Optical vs. Acoustic Measurements of Suspended Sediments

Marco D. Masciola[1] (mmascio1@fau.edu), Timothy P. Stanton[2]
Oregon State University 2005 REU

1. Abstract

In an effort to better understand the near shore process, acoustic devices are often used to measure sediment concentration in the water column. The ability to make this measurement is important to the scientific community since it will provide data for future studies. Under typical circumstances, acoustic transducers are used to perform underwater measurements that cannot be recorded visually. In this study, the optical intensity of the suspension will be correlated with the data obtained through a BCDV (Bistatic Coherent Doppler Velocimeter and Sediment Profiler) (Stanton, 1996). It will be shown that optically measuring sediment concentration in the water column has a strong relationship to the BCDV data.

2. Introduction

There are several effective experimental methods that are actively used for determining sediment suspension concentration levels in the water column (Lorhmann, 2001, Stanton, 1996). Each technique has a common emphasis, in that they all use acoustic devices to perform this type of measurement. To perform studies that contribute to the understanding of coastal processes, a systematic approach has to be made for obtaining the data. This is the underlining reason to justify improving data acquisition methods. An interesting aspect in researching this activity is how the near shore seabed constantly evolves and contributes to the sediment transport phenomena. By forming a model that can accurately predict coastal processes, foreseeable obstacle can be bypassed.

Before this study can be performed, a trustworthy experimental platform must be conceived so that there is enough confidence in the data for future analysis. As previously noted, acoustic devices are by far the most widely used instruments for this type of investigation. As waves are generated and begin to break, the turbulence at the seabed boundary layer causes sediments to stir up and saturate the water column. Through the aide of an acoustic transducer, sound is radiated into the suspension. The returning signal can then establish a plot of sediment concentration versus height from the seabed.

However, as with most data recording instruments, they have their weakness. Acoustic measurements in the coastal region present itself as a difficult barrier to cross since the water in this area is typically shallow. Some problems associated in this region are due to reverberation and premature reflection of acoustic energy (Urick, 1983). As acoustic signals propagate, they are repeatedly bounced back between the seabed and water surface. During the data-recording phase, a transducer may register a signal that was received as an indication of sediment concentration strength, but when in fact it may be noise due to premature reflection or reverberation. The response of the transducer may appear as another problem with measuring sediment concentration. There are two important factors that have to be determined before a transducer is constructed, which are the acoustic frequency of the radiated sound and the radius of the transducer plate. These factors are based on the density and the speed of sound of the medium that the sound is traveling in. Kinsler and Frey's (2000) theorem on reversible transducers states that a reversible transducer is "one that can be used either as a source or a receiver of acoustic energy". Taking this one step further, the acoustic energy echoing off sediments suspended in the water column can be treated as a transducer since it is radiating acoustic energy back to the source. It was stated above that one of the formative factors of

---

[1] Florida Atlantic University, Department of Ocean Engineering
[2] Naval Postgraduate School, Department of Oceanography, Graduate School of Engineering and Applied Sciences

determining the response is the radius of the source transducer. Since the frequency of acoustic radiation is fixed, the only other element that can change is the radius of the sediment in the water column, since particle grain size is random. In theory, it can be suggested that acoustic transducers are tuned to be more sensitive to particle of a given size (Lorhmann, 2001). Figure 1 displays the acoustic sensitivity of a transducer with varying k*a values, given by Sheng and Hay (1987).

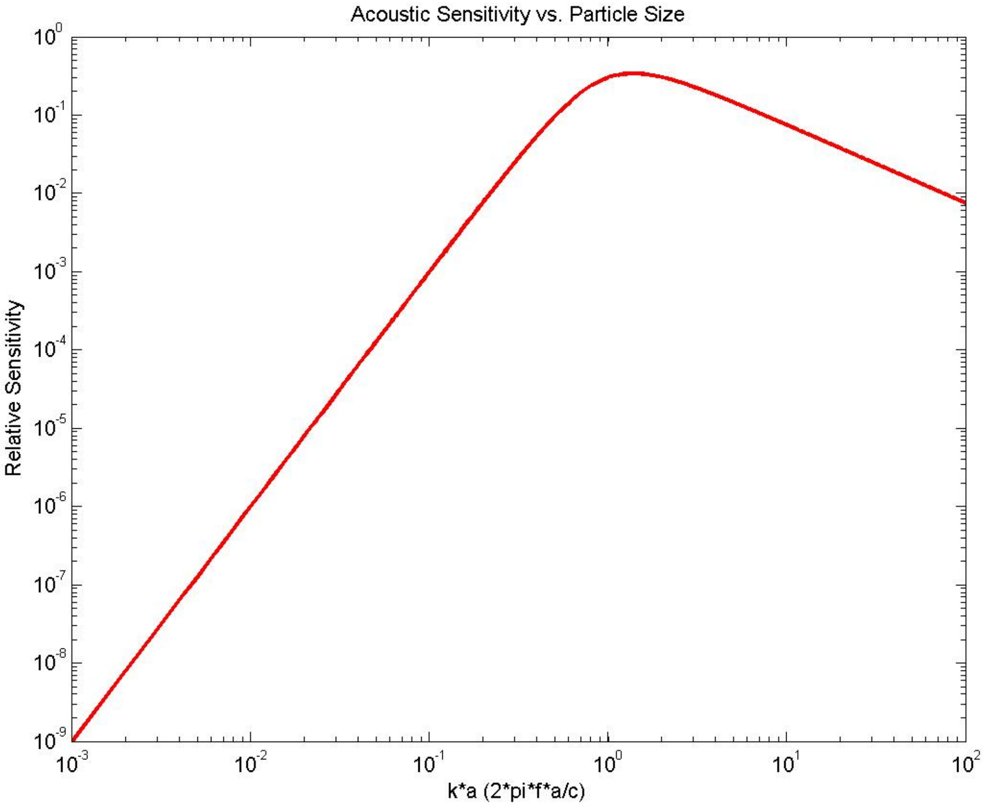


Figure 1 The sensitivity of an acoustic transducer as ‘a’, particle size, varies.

The ‘k’ term is known as the wave number, and is simply the angular frequency of the radiated sound over the speed of sound through the medium. The ‘a’ term, the particle radius, is the value that is changing with respect to sensitivity. As it is shown, the acoustic sensitivity is dependent on the size of the target.

The purpose of this report is to present an alternative method to measure sediment concentration by assessing the optical intensity just above the seabed. With the limitations of measuring suspended sediments through acoustics exposed, an attempt will be made to succeed where acoustic measurements fail and to optically record sediment activity in the water column. Given that there is a known time series of sediment concentration versus height provided by an acoustic acquisition system, an attempt will be made to visually record the activity of the seabed at the location near the transducers. The image of the seabed will be digitally enhanced and analyzed. During the analysis phase, the optical intensity of the seabed will be compared to the BCDV (Bistatic Coherent Doppler Velocimeter and Sediment Profiler) backscatter (Stanton, 1996).

3. Experiment Methodology

The experiment was carried out at the O. H. Hinsdale Wave Research Laboratory, Department of Civil Engineering, at Oregon State University. Utilizing this state of the art facility was a vital control aspect in this experiment to achieve the desired wave characteristics. At a length of 104 meters, the wave tank was filled with beach sand from Newport, OR, so that a 1:3 scale model beach profile could be attained. To carry out the experiment, a platform containing the essential scientific equipment was situated above the wave tank and on its walls. It was imperative to situate all the equipment on a moveable dolly that was also rigid enough to withstand unpredicted movement.

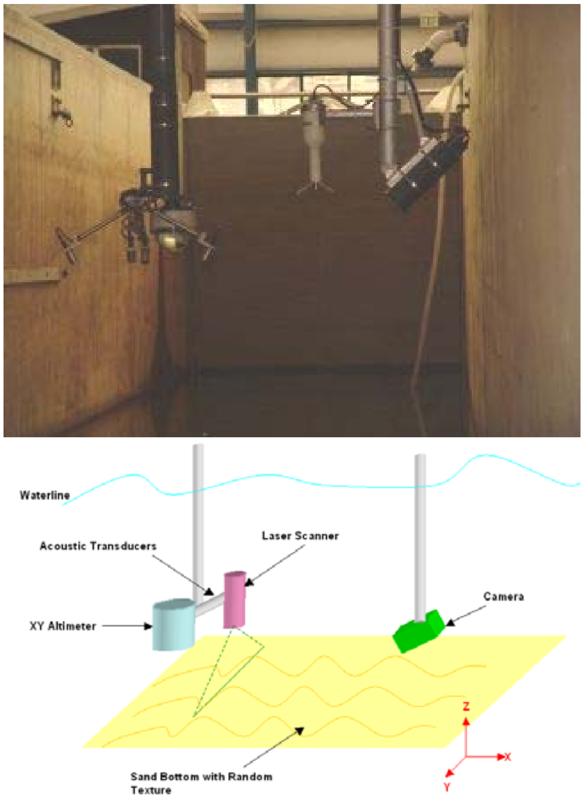


Figure 2 Top: Actual BCVDSP, High Intensity Laser, and CCD Camera above the water line.
Bottom: Schematic of scientific instruments.

Figure 2 depicts the equipment orientation in the large wave flume. The CCD Camera is set at an angle of 45 degrees to the horizontal and has a sample rate of 60 Hz. Given that the camera is not perpendicular to the seabed and observes the high intensity laser obliquely, small valleys and gorges will register. Through some mathematical interpretation, the morphology can also be plotted from each instant of time. As the wave turbulence interacts with the seabed, particles are picked up and highlighted by the rapidly scanning high intensity laser. The intensity level of the highlighted particles is used to determine the sediment concentration level in the water column.

In order to achieve a detailed sediment profile of the suspension, the BCDV will radiate acoustic energy into the water at a frequency of 12.5 MHz with a sample rate of 20 Hz (Stanton, 1996). At this frequency, the beam pattern produced by the transducer will have a diameter of 2 cm at the seabed (Stanton, 1996). The location where the main lobe of the beam pattern meets the seabed is not known, however, it is located along the high intensity laser line. In the course of performing the analysis of the video feed, the BCDV data will be correlated with the optical intensity of the suspended sediments to determine the vertical location of the transducer along the high intensity laser line.

3.1 Video Analysis – 3-Dimensional Mapping

The video feed that is used to perform the optical analysis is shown in figure 3. This image is optically enhanced though a digital image processing routine to add contrast between the background and the high intensity laser. It is apparent from the tilt of the camera that there is a random texture on the seabed, as is expected. Since the spatial setup of the equipment is known, the bathymetry can be plotted 3-dimensionally in MatLAB over the course of several video frames. In turn, it will produce a history of how the bathymetry changes with time. Before this image can be made, it will be necessary to determine where the high intensity laser line is located on the image. The image processing routine determines the location of the highest optical intensity on the raw image. In figure 3, a blue line paints the location of highest optical intensity in the raw image. To determine the area with the greatest optical intensity, the location of the brightest pixel is averaged over 60 frames (1 second) for the corresponding vertical location. For the duration of the image processing, the area of interest will only occur above this reference point.

The morphological history of the seabed can be produced from the raw image provided by the CCD camera. For each frame, the seabed is mapped out digitally with the inserted blue line, dictating the bathymetric profile. If multiple histories are assembled together, then a 3-dimensional profile can be achieved. The morphological data is calculated using the distance of the CCD camera to the laser generator, and is not dependent on the height of the instruments from the seabed; the height of the instruments to the seabed will change over time due to the redistribution of sediments. To perform this analysis, it was essential to note the viewing angle of the camera. For the particular camera used in this experiment, the vertical viewing angle is 30 degrees. Given that the camera angle and number of pixels in the camera is known, the change in angle between pixels can be found, given as

$$\theta_y = \frac{Camera\ Angle}{Pixels}$$

Where θ_y is the change in angle between vertical pixels, *Camera Angle* is the camera viewing angle in the vertical direction, and *Pixels* is the number of pixels in the vertical direction. For the scenario presented, the number of pixels in the vertical direction is 480 and the camera-viewing angle is .524 radians, yielding a θ_y value of .00109 rad/pixel. It is assumed that the laser line is running perpendicular to the camera face. Taking this assumption into account, the vertical distance from the camera face to the point of highest optical intensity on the raw image can be determined. Specifically, this mathematical relationship takes the form as

$$Z = d \times \tan(\theta_y)$$

Where *d* is the horizontal distance of the CCD camera to the high intensity laser generator. A result of this analysis is presented in figure 4.

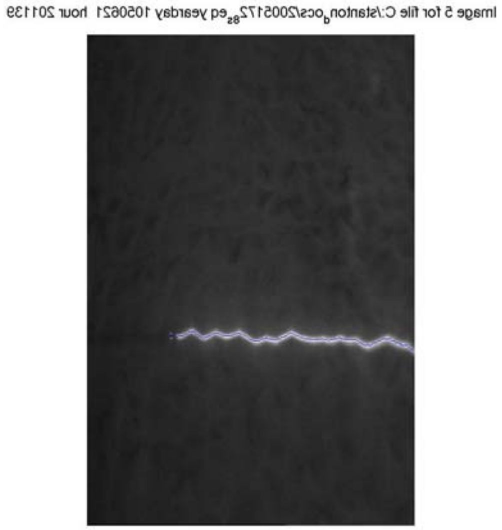


Figure 4 3-Dimensional model representing the bottom morphology. This image displays how the seabed changes over time due to sediment dispersion.

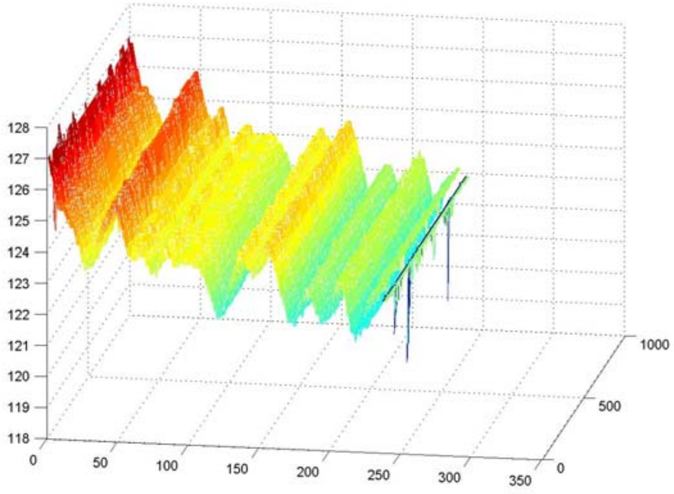


Figure 3 Raw image of the seabed showing the texture outlined by the high intensity laser. The blue line inserted on the image represents the area of highest optical intensity.

3.2 Video Analysis – Suspended Sediment Concentration

During a period of dynamic wave activity, the CCD camera can record the disruption of the sediment on the seabed. This testimony is given in figure 5. During this period of sediment scattering, the high intensity laser will highlight suspension activity. Theoretically, this activity should correlate with the action registered by the BCDVSP. To plot a time series of the optical intensity of the suspension, the image will be vertically averaged. Using the blue line dictating the bottom of the bed, a vertical average will be performed for the first 25 pixels above this reference. In our observation, 25 pixels represent a height of 6 cm above the seabed. Performing this analysis with a vertical pixel average of more than 25 would skew the results. It is apparent from figure 5 that there is a peak activity of the suspension before the background becomes noticeable. If our analysis went beyond this peak, then background noise will enter into our data.

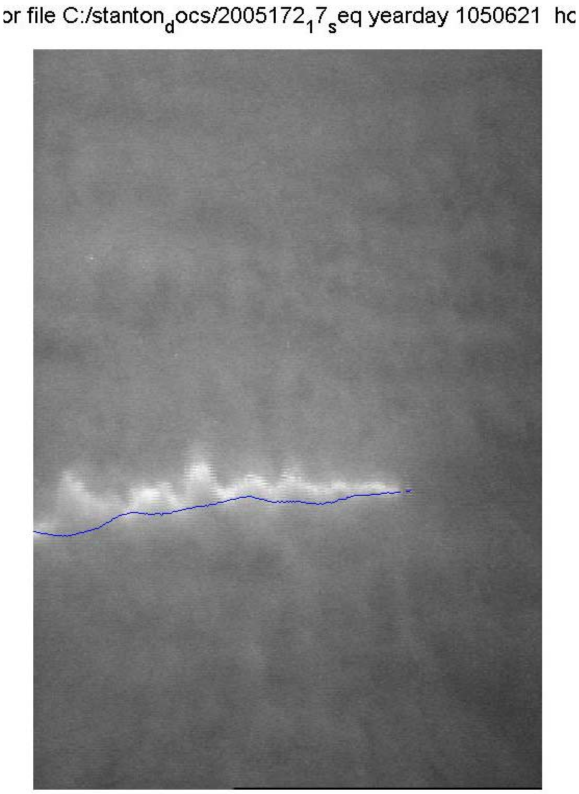


Figure 5 Raw image from CCD camera that shows the sediment suspension during extreme wave activity. The blue line delineated on the image represents the seabed profile.

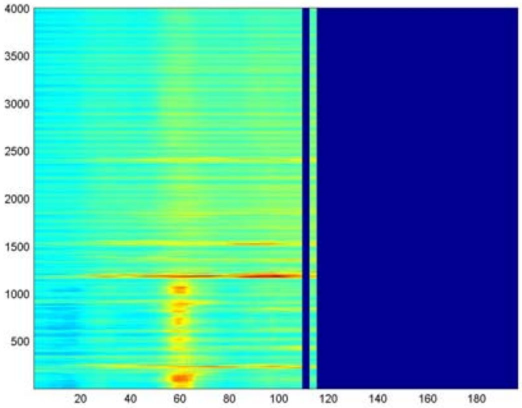


Figure 6 Pseudo color plot of the history of the optical intensity of the suspended sediments. Warmer colors represent high concentrations of sediment in the water column.

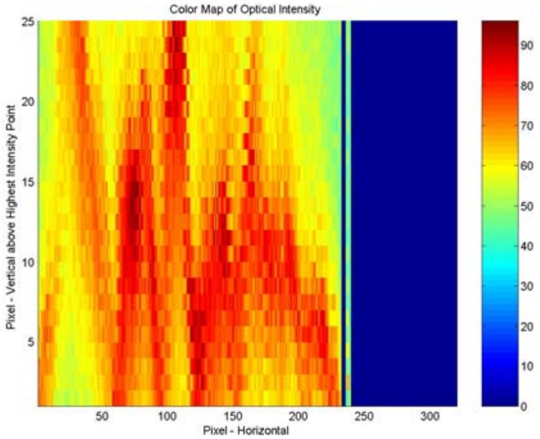


Figure 7 Pseudo color plot of the optical backscatter of the suspended sediments for the first 25 pixels above the bottom reference. This image was taken at the same instance of Figure 5.

A single average for optical intensity was not computed; instead, averages were performed along each vertical pixel. If an average the whole image was performed to obtain one value for sediment concentration, then we would stating that at each point along the laser line, sediments rise uniformly and without regard to wave activity. Also, when we correlate the BCDVSP data with the optical intensity, we want to determine the position of the acoustic transducer along the high intensity laser line. This could not be done if we had one value per frame for the optical intensity. However, with 320 data points per frame, it increases our chances of narrowing down the exact location where the acoustic transducer is gathering the data.

3.3 BCDVSP Data Interpretation

Raw data from the BCDV is provided in Figure 8. From the data obtained from this device, the sediment concentration in the water column can be determined. It is clear that we are interested in the first 6 cm of BCDV data above the seabed, as defined by the process performed in the optical intensity analysis. To determine the location of the seabed, the mean of all the data points are calculated, represented by the blue line on Figure 8. Since the depth of the seabed will not fluctuate greatly, MatLAB concentrates its search for the bottom between the 80 cm and 90 cm mark. Any point that is greater than the mean will be recognized as the seabed. The first data point that exceeds the mean value will be stored as the beginning of the seabed, thus an average of the previous 6 points will be averaged together to form the sediment concentration profile from an acoustic perspective. To produce the BCDV profile displayed in Figure 8, data is averaged over a history of 11 time instances (the previous five profiles and the next 5 profiles). For example, at a sample rate of 20 Hz, the suspension concentration profile is averaged over a .55 second time span.

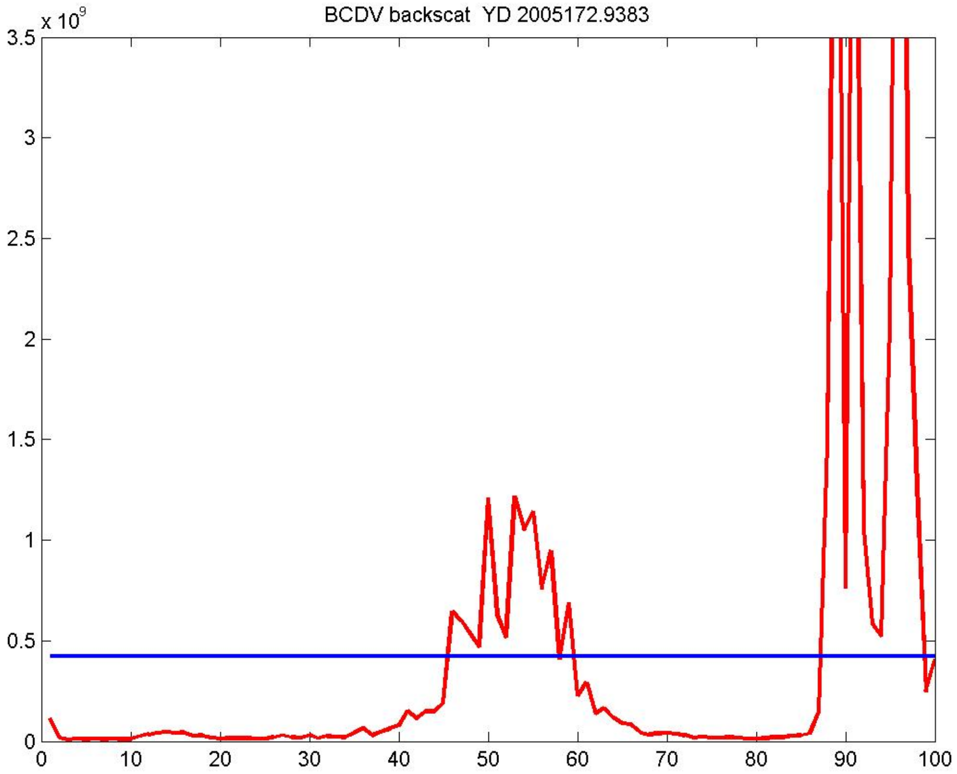


Figure 8 BCDV Sediment Profile.

4. Compilation of Acoustic Backscatter Time History

At this time, it is appropriate to exhibit Figures 9 and 10. Presented are two separate scenarios illustrating the sediment suspension activity as a function of time recorded by the BCDV. To produce this image, data acquired from the BCDV (Figure 8) is averaged for 6 cm above the seabed over a half-second period. By time-averaging the data provided by the BCDV, some of the spikes created by noise were eliminated. Scenario 1 was produced during a 66 second interval of strong wave activity as compared to scenario 2. The steady state acoustic intensity for each interval are about the same with a value of 1x10^7. However, the peak values differ due to the sediment concentration in the water. The sediment concentration is directly related to the wave activity dictated by the wave generator. It is noticeable from both figures that the sediment concentration does not decrease to its steady state quickly as it rises. Since extremely small particles remaining in the water column take more time to settle than the larger grains, a lag between peak activities to steady state will be present.

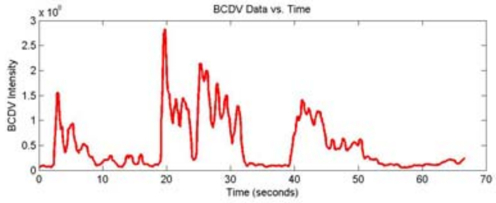


Figure 9 BCDV Intensity recorded against time, scenario 1.

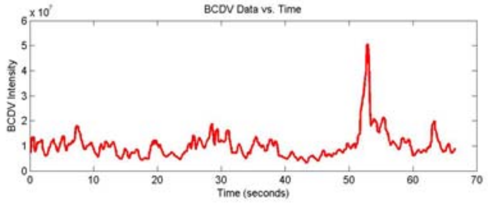


Figure 10 BCDV Intensity recorded against time, scenario 2.

5. Correlation of Acoustic Backscatter and Optical Intensity

As previously stated, it was affirmed that we would use the correlation coefficient to determine the recording location of the acoustic transducer. To perform this analysis, the history of the optical intensity (Figure 6) was correlated to the acoustic backscatter. Also called Pearson's coefficient, the correlation coefficient determines how much dependency there is between one random variable to another. Cooper and McGillem (1986) and Coulon (1986) present the correlation coefficient as

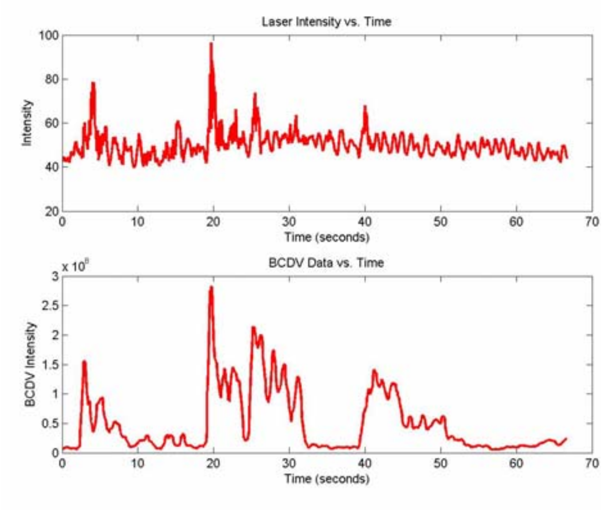
$$r = \frac{E(XY) - \overline{X}\,\overline{Y}}{\sigma_x \sigma_y} = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

The value 'r' is real and can only have the values between -1 and 1. A correlation coefficient of 0 indicates that the two random phenomena's have no dependency to one anther. Under normal situations, this is generally the case. With a correlation coefficient of 1 or -1, the two separate random events are directly related to one another. Ideally, an 'r' value of 1 is desired. This will impart that both the optical intensity measurements and BCDV data have a dependency on the one another. In advance of any calculations, intuition would predict that the suspension of sediment seen by the camera (Figure 5) would have a direct relationship to the particles recorded by the BCDV.

By employing this method, the horizontal pixel location on the optical intensity pseudo color chart (Figure 6) that correlates to the BCDV data (Figure 9) the most will try to be determined. The pixel that provides the largest 'r' value will determine the location of the transducer along the high intensity laser line. Once the location is selected, a time series of optical intensity versus time will be constructed. Consequently, a comparison between the acoustic backscatter and optical intensity can be made to determine the sediment concentration levels in the water column.

Three separate data sets were analyzed to determine the location of the BCDV along the laser line. One wave data set contained high amplitude waves that created tremendous disruption at the seabed (Figure 9). The second data set produced a minor disturbance, while the last data series analyzed created sediment scattering that is an average between the pervious two. It was deliberate to choose data sets with different intensity levels to see how well the data correlates with various environmental changes. Once all the data sets were examined, the location of the BCDV was determined to be around the 165 - 169 pixel location. For scenario 1, the correlation coefficient was determined to be r = .5465, while the coefficient for scenario 2 was revealed to have a value of r = .2247. For the final analysis, the correlation coefficient was calculated to be .4705. The initial results from these measurements reveal that measuring suspended sediments in the water column optically is more effective with a higher concentration of particles remaining in the water. For reflection to occur, particles have to remain in the water column in order for light to be scatted.

Since the location where the BCDV is collecting its data along the high intensity laser line has been determined, the time series of the optical intensity can then be computed. To produce this image, the vertical pixel location that produced the highest correlation coefficient is plotted against time. The result of this analysis is presented in Figures 11 and 12. As the evidence suggests, the optical intensity and acoustic backscatter have a strong correlation during periods of turbulent activity at the seabed. Another problem is that the signal received from the camera is pretty random during periods of calm surf dictated by the BCDV data (Figures 9 & 10). If certain frequencies were eliminated though the use of a filter, the belief is that the signal would be more clearly defined by reducing the noise.



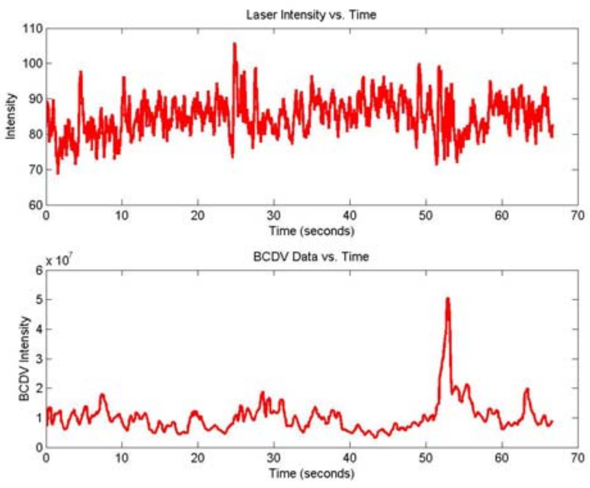
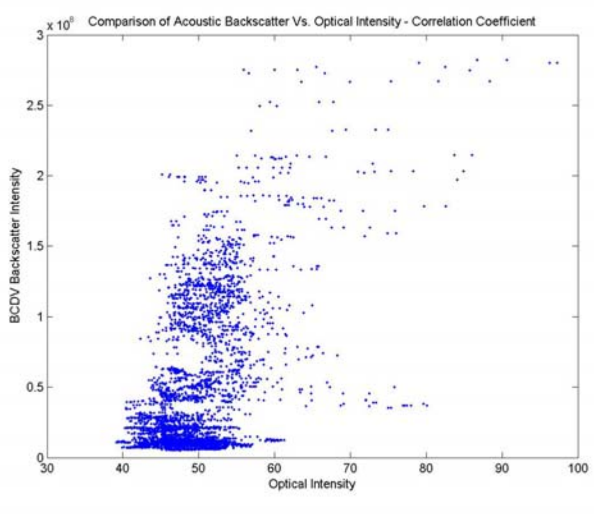


Figure 11 Comparison of optical intensity to the acoustic backscatter, Scenario 1. The peak activity recorded by the BCDVSP is predicted by the optical intensity with some degree of accuracy. From this data set, a correlation coefficient of .5465 was calculated at. The BCDVSP data most closely correlated with the optical intensity at a camera pixel value of 165 from the left.

Figure 12 Comparison of optical intensity to the acoustic backscatter, Scenario 2. The peak activity recorded by the BCDVSP is predicted by the optical intensity with a minimal degree of accuracy. MatLAB calculated a correlation coefficient of .2247 at a pixel location of 168.



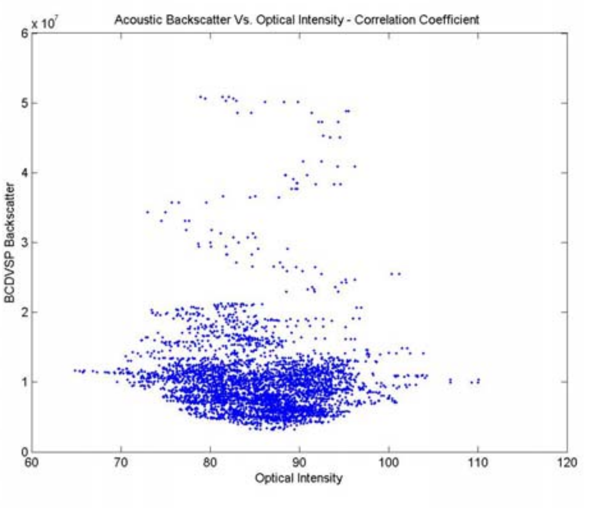


Figure 13 Corresponding to Figure 11, displays the interdependence between optical intensity and acoustic backscatter. This random event had a correlation coefficient of r = .5465.

Figure 14 Analogous to Figure 11, displays the lack of dependence between optical intensity and acoustic backscatter. This event produced a correlation coefficient of r = .2247

6. Data Filtering

By filtering the data shown in Figure 11, an attempt will be made to reduce most of the fluctuation produced by background noise. We chose to filter the data set produced in Figure 11 since it has a high correlation coefficient and multiple peaks where sediment concentration in the water column is elevated. Without filtering, analysis in the time domain can be difficult, especially when dealing with underwater acoustics. If the measurements were to be conducted in the open water, acoustic transducers will be exposed to a wide variety of background noise produced in the ocean. The unwanted background noise may have several sources, including shipping traffic, ocean turbulence, biological factors, and wind interacting with the ocean surface (Kinsler, 2001). Each sound source contributing to the noise in the signal is radiated at a specific frequency. For example, if an acoustic signal is radiated in the water at a frequency of 20 kHz, the transducer will receive the echo at the same frequency. However, the background clutter will also make it to the receiver, which is active on a wide range of frequencies. In effect, when plotted in the time domain, the 20 kHz signal will be hidden in the returning signal lieu of the noise. When properly used, filtering can eliminate the unwanted frequencies and reproduce the pure 20 kHz signal as a function of time.

The fluctuation of optical and acoustic intensity is driven by the amount of sediment in the water. This is directly related to the wave activity produced by the generator. From the set up of the experiment, it is known that the wave generator produce waves at a period of 4 – 8 seconds (.125 - .25 Hz). Hypothetically, the sediment suspension activity should be dependent on the action that the wave generator is undergoing. For example, when the wave generator is stationary, there is no sediment activity at the seabed. During periods of strong surf, the recorded history of the sediment suspension documents a higher intensity. Dependency between wave height and sediment suspension is evident. For this reason, a third-order band-pass filter will be utilized, with cut-off frequencies between .125 and .25 Hz.

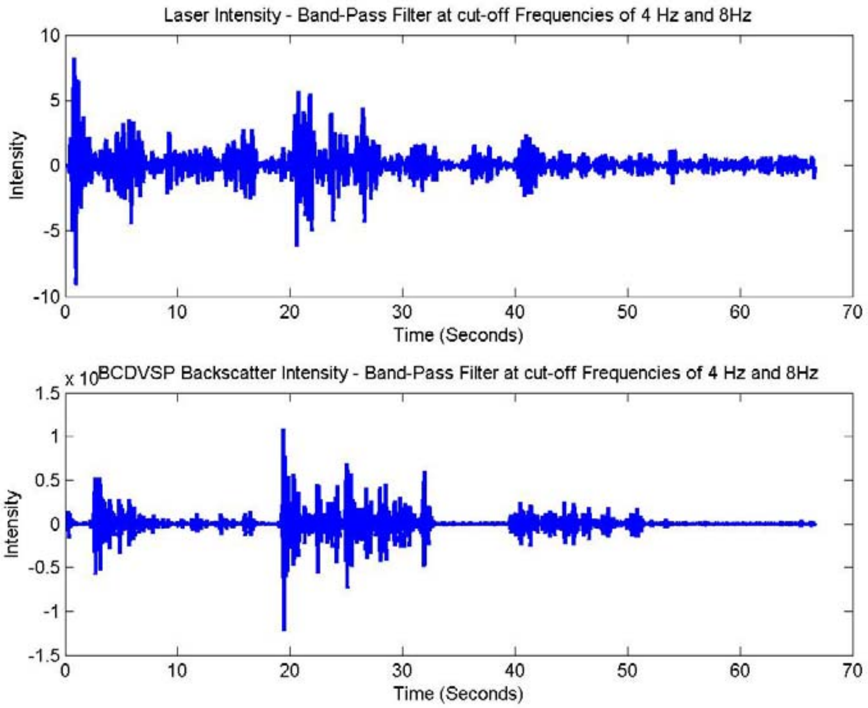


Figure 15 Filtered optical intensity and acoustic backscatter

7. Results

Results from selected wave runs are tabulated below (Table 1). Analysis of the data proves that measuring the sediment concentration optically does correspond to the data that the BCDV is recording. In our observation, the peak activity is where most of the data correlates. During periods when the wave activity is not dynamic enough to excite the seabed, random noise in the optical intensity graph is introduced, caused by ambient light reflected into the wave tank. On this premise, it was decided to filter the output of both the optical intensity and acoustic backscatter.

The ambient light being reflected into the wave tank would be dependent on the waves, which are generated with a period between 4 – 8 seconds. For this reason, we filtered within this frequency range to construct the reduced-noise chart. The observation of this graph depict that the peaks have a greater dependency on one another, while eliminating most of the background noise.

Table 1

Wave Run File Name	Correlation Coefficient	Vertical Pixel with greatest BCDV Correlation
2005172_17_seqbcdv	0.5465	165
2005172_14_seqbcdv	0.4705	169
2005172_8_seqbcdv	0.2247	168

In addition, the location where the BCDV is recording the sediment concentration levels along the high intensity laser line has been determined. Despite that each wave run produced seabed disturbances of varying degree, the overall consensus is that the BCDV is located approximately at the 167 vertical pixel location.

8. Conclusion

Analytical evidence suggests that there is some correlation between optical intensity and acoustic backscatter. This will suggest that measuring the sediment concentration optically is a rudimentary alternative to the expensive means of a BCDV acquisition system. However, this technique has to be developed further before it can generate the level of confidence that an acoustic acquisition system garners. The method employed here for measuring the optical intensity of sediment concentration is only useful for validating BCDV data.

9. Acknowledgements

Support for the REU program at the O.H. Hinsdale Wave Research Laboratory was provided by the National Science Foundation (EEC-0244205). The O.H. Hinsdale Wave Research Laboratory receives additional support through the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) program of the National Science Foundation (CMS-0086571).

Special thanks goes out to William Shaw of the Naval Postgraduate School, Monterey Bay, California, and to Alicia Lyman-Holt. Also, the authors would like to thank the faculty and staff at the O. H. Hinsdale Wave Lab.

10. References

Cooper, G. R., McGillem, C. D., Probabilistic Methods of Signal and System Analysis. New York:Holt, Rinehart and Winston, 1986

Coulon, F., Signal Theory and Processing. Deham, MA:Artech House, Inc. 1986

Kinsler, L. E., Frey, A. R., Coppens, A. B., Sanders, J. V., Fundamentals of Acoustics. New York:John Wiley & Sons, Inc. 2000

Lorhmann, A., “Monitoring Sediment Concentration With Acoustic Backscattering Instruments” Nortel Technical Notes 2001:Document No. N4000-712

Hay, A. E. and Sheng, J., 1986. “Frequency Dependence of the Interaction of Ultrasound with Suspended Sediment Particles”, Progress in Underwater Acoustics, ed. H.M. Merklinger, 1987.

Stanton, T. P., 1996. "Probing Ocean Wave Boundary layers with a Hybrid Bistatic / Monostatic Coherent Acoustic Doppler Profiler". Proceedings of the Microstructure Sensors in the Ocean Workshop, Mt Hood, October 1996.

Urick, R. J., Principles of Underwater Sound. New York:McGraw-Hill Book Company, 1983