Estimation of suspended sediment concentration from Acoustic Doppler Current Profiler (ADCP) instrument: A case study of Lembeh Strait, North Sulawesi

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Abstract. Measurement of suspended sediment concentration (SSC) is one of the parameters needed to determine the characteristics of sediment transport. However, the measurement of SSC nowadays still uses conventional technique and it has limitations; especially in temporal resolution. With advanced technology, the measurement can use hydroacoustic technology such as Acoustic Doppler Current Profiler (ADCP). ADCP measures the intensity of backscatter as echo intensity unit from sediment particles. The frequency of ADCP used in this study was 400 kHz. The samples were measured and collected from Lembeh Strait, North Sulawesi. The highest concentration of suspended sediment was 98.89 mg L\(^{-1}\) and the lowest was 45.20 mg L\(^{-1}\). Time series data showed the tidal condition affected the SSC. From the research, we also made correction from sound signal losses effect such as spherical spreading and sound absorption to get more accurate results by eliminating these parameters in echo intensity data. Simple linear regression analysis at echo intensity measured from ADCP to direct measurement of SSC was performed to obtain the estimation of the SSC. The comparison result of estimation of SSC from ADCP measurements and SSC from laboratory analyses was insignificantly different based on t-test statistical analysis with 95% confidence interval percentage.

1. Introduction
One of the important parameters to understand the sediment transport is suspended sediments concentration (SSC). The measurement of SSC in the water column can be conducted in several ways, such as conventional, optical, and acoustic methods. Conventional method use gravimetric assessment in laboratory addressing some measurement issues and is relatively difficult to obtain because it need to be analyzed at laboratory [1] and require collection of numerous water samples in each point of research area; and lack of continuous data because it required continuous water sampling, where the necessary data within a particular period of observation. The other disadvantages of measurements by conventional method were slow and high cost [2].

One of the instruments that can estimate the concentration of suspended solids is Acoustic Doppler Current Profiler (ADCP). Through the acoustic technologies used, ADCP can measure various objects in the water column; one of them is the estimation of SSC [3]. The most important factor and advantage
of using this instrument is to obtain as nearly as practicable the true concentration of SSC with long period of time [4]. The measurements result using this instrument have spatial and temporal resolution, the important factor what conventional measurements cannot provide [5][6].

Currently, the acoustic technology is growing and continues to be used in research in marine field. On the other hand, not many researchers use ADCP as a scientific echosounder for the detection and quantification of underwater targets. For more than two decades, ADCP have been used for estimate suspended sediments concentration [7], and is becoming common used for sediment transport studies in estuaries, bay system [8], lake [9], and mud-dominated environment [10]. The application of most of these studies used at high frequency ADCP (>100 kHz) to provide qualitative estimates of suspended sediment concentration [11]. Recent studies also found good correlation between acoustic backscatter from ADCP and measured concentration by direct measurement and showed a good correlation between these methods [12]. Many research also used numerical analysis to compare the measured SSC from ADCP and model [13]. But using this instrument in a strait with strong tidal effect is need to be observed, and this paper will discuss that ADCP can provide some advantages over conventional measurements for estimating time series analysis of SSC in that main observation.

The method of calculating conversion into SSC backscatter can be done based on the principle of sonar equation [14]. The direct measurement of SSC was then being correlated with echo intensity from ADCP using simple regression linear equations. After that, time series data of backscatter value from the ADCP can be converted into SSC in mg L\(^{-1}\). This paper describes the results of a field experiment in which time series of SSC were estimated at multiple layer of depth from the ADCP. The aims of this study were as follows: (1) to estimate SSC and the temporal SSC data of Lembeh Strait, (2) to provide baseline information for sediment transport study, and (3) to assess acoustic technology using ADCP to monitor SSC and compare to in-situ SSC measurement.

2. Materials and methods

2.1. Research location

This research was conducted in April 2016 at Lembeh Strait, located at North East Coast of Sulawesi near the city of Bitung, North Sulawesi. ADCP instrument was deployed at 30 meters (visualized at figure 1) with geographical position 1°28'00.6" N - 125°14'07.7"E (figure 2). Lembeh Strait is a narrow strip of water between Sulawesi Island and Lembeh Island, stretching from Sulawesi Sea to Maluku Sea with depth ranging from 15 to 30 meters.

The oceanographic condition in Lembeh Strait is strongly influenced by the tidal currents [15], where the water moves from Sulawesi Sea to Maluku Sea and vice versa. Lembeh Strait has a reputation for its clear water visibility for diving activity, and it indicates that this site has low concentration of suspended sediments. The strait has a great biodiversity of colorful marine life, and also has transparency of 10-25 m, which is generally suitable for growth of benthic organism especially in coral reefs [15].

The main consideration of site selection is a large port called Port of Bitung there. This port is considered strategic for export-import activities, because it directly faces the Pacific Ocean region. The construction of the port activity such as dredging and disposal to the water column will affect the suspended sediment concentration.

![Figure 1. The location of moored ADCP in the bottom of the Lembeh Strait.](image)
2.2. Materials and equipment

Equipment used in this study was ADCP Nortek WAV 6579 400 kHz with upward-looking setting, bin size 1.5 m, and started to measure from 2.5 m above bed. The time series data was acquired from 4 April 2016 to 22 April 2016 with 20 minutes interval of data recording. Other equipment used was Horiba U-50 for temperature, salinity, and pH data loggers. Water samples were collected from 50 sampling depth. All water samples were preserved in pre-cleaned polyethylene bottles before filtered using Whatman filter paper (pore diameter: 47 mm). SSC direct sample determination referred to APHA gravimetric method [16]. Processing and data modelling were conducted using MATLAB 2016a (Mathwork, Inc.).

2.3. Data analysis

2.3.1. Counts to decibel (dB) conversion.

Echo intensity (EI) detected from this ADCP were converted to SSC through some processing. Conversion of EI to dB is stated on equation (1).

\[ I_{dB} = K_c I_{counts} + TL - 10 \log_{10} \left( \frac{L_{Xmit}}{\cos \theta} \right) \]  

(1)

where \( K_c \) is the echo intensity scale, \( I_{counts} \) is echo intensity (EI) RSSI detected from ADCP, \( TL \) is two-way transmission losses, \( \theta \) is the beam angle, and \( L_{Xmit} \) is the transmit length [7]. In the form of detection range, \( K_c \) is given as follows in equation (2):

\[ K_c = \frac{127.3}{(Te+273)} \]  

(2)

\( Te \) is the temperature measured by ADCP (°C). Based on the equation (1), echo intensity in dB is a function of distance, sound absorption, beam spreading, transmitted power, and the backscatter coefficient.

2.3.2. Transmission losses and absorption.

Some correction is required for sound propagation, for example geometrical spreading and attenuation beyond the near zone distance. Transmission losses were calculated by using the formula on eq. (3):

\[ TL = 20 \log_{10} R + 2 \alpha R \]  

(3)

Where \( \alpha \) is sound absorption coefficient (dB m \(^{-1} \)) and \( R \) is distance between ADCP transducer to measured layer or bin (m). ADCP measured EI from each layer of depth bin with 1.5 meter measurement. The distance from ADCP to bin can be measured by equation (4):

\[ R = r + \frac{D}{4} \]  

(4)
Where \( r \) is distance from transducer to center of bin or a half of bin size, \( D \) is distance from each bin in meter. Absorption coefficient value was depending on environmental condition such as temperature, salinity, depth, pH, and material absorbing the sound wave. The materials were boric acid (\( f_1 \)) and magnesium sulphate (\( f_2 \)). Beside those factors, absorption coefficient also depends on frequency used in ADCP. Absorption coefficient can be measured using the formula in equation (5) [17]:

\[
\alpha = 0.106 \frac{f_1 f_2^2}{f_1^2 + f_2^2} e^{(pH-8)/0.56} + 0.52 \left( 1 + \frac{T}{43} \right) \frac{s f_2^2}{f_1^2 + f_2^2} e^{-D/6} + 0.00049 f_2^2 e^{-\left(\frac{T}{27} + \frac{D}{17}\right)}
\]  

(5)

Where \( f \) is the frequency of ADCP (400 kHz), \( T \) is the average water column temperature (ºC), \( D \) is the maximum detected depth (m), pH is the average pH of water column, and \( S \) is the average salinity (psu). The \( f_1 \) and \( f_2 \) parameters are given as follows in equation (6) and (7):

\[
f_1 = 0.78 \left( \frac{S}{35} \right)^{1/2} e^{T/26}
\]  

(6)

\[
f_2 = 42 e^{T/17}
\]  

(7)

2.3.3. Estimation of suspended sediments concentration.

Calibration with known values of concentration by direct measurement of SSC is therefore required for ADCP-based estimation of SSC. Water sampling was conducted at some depth in the station along with its high and low water tidal condition. Water samples were taken at 10 different depths, started from 2 meters until 20 meter for each 2 meter, using van Dorn bottle. The amount of water sample was 1 liter and then stored in polyethylene bottles and place the bottles in the cooler box with ice cube (<4 °C) before analyzed in the laboratory. This process repeated for 5 times in a different water tidal condition (from high water tide, ebb tide, and then low water tide). The 200 mL of water (C) was then filtered using filter paper. Before the filtration process, the filter paper was dried at a temperature of 103-105 °C for 1 hour, and then the filter paper was cooled in a desiccator and weighed (B). After water filtration process, filter paper plus residue was dried again at least one hour at 103-105°C, cooled in desiccator and weighed (A). Direct SSC measurement (mg L\(^{-1}\)) can be calculated by equation (8):

\[
SSC_{direct} = \frac{(A-B) \times 1000}{C}
\]  

(8)

Collecting data using ADCP at regular intervals can produce changes in \( L_{dB} \) value as movement of suspended particles. \( L_{dB} \) value changes can be attributed to changes in the concentration of suspended particles (SSC). These relations are based on sonar equation by the equation (9):

\[
SSC_{ADCP} = 10^{(\text{Intercept} + \text{slope} \times L_{dB})}
\]  

(9)

Where intercept and slope can be calculated by empirical formula from the simple linear regression. Water sampling should be located at a depth equal to the depth of bin observed by ADCP [18]. The comparison between SSC measured by ADCP and SSC from laboratory analyses were then tested using an analysis of independent-samples t-test with 95% confidence interval percentage.

3. Results and discussion

3.1. Conversion of echo intensity in counts to dB

Above frequency of 100 kHz, absorption coefficient must be matched to local environmental condition [19]. By using equation (5) and substituting the environmental condition on research location with \( T = 27.5°C, S = 33.23 \) ppt, pH = 8.13, the sound absorption was 0.1618 dB m\(^{-1}\) and two-way transmission losses can be determined in each layer of depth. To produce an accurate measurement of echo intensity, determination of relative backscatter at each bin was conducted by removing RSSI reference level, correcting for transmission loss. Finally, for the determination of the echo intensity in dB, the following practical approaches were used, and signal coefficient factor as given on equation (2) was 0.42, and from the equation (1) can be calculated that the measured 1 count intensity equal to 0.4 dB.
The acoustic signals in upper and lower layer were significantly different, while in bottom layer the echo intensity in dB was higher (figure 3). The acoustic backscatter value ranged from 53-89 dB in surface area, 68-107 dB in water column, and 72-134 dB in near bottom area. Until this stage, the transmission loss factors were no longer the issue at each depth. The sound attenuation due to prevailing sediments in suspension appeared to be calculated. Since acoustic signal was high, it indicated that $S$ would be high as well. But it still needs to be corrected and calibrated to actual SSC, in this case to direct measurement. Because the limitation using ADCP based on theoretical for the acoustical signal is Rayleigh parameters. The acoustic backscatter is very sensitive to the size of sediment particles. Most suspended sediments are small compared to the wavelength of the sound.

3.2. Calibration and validation

The echo intensity in dB and direct measurement SSC were used in the calibration and validation process (figure 4). From this analysis, the regression line correlated direct sample and echo intensity data from ADCP. Simple regression analysis was used to find the regression slope ($A$) and intercept ($B$). The range of direct measurement SSC was between 49 – 64 mg L$^{-1}$ and EI in dB was between 64-90 dB.

The calibration show that a linear relation between echo intensity and SSC from direct measurement is generally valid, but the slope of the best-fit linear lines may be different. The constant of this proportionality needs to be assessed empirically for each site selection. This regression analysis employed 50 data pairs with result $A$ and $B$ were respectively 0.0392 and 1.4021. The determination coefficient ($r^2$) was found to be 0.8943.
3.3. **Suspended sediment concentration**

The time series from this ADCP exhibit a general agreement between the acoustic backscattering signals (dB) with the corresponding SSC direct measurement (figure 5). The concentration of SSC in near bottom area was higher than in the surface and water column. This indicates sediment resuspension in this site, where sediment settled to the bottom. The fluctuation of SSC between depths of 25-30 meters may occur due to tidal effect. The formation and destruction of flocculated sediment may result in an increase and decrease of the acoustic backscatter from ADCP, and it also will affect SSS in this case.

![Figure 5. Time series of suspended sediment concentration in mg L\(^{-1}\). From this data, it can be showed that at the upper layer of the water column has lower concentration compared to bottom layer.](image1)

The maximum SSC were evident during high water tides, the low water tides showed less concentration of suspended sediments (figure 6). The change of SSC in low and high water tides time also indicated there were effects of advection and tidal resuspension especially in near bottom area; although there was no evidence of any relation between the time series of the SSC and monthly tidal amplitudes. From this result, it proves that the tidal condition affected the SSC [7], especially tidal currents that provide the main energy source for particle resuspension and transport.

![Figure 6. Estimated suspended sediment concentrations during the high and low water tide.](image2)
3.4. Comparison results between ADCP and direct measurement

In evaluating SSC measurement from ADCP results, it is important to understand that the results from ADCP have correlation with SSC from direct sampling. Since accuracy and precision are the advantages of using ADCP for SSC estimation, they still have calibration error. Results of the acoustic method compared to direct measurement show generally good qualitative agreement showed at figure 7 by $R^2 = 0.7391$. There are possible factors for this, for example different particle size distribution at different depth and differences in sample interval for the ADCP and direct measurement [20].

Figure 7. Validation of estimated SSC from ADCP compared to SSC from direct sampling. This analysis showed that a good correlation of direct sampling measurement and acoustic based with $R^2 = 0.7391$ although the measurement of ADCP was slightly lower than conventional analysis.

Comparing the 1:1 line with linear regression line, the ADCP-based SSC estimates were slightly lower than measured SSC. Despite the possible influence of flocculated sediment, large differences between the slopes in figure 5 may be at least attributed to grain size variation. This calculation has provided insight into potential of ADCP backscatter for the measurement of SSC [10].

Statistical analysis (t-test) was used to compare the results from ADCP and direct measurement. Based on comparison results (figure 7), with a 95% confidence interval statistical analysis, it was shown that the results from ADCP compared with direct measurement of SSC has similarities and insignificantly different. Averaged standard deviation from comparison of all measured data from ADCP and direct sampling was no more than 5 mg L$^{-1}$. This suggests that measurement of SSC from ADCP was as good as conventional method, and can be used as monitoring SSC in a long period time.

4. Conclusion

Suspended sediment concentration could be estimated using the acoustic backscatter intensity. The acoustic results confirmed a comparable estimation performance with respect to those given by direct measurement of SSC, although the result was slightly lower compared with direct measurement. Error of comparison between ADCP and direct measurement was not more than 5 mg L$^{-1}$. The monitoring of SSC with ADCP could be considered as a good method to observe time series data of SSC, where it relatively not possible with conventional measurement. Although ADCP show potential for estimating SSC quickly, several issues remain to be explored: Rayleigh parameter for different grain size of suspended sediment, a better understanding of instrument error, and still required a water sample analysis to calibrate the sonar equation.

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References

[1] Zhang T, Stansbury J, Branigan J 2013 Development of a field test method for Total Suspended Solids analysis Final Reports & Technical Briefs from Mid-America Transportation Center 52

[2] Holdaway G P, et al. 1999 Comparison between ADCP and transmissometer measurements of suspended sediment concentration Continental Shelf Research 19 421-441

[3] Park H B, Lee G, 2016 Evaluation of ADCP backscatter inversion to suspended sediment concentration in estuarine environments Ocean Science Journal 51 109-125

[4] Moore S A, et al. 2012 On the application of horizontal ADCPs to suspended sediment transport surveys in rivers. Continental Shelf Research 46 50-63

[5] Gartner J W, Cheng R T 2001 The promises and pitfalls of estimating total suspended solids based on backscatter intensity from acoustic Doppler current profiler Proc. of the Seventh Federal Interagency Sedimentation Conf. Reno (Nevada) 119-126

[6] Tessier C, et al. 2008 Estimation of suspended sediment concentration from backscatter intensity of Acoustic Doppler Current Profiler Comptes Rendus Geoscience 340 58-67

[7] Ghaffari P, et al. 2011 Estimating suspended sediment concentrations using a broadband ADCP in Mahshahr tidal channel Ocean Science Discussion 8 1601-1630

[8] Gartner J W 2004 Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay, California Marine Geology 211 169-187

[9] Wood T M, Gartner J W 2010 Use of acoustic backscatter and vertical velocity to estimate concentration and dynamics of suspended solids in upper Klamath Lake, South-Central Oregon: implications for Aphanizomenon flos-aquae USGS Scientific Investigations Report 5203 1-20

[10] Hoitink A J F, Hoekstra P 2005 Observations of suspended sediment from ADCP and OBS measurements in a mud-dominated environment Coastal Engineering 52 103-118

[11] De Stigter H C, et al. 2011 Recent sediment transport and deposition in the Lisbon–Setúbal and Cascais submarine canyons, Portuguese continental margin Deep Sea Research Part II: Topical Studies in Oceanography 58 2321-2344

[12] Guerrero M, et al. 2016 The acoustic properties of suspended sediment in large rivers: consequences on ADCP methods applicability Water 8 1-22

[13] Bayram A, et al. 2012 Estimation of suspended sediment concentration from turbidity measurements using artificial neural networks Environmental Monitoring and Assessment 184 4355-4365.

[14] Wall G R, Nystrom E A, Litten S 2006 Use of an ADCP to compute suspended-sediment discharge in the tidal Hudson River, New York Geological Survey Scientific Investigations Report 5055 16

[15] Baohong C, et al. 2016 A baseline study of coastal water quality in the Lembeh Strait of North Sulawesi, Indonesia, in 2013 Marine Pollution Bulletin 104 364-370

[16] American Public Health Association 2012 Standard Methods for the Examination of Water and Wastewater 22nd Ed (Washington: APHA)

[17] Ainslie M A, McColm J G 1998 A simplified formula for viscous and chemical absorption in sea water Journal Acoustic Society America 103 1671-1672

[18] Poerbandono, Suprijo T 2013 Modification of attenuation rate in range normalization of echo levels for obtaining frequency-dependent intensity data from 0.6 MHz and 1.0 MHz devices Journal Engineering Technology Science 45 140-152

[19] Furusawa M 2015 Effect of noise and absorption on high frequency measurement of acoustic backscatter from fish International Journal of Oceanography 2015 1-11

[20] Poerbandono Mayerle R 1998 Assessment of approaches for converting acoustic echo intensity into suspended sediment concentration Proc. 3rd FIG Regional Conference (Jakarta) 1-13