light guide where the spectral camera collects imagery of the colloidal particulates.

Figure 5(A) shows the actual subsurface camera system (left) and camera calibration targets used for focusing and pixel size calibration before deployment. Calibration targets are used for focusing adjustments shown in Figure 5(B, C, D).

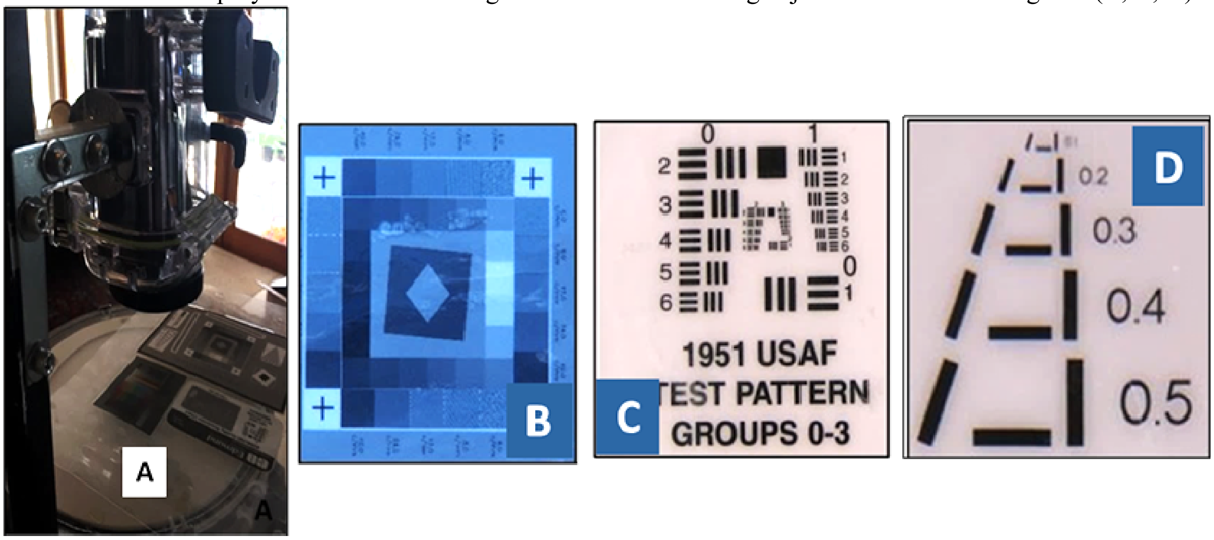


Figure 5. Image showing the floc multispectral camera system (A) and camera calibration targets used for focusing the camera before deployment from a vessel (images B, C, D) and for determination of effective pixel size resolution when viewing the illuminated circular LED light guide.

3. RESULTS

3.1 Multispectral Camera System

Subsurface light seen above the water surface shown in Figure 6(A) during a Wabasso, Florida deployment on August 2015 at transect 2. *In-situ* subsurface Nephelometric (turbidity waves) were captured by viewing the submersed system as indicated in Figure 6(B) by a camera located just below the water surface, but above the system. A *fixed location* acoustic image (echogram) taken at 455 KHz during a ~30 second scan period is shown in Figure 6(C) and also indicates the near bottom Nephelometric waves in at the edge of the ICW. The water depth in the channel was 3-4 meters. Tidal currents moved onto the more shallow bank (2.5 m) outside the channel where the camera was positioned.

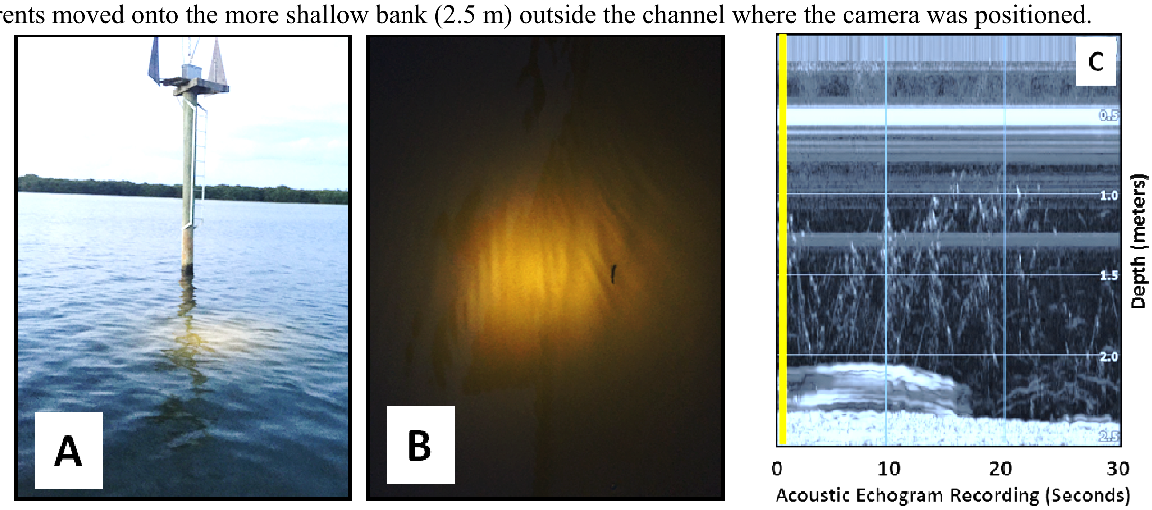


Figure 6. Above surface image (A) showing the *submerged* multispectral floc camera system position and underwater light field. Subsurface image (B) of the illumination area using an independent multispectral camera located below the water surface indicates the presence of near bottom nephelometric waves at the top of the moving lutocline. Acoustic echogram (C) taken with a 455 KHz *fixed location* (yellow line) downscan acoustic fanbeam. The echogram also recorded the presence of turbidly waves in the bottom boundary layer.

Figure 7 was taken with the floc camera during deployment. The particles are air bubbles on the image plane. The image has been histogram equalized and demonstrates the ability of the camera system to resolve small particles.

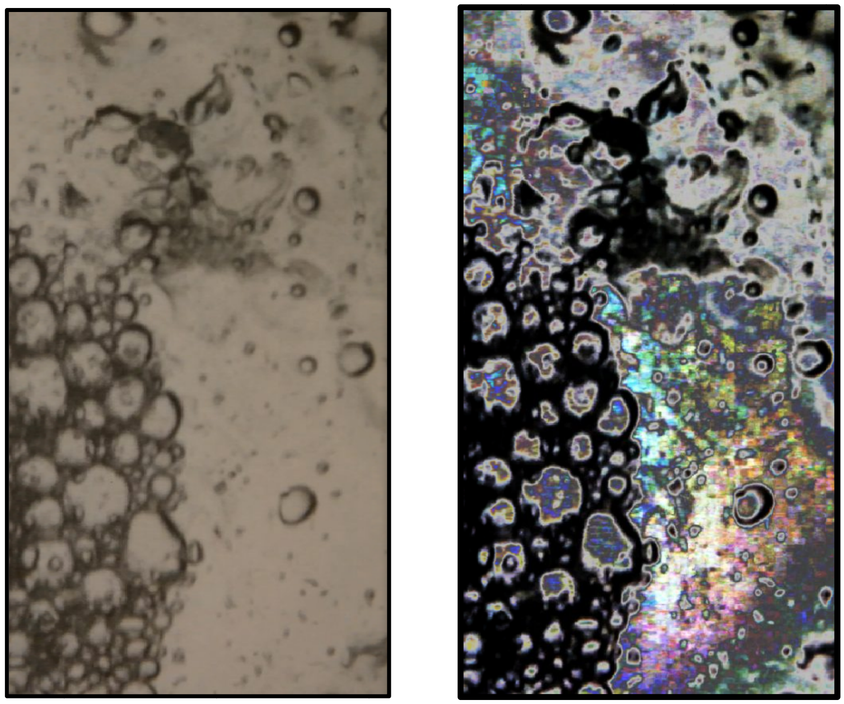


Figure 7. Multispectral mage acquired during deployment of the floc camera system. Small bubbles are observed as the system enters the water. The same image (right) is a contrast stretched image of bubbles at the surface of the circular LED light guide. The ability to discriminate small particles such as bubbles allows for independent particle size calibrations

Using an image processing approach with focusing upon the light guide plane, only particles and assemblages on the circular light guide surface are "*in focus*" and used to determine particle sizes and particle velocity distributions - horizontal speed and directions (in the x, y plane). These are reported as probability density functions for (a) size of flocs, (b) movement and (c) direction. Particles are excluded from the analysis if they move out of focus and/or particles cross paths. A frame rate of 30 HZ or higher with close proximity sensing and high spatial resolution imaging of the circular LED glass wave guide allows particles to be tracked as they pass across the light guide. Very small particulates and flocs are resolvable similar to systems reported by Manning and Dyer, 2000 and Manning, et al. 2011.

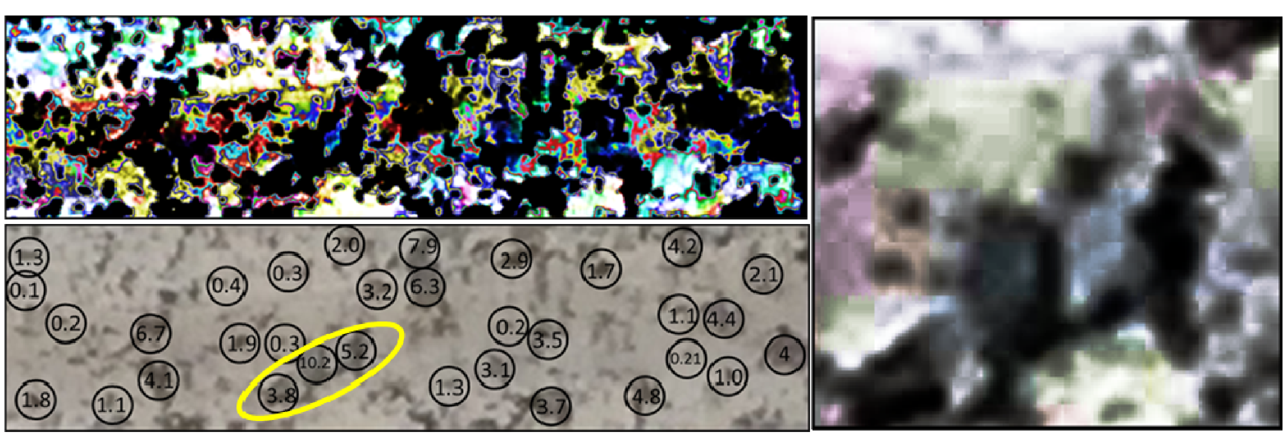


Figure 8a. Enhanced multispectral image (upper left) showing the contrast between flocs. Flocs and estimated effective floc sizes (lower left) are indicated with effective floc diameters shown in mm. The area within the yellow area is shown to the right and suggests a *colloidal aggregate of connected flocs*.

Effective particle size distributions suggest the size distributions follow the exponential distribution for floc effective cross-sectional diameter (KS <0.001), N=33). The floc effective diameters at station TCB1 in Palm Bay were 0.1 mm – 10.2 mm with a mean diameter of 2.77 mm, variance of 5.952 mm. The *median* effective cross-section area of ~30 mm^2 is shown in Figure 8 where floc cross-sectional areas are shown in terms of probability distributions (CDF's or PDF's).

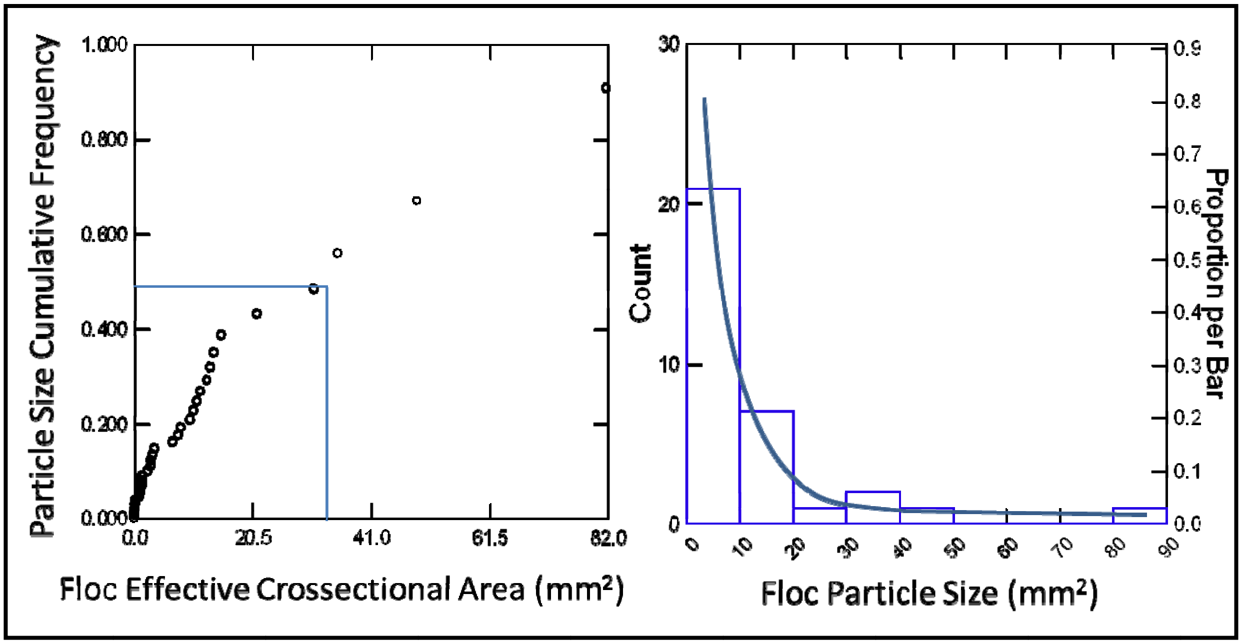


Figure 8b.Measured probability distributions (CDF-left) and (PDF-right) of floc cross-sectional areas obtained from the multispectral camera system

The *in-situ* camera can be operated as an "*optical particle velocimetry imaging system*" (OPVS) and was deployed at transect 2 on the west side of the waterway on August 10-11, 2015. The system was deployed at the same height as passive horizontal passive sondes[12] that measure the mass flux (g cm^{-2} sec^{-1}). Two MAVS3 acoustic velocity current meters were deploy at the same location. Results from the test deployment with focal focusing upon the top of the LED circular light source, allowed for comparison to a MAVS3 and Marsh McBirney electromagnetic current meter (201D) system. Results suggest water and particle velocities are in reasonable agreement (see Figure 9). The electromagnetic MB201D indicated velocities just near 0.25 cm sec^{-1}. The acoustic velocity MAV3's indicated velocities centered near 1.5 cm $^{-2}$. All 3 systems operated simultaneously and resulted in similar values as shown in Figure 4.

The system shown in Figure 5 is currently being modified to simultaneously measure hyperspectral signatures of the particles and flocs with approximately 3 times the spatial resolution in order to resolve particles moving with sizes on the order of 0.04 mm or approximately 40 microns in size. The particle spectral signatures produced will be enable one to detect particulate composition. The 3 band multispectral video camera combined with a hyperspectral imaging system is being developed to utilize optimized spectral image data fusion methods used in target detection and recognition applications[17].

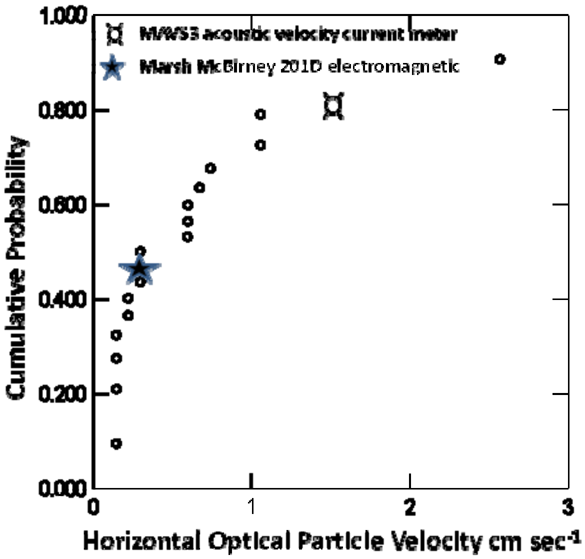


Figure 9. Comparison between the floc camera acting as an *optical particle velocimetry system* (**OPVS**) for estimating particle Lagrangian speed and (a) MAVS3 (modular acoustic velocity) current meter (right) and (b) digital Marsh McBirney 201D electromagnetic current meter. The OPVS data analysis can provide horizontal particle and floc velocities in terms of cumulative density functions (CDFs) as shown.

The two MAV3 3D acoustic current meters (see upper right image) deployed during this deployment period indicated strong boundary layer vertical velocities of several cm sec^{-1} at the western side of the waterway where water depth changed abruptly. Other acoustic imagery showed what appeared to be wavelike acoustic backscattering (burst like) bottom features (see Figure 6 – C) occurring in the bottom boundary layer. A 5 channel acoustic imaging sensing system was used to obtain images of the moving turbidity waves. The channel at 455 KHZ produced the best resolution of the moving turbidity structures at the top of the lutocline (see Figure 6 - B and C) and just above the floc camera system.

4.0 SUMMARY & CONCLUSIONS

The research reported describes the design, operation and initial deployment results from a new (*in-situ*) multispectral floc camera system. The system is compact and can be deployed in shallow water or deep water aquatic habitats. The system design allows one to calculate the effective diameter and cross-sectional area of flocs and colloidal aggregates (loosely joined flocs). Time dependent analysis of image frames also allows the system to be operated as an *optical particle velocimetry system* (OPVS) in order to provide velocities and direction of movement of the flocs and particulates. The system is being used in conjunction with fixed location acoustic echogram recordings and direct *in-situ* observations of horizontal moving fluid mud in term of mass flux (g m^2 sec^{-1}). The new instrument allows one to make *in-situ* measurements of flocs at the top of the moving lutocline and can be used to measure nephelometric (turbidity) waves in the bottom boundary layer in natural waters. The multispectral bands used can be modified by deployment with different camera systems and filters. Additional research is being conducted to attach a line scanning hyperspectral camera in order to provide compositional information regarding the flocs moving across the LED circular wave guide as well as modifying the illumination system for (a) pulsed operation and (b) narrow band illumination options.

In general, the camera system represents a passive sediment sampling methodology needed to characterize the bottom boundary layer and transport of particulates in aquatic systems. The goal is to combine the new system with direct methods of sediment fluxes[12] and other surrogate acoustic and optical methods in order to develop data for dredging related water quality and sediment transport modeling[18,19,20,21] under different water wave conditions that influence the bottom boundary layer[21,22,32,24,25,26,27].

5.0 ACKNOWLEDGEMENTS

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