Moving fluid mud sondes, optical and acoustic sensing methods in support of coastal waterway dredging

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ABSTRACT

Airborne, Satellite and In-Situ optical and acoustical imaging provides a means to characterize surface and subsurface water conditions in shallow marine systems. An important research topic to be studied during dredging operations in harbors and navigable waterways is the movement of fluidized muds before, during and after dredging operations. The fluid movement of the surficial sediments in the form of flocs, muck and mud is important to estimate in order to model the transport of solids material during dredging operations. Movement of highly turbid bottom material creates a lutocline or near bottom nephelometric layers, reduces the penetration of light reaching the water bottom. Monitoring and measurement systems recently developed for use in shallow marine areas, such as the Indian River Lagoon are discussed. Newly developed passive sondes and subsurface imaging are described. Methods and techniques for quantifying the mass density flux of total particulate matter demonstrate the use of multiple sensor systems for environmental monitoring and provide directional fluxes and movement of the fluidized solids. Airborne imaging of dredge site provide wide area surveillance during these activities. Passive sondes, optical imaging and acoustical sensors are used to understand horizontal and vertical mass flux processes. The passive sondes can be directionally oriented and are deployed during optical particle velocimetry system (OPVS) imaging of the flocs, particles and colloidal material motion. Comparison of the image based particle velocities are compared to electromagnetic and acoustic velocity imaging results. The newly developed imaging system provides a pathway for integration of subsurface hyperspectral imaging for particle compositional analysis.

Key Words: sondes, subsurface sensing, acoustic imaging, optical imaging, hyperspectral systems, satellites, airborne imagery, ocean, coastal, lagoons, estuary, water quality, water monitoring, coastal ocean, environmental surveillance, optical monitoring, surface wave imaging, shallow water sensing, particle velocimetry, turbidity, video imaging, remote sensing, dredging, fluid mud, fluidized muck, noncontact sensing, video analysis, subsurface probes

1. INTRODUCTION & BACKGROUND

Background

The movement or motion of fluid mud has been previously considered by Odd & Cooper, 1986 and Waters, 1987. Instrumentation has been developed to explore theory related to movements of muds and results reported by Odd, Bentley & Waters, 1993. They reported data as not being accurate and repeatable in field studies, unless field observations are repeated several times in order to produce good quality data.

Measurements have included settling and entrainment fluxes related to fluidized mud and muck. The flux of fluid mud is most often measured in terms of dm/dt with units of mass per unit area (m), per unit time (t) as reported by Futawatari & Kusuda, 1993 and McAnally & Mehta, 2001. Generalized fluidization (liquefaction) of fluid mud has also been reported by Mehta, Lee, and Li, 1994, including the thickness of the fluidization and its estimation. Foda, Hunt & Chou, 1993 reported on fluidization of marine mud and considered the effects of wave-mean pore water pressure variations similar to Feng, 1992 whose measurements included settling and entrainment fluxes.

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Feng, 1992 also considered pore water cavities and pressure fluctuations caused by surface waves as an important process in cohesive sediment fluidization processes. In general, the influence of water waves and currents over muddy bottoms has been studied in terms of modeling and experimental measurements in field and laboratory studies. However no standard methods or protocols have been reported for direct measurements of dm/dt integrated over periods of hours to days in order to test various models developed over the last several decades. Mathematical model assumptions for tidal cycle or longer simulations of mass flux of mud & muck over "muddy" water bottoms is complicated by the rheological characteristics as they deform and begin to move. In essence, the muds and fluidization process is non-Newtonian (Barnes, Hutton and Walters, 1989). The sondes developed by Bostater during 2013 and first reported in Bostater and Yang, 2014, directly measure *in-situ* settling (deposition) and horizontal fluxes or movement (mass m^{-2} day^{-2}) of fluid mud & fluidized muck. These passive sondes and their estimated flux measurements operate by particle entrainment mechanisms (small scale advection & turbulent momentum fluxes). The sondes are independent of measurement scale effects since they are "scalable in size".

A review of existing sampling methods used to measure bottom fluid mud, fluff or muck and associated bottom lutoclines and nephelometery layers is shown in a table at the end of this paper (see Table 3). Most methods have been developed for measuring concentrations of particulate matter and colloidal aggregates, but none have been developed for directly measuring the vertical and horizontal fluxes ($m\ L^{-2}\ T^{-1}$). Indirect measurement techniques are considered "surrogate" methods and do not conserve mass flux in a control volume. As pointed out by Kineke, 2014 and Kineke & Steinberg, 1992) measurements of high concentrations of suspended matter using selected optical backscatter sensors yield noisy calibrations when compared to filtration based sample techniques. Field calibrations of electromagnetic sensors to suspended sediment concentrations are known to be poor because of the loss of suspended sediments due to flocculation (Milligan, Hill, & Law, 2007). Heath (2009) also demonstrated disaggregated grain size distributions for settling suspensions suggests flocculation (and their disaggregation) plays an important role in the formation of fluid mud. The disaggregated floc particles enhance settling of fine sediments. Rapid settling of fine grain suspended sediment has been suggested to be required to form fluid mud (Kirby & Parker, 1977). Flocculation increases particle size and thus settling rates are faster than Stokes Law estimates based upon idealized sphere sizes. Flocculation and flocs of irregular shapes is thought to be necessary to form fluid mud, fluff or muck. Thus, Curran, et al (2004) reported optical observations of flocs would be an ideal tool to help understand the formation of fluid mud, fluff and thus fluidized muck. Hence in this paper we report on the development and initial results of flocs and their movement velocities in the *moving fluid mud layer* defined by Ross &Mehta (1989). The passive sonde methodology reported in this paper in conjunction with the optical and acoustical methods describe herein are timely and needed. As clearly stated by Bianchi (2006) *in-situ* investigations of mobile and fluids in the bottom boundary layer are not possible with conventional equipment using submersible pumps and samplers, CTD, OBS (optical backscattering sensors) and ADPs (acoustic doppler profilers), since these instruments are too coarse. These systems use only "point" sampling resolutions. Such systems do not allow the reliable calculations of volume mass flux in a conserving form necessary to estimate moving fluid muds necessary for hydrodynamic and scalar substance modeling studies in estuaries. A review of advances and limitations of suspended sediment surrogate monitoring (Gray and Gartner, 2009) concluded multifrequency backscatter and acoustic sensing arrays may help revolutionize indirect or surrogate suspended sediment sensor technologies if properly calibrated (Sassi, Hoitink and Vermeulen, 2012). The work reported in this paper also includes the use of acoustic travel time sensors that are independent of particle scattering but they sample a water volume. This method enables estimates of the moving water volume in a moving fluid mud and lutocline bottom boundary layer with dense moving particle and a colloidal assemblage independent of particles being present. These sensing system can also be used in the deepest ocean clear waters around hydrothermal vents and oil rig environments. These systems (Thwaites and Williams, 1996) now include MAVS (modular acoustic velocity system) and utilize differences in acoustic signal propagation within a fluid volume. They are small enough to be used in shallow water bottom layer water, tributaries and streams and provide 3 components of velocity (u, v, w) unlike the horizontal 2D ADCP sensing systems (u, v). MAVS provide resolution of 3D turbulence down to the inertial subrange (0.05 cm sec^{-1}) in bottom boundary layers, midwater, and surface water wave fields.

In addition to reporting on a standard methodology for *direct* flux measurements of the moving fluid mud, fluff and lutocline layers using passive sondes, results and descriptions are reported below for simultaneously deployed optical imaging and acoustic measurements. These remote sensing modalities complement and help to understand the scientific basis of direct fluid mud flux (movement) measurements via the passive sondes. Last, this paper describes acoustic imaging sensors being used along with the sonde, MAVS, and optical particle velocimetry systems (OPVS). As will be demonstrated, the sondes provide a direct measurement methodology to calculate fluid mud movement, as a function of direction in a quantitative manner applicable to exploring the efficacy of dredging operations (pre-dredge, during dredging, and post dredging).

The subsurface fluid mud regime for shallow water environments is shown in Figure 1 below. This region in shallow water is characterized by the vertical structure of several layers characterized by a (time averaged) ***mean*** flux (g m^{-2} sec^{-1}) of moving mud, fluff or muck and the ***mean*** horizontal velocity of the free flowing water column (m sec^{-1}).

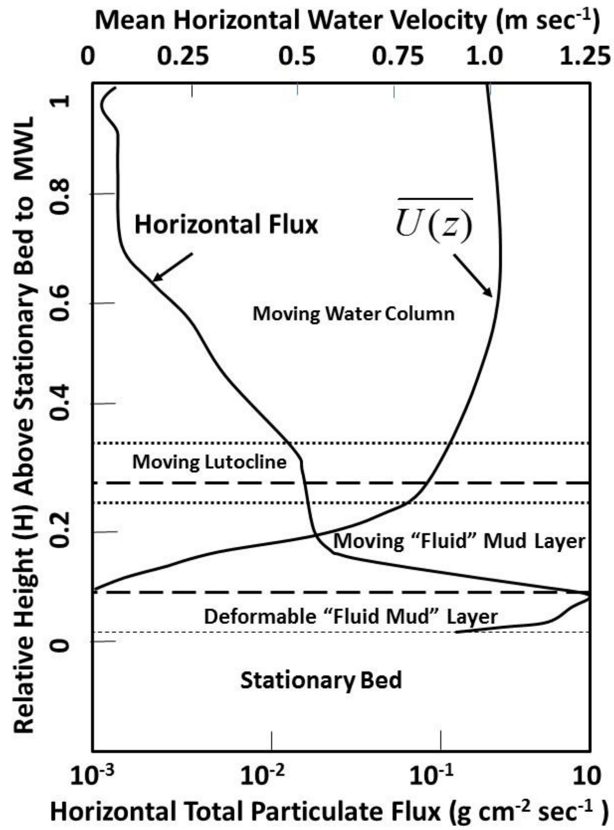


Figure 1. A conceptual diagram of the bottom water column based upon previous observations and mathematical models modified after Mehta, et al, 1994 USACE; Ross & Mehta, 1989 and Kineke & Sternberg, 1995. Note – the mean observation flux measurements clearly allow the estimation of total particulate matter in the fluidized mud and lutocline based upon measurements made at Hillsboro Bay, Florida, laboratory flume tests and associated mathematical modeling. Relative depth scale for an approximate 2-4 meter water column.

Modeling and measurements under 2-4 cm water waves clearly demonstrated the fluidization depth ranged from near zero to greater than 10 cm above the bottom. Flume studies and models demonstrated the existence of a moving lutocline. The lutocline is a high particulate matter layer above the deformable and moving fluid mud layer (Mehta, et. al, 1994).

Figure 2 shows a satellite image of the study. The site is located in Indian River Lagoon, Florida where four transects and stations for *in-situ* data and imagery (surface & subsurface) was collected. The transects across the intracoastal waterway were selected based upon a stratified random sampling of over 12 possible transects within a maintenance dredging project funded by the Florida Inland Navigation District (FIND).

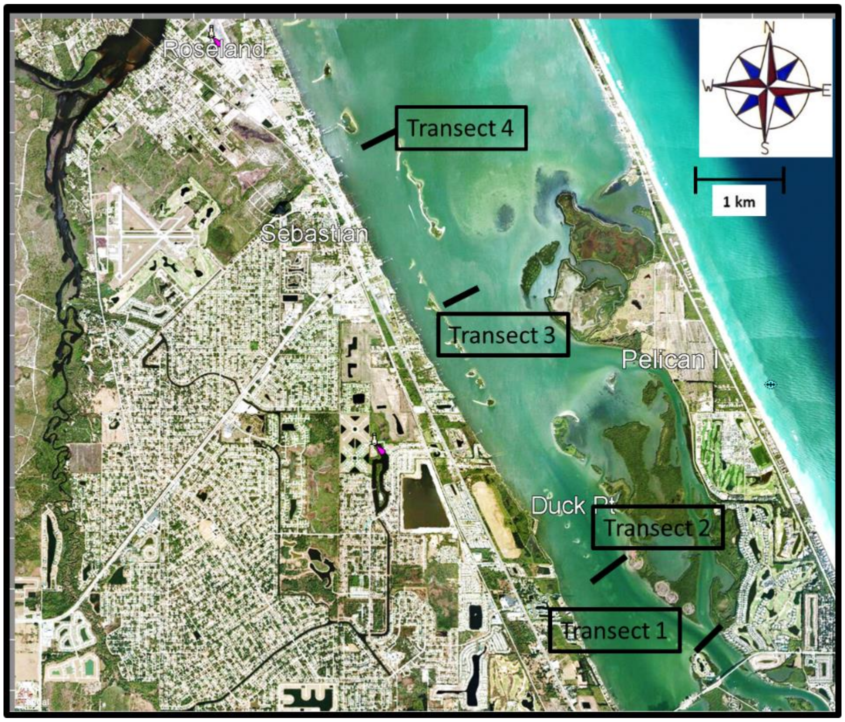


Figure 2. Multispectral satellite image (courtesy Digital Globe) showing the location of the study area and the 4 transects where in-situ, subsurface, and surface data were collected from February through August, 2015. The study are is along the Atlantic coast of Florida, south of Sebastian Inlet.

2. TECHNIQUES & METHODS

2.1 Moving fluid mud passive sondes

A sonde is defined as a device or probe that measures a physical quantity. The sondes developed and reported by Bostater and Yang, 2014 have been shown in deployments to measure total particulate matter defined as fine sand 500-62 μm, silts 62-4 μm and clays 4-0.24 μm as defined by Newcombe, 1996 and the American Geophysical Union's Subcommittee on Sediment Technology. At stations shown in Figure 1, selected sample analyses indicated particles collected were ~80-90% << number 04 sieve (500 micron, 0.0197 in., # 35 mesh) by wt. After rinsing and final settling (~ 5 to 6 hr.) the moving fluid particulate matter was > 75 % water content and approximately 10-20% organic matter by weight based upon loss on ignition analysis (100^o C drying followed by placement in a furnace at 550^o C). The sondes collect moving particles and smaller floc aggregate particles (after floc disaggregation) with settling velocities ranging from <26 to 53 mm sec^{-1} for fine sands and 3 to 0.044 mm sec^{-1} for silts and less than 0.011 mm sec^{-1} for clays (Cooke, et al., 1993). The passive sondes used in conjunction with optical and multifrequency acoustic sensing are shown below and the sondes were previously reported in Bostater and Yang, 2014. See Figure 3 below.

The *in-situ direct passive sensing* and measurement technique yields a direct measurement of the mean flux (g m^{-2} t^{-1}) where the mass of the total moving particulate matter is calculated in the laboratory. The area m^{-2} is based upon the crossectional area of the sonde wherein particles enter a fixed control volume. Particles moving into the volume of the sonde have momentum and after entrainment across the control surface, momentum is lost due to turbulent dissipation and the particles fall to the lower portion of the control volume. The horizontal sondes are inexpensive and made of PVC fittings that can be anchored to the water bottom. The vertical sondes are basically a type of trap that is based upon larger and similar designs currently used in monitoring fluxes of marine particles and marine snow or flocs. The units of measurement calculated from these vertical sondes is also a mean mass flux. The sondes essentially measure the total particulate deposition within their respective control volumes.

In ocean and environmental engineering as well as marine science, this depositional flux - $M/(L^2\,T)$ can be calculated from "point measurements " of the product of velocity U (L/T) and concentration C (M/L^3) or UC. However these point measurements are very noisy. By averaging this product over time and a crossectional area (L^2) one obtains what is called an estimate of the mass transport $T = \overline{AU_A C_A}$ (see Bostater and Ambrose, ASTM, 1981) and is a standard method used in modeling fate and transport of chemicals and materials. In this case the total mass transport represents the resulting mean horizontal or vertical deposition of particulate matter within a sonde control volume V (L^3). The above value of T can also be expressed as a time derivative or d(M(t)/dt, where mass in the sonde volume is $M(t) = V \cdot C(t)$.

In the case of a constant control volume with a mass input rate (here the mass input of particles into the sonde volume) the time rate change of mass input rate in the sonde is also given by d(VC(t))/dt=M and this change in mass input is also known as a source term M. This relation is also known as a mass balance equation. In the case of the sondes the volume of the sondes are constant and the above can be rewritten as V d(C(t))/dt =W. This also shows that the mass input rate or flux into the sondes are a function of the integral of d(C(t))/dt where dt=Δt is the deployment time and $\int dc(t)$ represents the time integrated input or accumulation of particulate matter into a sonde as function of a variable water concentration of particles deposited over the deployment period and across the fixed crossectional area or opening. In essence, the sondes passively collect the mass depositional mass of particulate matter moving through the opening during a deployment period Δt. This mass input per unit area during a time period into a sonde is decanted into plastic or glass jars, settled in the lab, rinsed with deionized water (to remove salts), weighed, and volume of settled material estimated. The material is then dried and bulk density calculated as well as porosity. Finally, loss on ignition is then calculated and final weight is determined. Thus % organic matter can be calculated after wet wt., dry wt., and ash wt. is determined. The total particulate and total particulate organic matter ($g\,L^{-2}T^{-1}$) deposited into the sondes from the settling process, resuspension process or horizontal flow process (in 4 directions, E, W, N, S) is thus obtained.

Figure 3. Passive horizontal sonde (left) 2 images and vertical sondes for estimating depositional total particulate fluxes and resuspended flux density of total particulate matter ($g\,L^{-2}\,T^{-1}$) from Bostater and Yang, 2014.

The horizontal passive sensing sondes are deployed ~15 to 20 cm off the bottom and have a ~10 cm diameter crossectional opening. They are typical placed in E-W and N-S directions or parallel and perpendicular to a waterway. The vertical depositional (settling) and resuspension (upwelling) sondes are placed in pairs near the bottom (~10). A duplicate pair are placed just below the 50 cm water depth. Thus the lower 0.5 meter of the bottom region is sampled. This deployment procedure results in 8 flux measurements to be made at a station location. The heights used were based upon the Hillsboro Bay, Florida, fluidization depths, lutocline and moving fluid heights and model predictions reported by Mehta, et al., 1994) under the influence of water surface wave amplitudes of 2-4 cm. These are assumed to be representative of conditions in the Indian River Lagoon watershed as well.

Figure 3 modified from Bostater and Yang, 2014 and reproduced above show the passive sediment flux sondes or probes used in the Sebastian Florida dredging project. The typical deployment period is on the order of 12-17 hours although longer periods (such as over the duration of a wind and/or rainstorm event) are easily accomplished. The size of the horizontal systems are easily scalable in size.

2.2 Optical particle velocimetry system (OPVS)

In conjunction with deployment of the passive fluid mud flux sondes described above, an optical subsurface imaging system is utilized. This system being tested is shown in figure 4 below. The current system consists of a high definition video camera system with low light level sensitivity. Using focal plane focusing, flocs and particles are tracked as they move across an illuminated surface. The video sequences or frames can then be individually analyzed in order to calculate individual flocs & particle velocities and directional movements within a moving fluid mud and lutocline layer.

This active sensing system can be oriented to view horizontal *or* vertical movements (speed and direction) of particles and colloidal assemblages. The frame rate can be increased or decreased according to flow conditions. Because of the extremely turbid conditions in lutoclines and the mobile fluid mud layer, an active light source is used. Instead of using backscattered light, the particle assemblages are viewed using a forward light level illumination system. This reduces the scattering effects that would otherwise involve two stream photon scattering. Thus the forward scattering portion of the total volume scattering phase function is used. This results in clearer viewing of the particles at low light levels since most scattering phase functions in water are peaked in the forward direction.

The illumination source is provided by a unique high density circular arrangement of light emitting diodes (LEDs). The LED photons pass into a coated glass plate in a manner that creates a circular light guide. In this case the light guide is approximately 20 cm in diameter. The arrangement allows the imaging of known calibration targets for focal plane focusing and spatial calibration of the image pixel sizes that can change upon user defined focal plane focusing. Multiple camera arrangements are being tested for volume imaging.

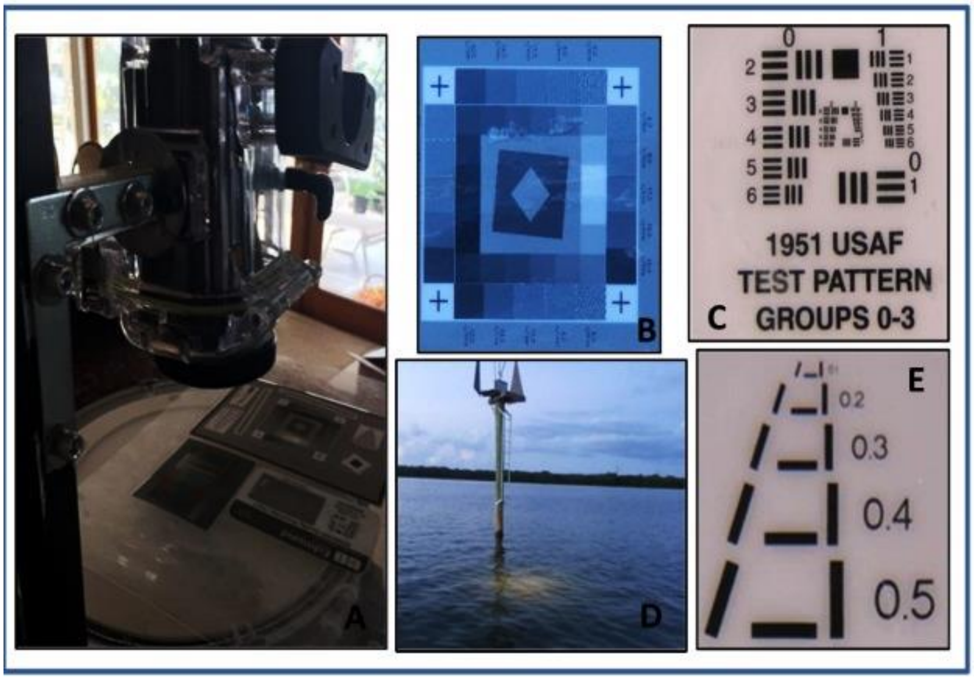
Using the unique imaging and associated image processing approach, only particles and assemblages on the circular light guide are “in focus” and used to determine particle sizes, speeds and directions that are reported as probability density functions. Particles are excluded from the analysis if they move out of focus or cross paths. This would indicate a change in the vertical movement away from or off the light guide and thus would result in an incorrect horizontal movement or speed estimate. Using a frame rate of 30 HZ or higher with close proximity sensing and high spatial resolution imaging of the circular wave guide, particles are tracked. Very small particles, total particulate particles and flocs are resolvable, not unlike systems reported by Manning and Dyer, 2000 and Manning, et al, 2011.

The system shown in Figure 4 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 spectral signatures produced will be able to detect particulate compositional signatures. The 3 band high definition video camera combined with a hyperspectral imaging system allows the use of optimized spectral image data fusion methods used in target detection applications (Bostater, Frystacky & Levaux, 2012).

2.3 Acoustic Sensing Systems

A 5 channel acoustic imaging sensing system was used to obtain crossectional depth information at transects shown in Figure 2. Frequencies selected for possible use were 50, 83, 200, 455 and 800 KHZ. The system allows for imaging as the vessel mounted system moves across the channel using a downscan, side scan or fathometer sensing fan beams. In addition, the downscan fan beam was tested and found to perform quite well for *fixed location sensing* in order to capture real time events such as passage of wave induced backscattering and particulate resuspension or upwelling events.

Modular acoustic velocity current (MAVS3) meter sensors for measuring three dimensional currents within the bottom boundary layer were deployed at the end of the study at transect 2. Special mounts were used to hold the current meters within approximately 5 cm of the mud bottom. The mounts utilized and the acoustic sensor head of a typical MAV3 is shown in Figure 5 below.



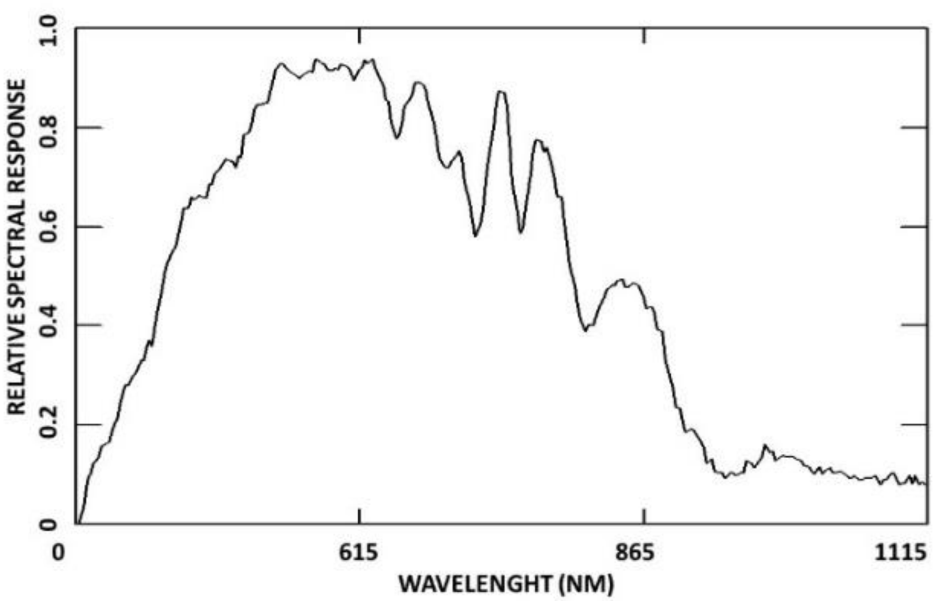


Figure 4. Particle velocimetry camera system (A) for horizontal and vertical deployments in the bottom boundary layer. The subsurface light (D) was visible during a deployment during post dredging monitoring near Wabsso, Florida. Images B, C, E show calibrations for *in-situ* particle velocimetry imaging using standard camera calibration targets. The spectral response curve (r) of the circular forward illumination light emitting diode light guide.

Figure 5. Mounts used for mounting the three axis (U, V, W) modular acoustic velocity current meters in the turbid bottom boundary layer (lutocline).

2.4 Airborne Imagery

Airborne imagery was collected during the dredging activities. A suite of several cameras as indicated in Figure 6 was available to be used to identify any plumes or effects from dredging operations and subsurface features in the study are. A full resolution high resolution camera (GZ-HM550) was selected and flown at 50 to 1000 meter altitudes since it has been shown to provide excellent imagery of shorelines and shallow waters as demonstrated in previous studies (Bostater, 2012). Three flights were conducted and sky conditions during the January 30, 2015 flight remained clear and selected results are shown below. Image acquisitions were made from a twin engine C414 aircraft. Imagery was acquired over the dredge material management area (DMMA) where dredged material was being pumped and held for dewatering. No overboard discharge from the cutter head dredge was made during the project.

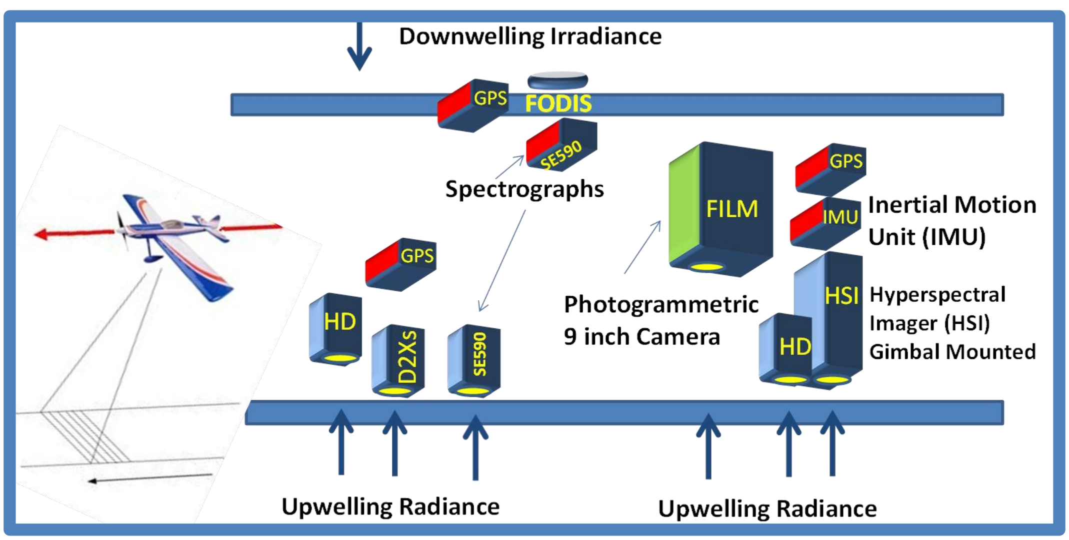


Figure 6. Schematic of the airborne imaging systems flown on the twin engine aircraft used in this study. Imagery selected for processing and reported below include full resolution high definition video cameras.

3. RESULTS

3.1 Passive sonde systems

Selected results for the intracoastal waterway from Wabsso Bridge (transect 1) to north of Sebastian Florida (transect 4) are shown in Table 1. Total dry weight fluxes from sondes were calculated and shown in terms of *directly measured fluxes* in metric tons (mT) per meter squared per day using the 4 horizontal and 4 vertical flux sondes. Sondes were deployed on the west and east side of the channel and at a mid-channel locations. The standard methodology is to place the horizontal sondes in an east, west and north, south direction aligned with the waterway. Figure 7 shows the total fluxes from the sondes at each transect before, during and after dredging in terms of total dry weight fluid mud movement.

Channel Location T1	Pre-Dredging	During	Post Dredging
West	0.11	0.35	0.09
Mid	-	0.25	0.39
East	0.05	0.30	0.47
Relative Flux	1	+5.6	+5.9

Channel Location T3	Pre-Dredging	During	Post Dredging
West	0.02	1.78	0.39
Mid	0.03	0.33	0.78
East	0.03	0.48	0.33
Relative Flux	1	+14.7	18.75

Channel Location T2	Pre-Dredging	During	Post Dredging
West	-	0.07	0.22
Mid	0.01	0.08	0.36
East	0.02	0.09	0.27
Relative Flux	1	+8	+28

Channel Location T4	Pre-Dredging	During	Post Dredging
West	0.02	0.34	0.18
Mid	0.15	0.37	0.25
East	0.15	0.11	0.23
Relative Flux	1	+4.5	+3.4

- **missing data**

Table 1. Channel positions and transect dry weight fluxes in mT day^{-1} for pre-dredge, during and post dredging conditions. Transect fluxes during and post dredging fluxes are shown (relative flux) relative to pre-dredge fluxes. Transect 4 results indicate moving mud reduction (MMR) occurred after dredging operations completed.

The relative fluxes at the channel and transect location is indicated by calculating the relative flux compared to the pre-dredging condition measurements as shown above. Transect four fluxes after dredging were less than fluxes during dredging operations, therefore at transect 4 muck movement reduction (MMR) occurred.

Calculation of the fluxes moving into the channel from the east and west directional sondes, and the settling fluxes provide an estimate of the degree to which moving fluid mud and muck enters into the channel and may be settling within the mud channel area. Calculations are shown below in Table 2. In general fluxes moving into the channel increased after dredging and settling fluxes increased within the channel after dredging. This suggests the waterway is acting as a sink for the fluid mud and muck.

The variability between the transect crossectional average horizontal fluid mud fluxes within a bottom layer 0.5 meter water column are shown in Figure 7. The results were analyzed by applying a nonparametric Kolmogorov test and indicates that the pre, during and post sonde fluxes are significantly different from each other ($p<0.001$) at each transect.

Transect 1

Channel Location	Pre-Dredging	During	Post Dredging
West (towards channel)	0.06	1.32	2.50
Mid (settling)	-	0.35	1.91
East (towards channel)	1.24	2.59	11.96

Transect 2

Channel Location	Pre-Dredging	During	Post Dredging
West (towards channel)	0.04	0.48	0.18
Mid (settling)	1.32	0.35	1.91
East (towards channel)	2.50	3.54	0.99

Transect 3

Channel Location	Pre-Dredging	During	Post Dredging
West (towards channel)	-	0.43	0.72
Mid (settling)	0.02	0.20	2.17
East (towards channel)	0.03	1.05	0.92

Transect 4

Channel Location	Pre-Dredging	During	Post Dredging
West (towards channel)	0.02*	1.31	0.38
Mid (settling)	0.21	0.91	0.17
East (towards channel)	0.02	0.48	0.45

*Sonde dry weight mass flux: lb. m^{-2} day^{-1} - missing data

Table 2. Directional fluxes from the passive direct flux sondes show the directional (east and west fluxes) and mid channel settling or depositional fluid mud fluxes. After dredging, the mid-channel vertical sonde fluxes showed increased settling (deposition) at 3 out of 4 transects. Fluid mud movement towards the channel after dredging was greater at all channels compared to pre-dredging direct measurements and indicates the waterway is serving as a sink for the broader area fluid mud and muck.

3.2 Airborne Imagery

Airborne multispectral (MS) images of the dredged material management area (DMMA) is shown in Figures 8 and 9. The submerged water features along the shoreline indicated attached algae common to the area. The lower upper fan area in Figure 8 shows the input of the dredge material being pumped into the DMMA settling basin that is used to hold the dredged material for dewatering. Figure 9 is a MS image of a dredge along the waterway that was used to help identify any plumes from the operations. No sediment plumes were identified close to or in the vicinity of the dredging operations.

3.3 Acoustic Imagery

In order to help identify movements of fluid mud using acoustic imagery, deployment of the transducer was made at a fixed location while the subsurface bottom was continuously scanned. This method of acoustic imaging allows one to observe a fixed location or fixed position as a function of time. Using this technique internal water column features moving pass an acoustic fan beam can be observed. These include internal waves that influence the vertical displacement of density layers and associated accumulation of particles at interfaces between different density layers with a water column. Figure 10 was acquired at the west side of Transect 2 during August, 2015. Imagery suggests short period boundary layer wave motions (bursts) in the backscatter signal. During this observation period there was strong channel south to north flows.

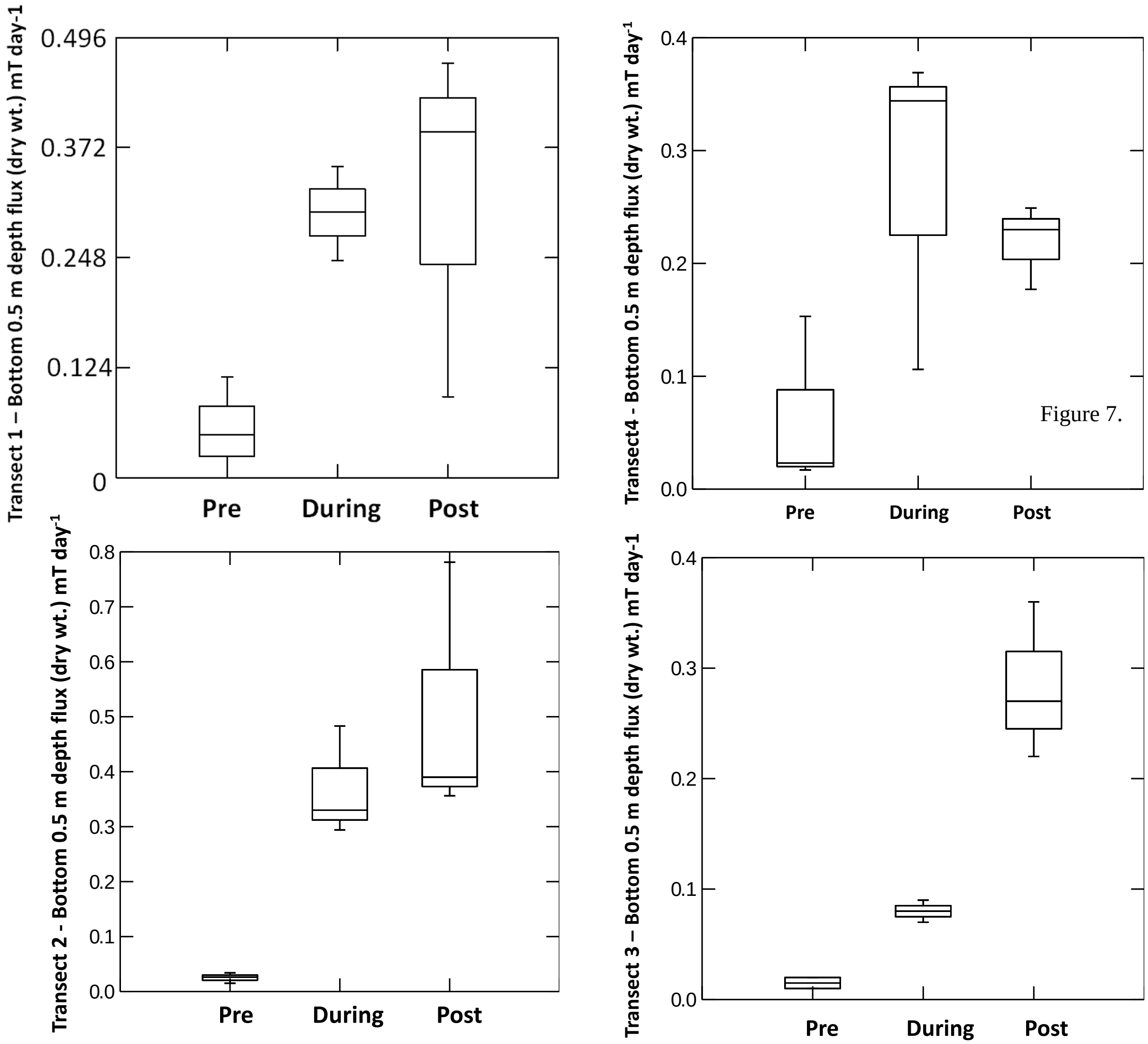


Figure 7. Fluxes in metric tons per day (mT day-1) at each transect applied to a 0.5 meter bottom crossectional area indicates the fluid mud mass flux or movement between the pre dredge, during and post dredge conditions was significantly different. At transect 4 the post dredging horizontal fluxes showed a reduction in moving fluid mud compared to observations occurring during dredging.

Figure 8. A multispectral 3 band airborne image collected by C. Bostater January 30, 2015 at approximately 1500 m altitude showing the shoreline and bottom features outside of the diked dredge material management area (DMMA). The bright fan shaped area in the upper right of the image shows the pumped dredge material entering the site.

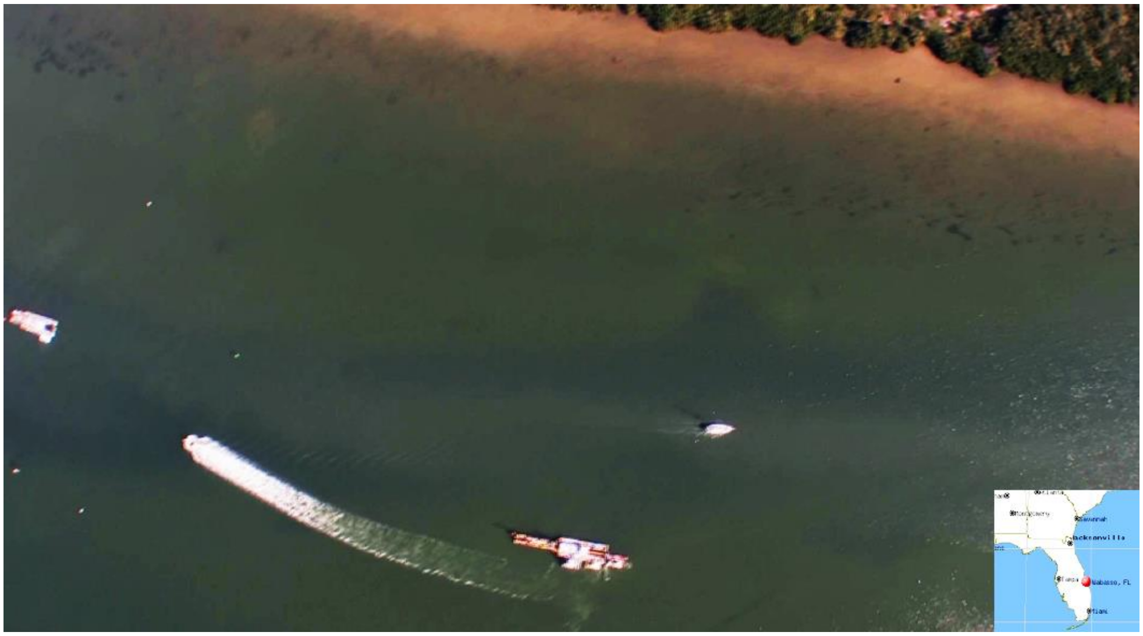


Figure 9. Airborne 3 Channel Multispectral (RGB) Image Display. Collected Friday Jan. 30, 2015 by C. Bostater. Snapshot MS image acquired between 10-11:45 AM at 760 m altitude. Florida Inland Navigation Waterway (FIND) Dredge Area, Intracoastal Waterway west of Preachers Island, Florida, Indian River Lagoon (~N 27.770541, W, -80.430797) enhanced to show submerged water features and turbidity plumes.

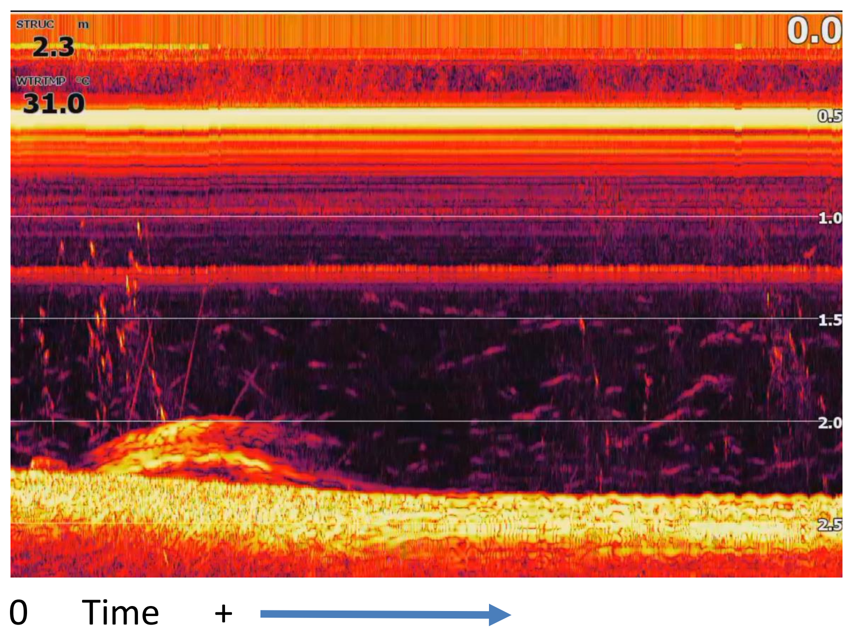


Figure 10. Acoustic mage using a downscan narrow fan beam at 455 KHZ at a *fixed location*. Using a fixed location platform approach and recording over time, wave and current induced resuspension events in the turbid bottom lutocline layer was observed at transect 2 during August, 2015. The technique demonstrates natural increases in bottom acoustic scattering at a specified station within the turbid moving lutocline layer described in Figure 1.The right hand side shows bottom layer wave features occurring at the water fluid mud interface. The above bottom feature (left) within the lower 0.5 meter bottom layer dissipated within 10-15 seconds as shown and was followed by wave like oscillations (right).

Two MAV3 3D acoustic current meters were deployed during this deployment period and 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 occurring in the bottom boundary layer interfaces as mentioned above.

The difference in measured water depths between the 83 and 200 KHZ acoustic channels were always approximately 10 cm. The 455 KHZ in structure scan mode produced similar depth profiles as shown below. Figure 11 shows the acoustic depth across the waterway channel at Transect 4 after dredging occurred. The image was taken as the vessel traversed from the west to the east sides of the channel.

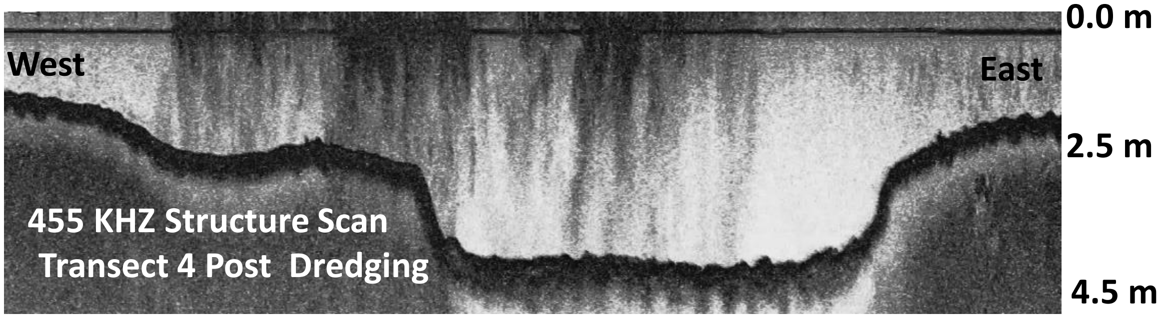


Figure 11. Transect 4 post dredging image of the waterway using a 455 KHZ acoustic channel structure scan beam taken aboard a small moving vessel during June, 2015.

3.4 In-situ Optical Imagery

The *in-situ* optical particle velocimetry imaging system (OPVS) 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 the passive horizontal passive sondes. Two MAVS3 acoustic velocity current meters were deploy at the same location. Results from the test deployment with focal focusing on the top of the system light LED circular source and comparison to the MAVS3 and MB201D system suggest water and particle velocities are in reasonable agreement. 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.

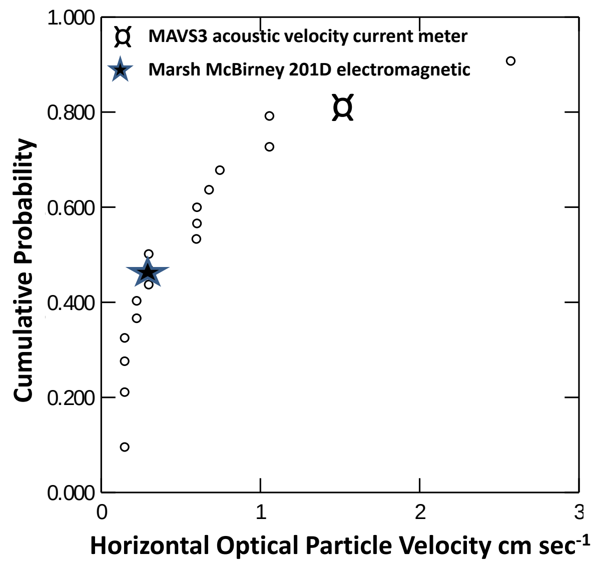


Figure 12. Comparisons between the optical particle velocimetry system (OPVS), a MAVS3 (modular acoustic velocity) current meter and a digital Marsh McBirney 201D electromagnetic current meter. The OPVS data can provide horizontal or vertical particle and floc velocities in terms of cumulative density functions as shown above.

4.0 SUMMARY & CONCLUSIONS

The research reported above documents the only known *direct in-situ observations of horizontal moving fluid mud in term of mass flux (g m^2 sec^{-1})*. The newly developed passively sensing sondes were developed to directly measure particle and flocs within the mobile fluid mud and lutocline layer in aquatic systems. The need for new instrumentation and techniques to directly measure the mass flux of fluid muds and muck has been reviewed in previous publications are cited in this paper. This passive sediment sampling methodology provides a way forward for developing the passive sonde methods as a standard protocol from which results from surrogate methods and instrument results can be compared.

Application to a specific dredging study in the Indian River Lagoon, near Sebastian Inlet has provided the first testing of the new techniques reported in this paper. Future work needs to continue in the development of the OPVS software and the incorporation of a hyperspectral imaging system. Ongoing research should allow for the development the passive sondes as protocol or standard method for fluid mud movement and for furthering the concept of muck movement reduction (MMR) in dredging operations. Data analysis of the direct flux measurements as shown provides one methodology to address the efficacy of dredging for environmental restoration.

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Table 3. Methodologies & Comparison of Reported Fluidized Sediment Flux Related Sampling

Operational Principle	Direct Methodology	Optical/Acoustical/Other	Benefits/Limitations
intrusive (*in-situ*) probes point measurement pumped samples or multi-parameter probes	energy scattering	optical backscatterance	high frequency sampling no mass flux estimated continuous calibration required noisy calibrations (Kineke, 2014)
Laboratory & field *in-situ* point sampling	filtration (e.g ~0.45µm)	-	quantitative (gL^{-3}) fluxes not measured
intrusive (*in-situ*) or laboratory point sampling	particle energy side scattering	optical nephelometery	light intensity units, flux estimation not possible, continuous calibrations required, inexpensive, widely used, noisy calibrations
bedload samplers: US BL-84, BLH-84 Helley-Smith Models 8015, 8025, 8035, 8055, 8075; ARNHEM, USFS, SPHINX,VUV,BOGARDI, US TR2 (Elwha, Toutle)	bag style samplers 125-1000 µm mesh based upon ASTM specs	-	sinks in mud bottoms (10-210lbs) fluff, mud, muck, pass through mesh bags, mass flux can be estimated
Composite Type Samplers and point probes, flow meters	Direct water point sampling with stage, flow or time composited suction samples; in-situ energy scattering,	optical nephelometery optional in probes	submersible, small, portable, expensive, point flux indirectly estimated with additional flow/stage meters & sensors
in-stream sediment collector 406-00, 406-008 with hopper & pump	direct bottom surficial trap sampler with pump & suction	-	Heavy, 4-6 ft, flow modified by device, larger particles trapped, fluff & mud trapping is flow dependent, flux directly measured, not suitable for open water applications
load-cell scour sensor 407-015	-	pressure load sensor	Scouring issues, not stand alone, limited open water applications, settling & horiz. Fluxes measured, horiz. flow rates affect results, for stones, cobbles, large grains, needs remote data logger & cable, lightweight

Table 3. (cont.) Methodologies & Comparison of Reported Fluidized Sediment Flux Related Sampling

cylindrical sediment traps	cylindrical settling tubes (moored, drifting, tethered) open & mesh covered top,	-	vertical flux directly measured, inexpensive, scalable in size, used around the world
acoustic backscatter (*in-situ*) & imaging; Single or multibeam/frequencies	active/passive acoustic energy scattering; doppler	multi-beam; multi-frequency; piezoelectric sensors; point or fan beam measurements	Widely used for depth of sediment layer, muck, fluff & mud layer thickness. Imaging produces transport related information but not direct particle flux, noisy calibrations
Disaggregated Inorganic Grain Size (DIGS)	optical	optical	Only measures particle size characteristics