Estimation of Suspended Sediment Concentration by Using Mobile ADCP Instrument

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Abstract. The measurement of suspended sediment concentration (SSC) by using Acoustic Doppler Current Profiler (ADCP) instrument still not widely used in Indonesia. The application of this technology uses sound wave by four direction transducers placed in the vessel, and this ADCP measured the intensity of backscatter from sediment particles. This study is equipped with RD Instruments WorkHorse Mariner 307.2 kHz ADCP, and the water sample collected from Lembeh Strait, North Sulawesi by using van Dorn bottle sampler. Beyond the experimental purpose of this installation, the interest in having wide area data at different tidal condition is that it provides the possibility of determining the effect of tidal to the SSC. The losses of sound signal were corrected to get more accurate results. Simple linear regression analysis performed to obtain the estimates of the SSC. Estimation of SSC of ADCP measurement was then compared with SSC on water analysis in the laboratory, and the result showed insignificantly different by statistical analysis. From this research, it showed that the concentration of suspended sediment ranged between 60-73 mg L\textsuperscript{-1} on location near the Port of Bitung, and 50-62 mg L\textsuperscript{-1} at a location away from the port. The result also observed that the highest concentration is in the region below the water column, and tidal condition was affected the condition of SSC. Based on all analysis, the mobile ADCP can provide a suitable measurement of suspended sediment concentration.

1. Introduction

Acoustical methods for measuring suspended sediment concentration have been extensively used especially in the study of sediment transport; one of them uses the Acoustic Doppler Current Profiler (ADCP) instrument. Not many researchers use ADCP as a scientific echosounder for the detection and quantification of suspended sediment in the water column. The using of ADCP still limited to measure speed and direction of water current in oceanography field. On the other hand, there was some research utilized acoustic signal from ADCP to measure the suspended sediment concentration as a baseline to sediment transport study [1, 2, 3].

The acoustic technology in ADCP can produce acoustic backscatter data. The acoustic wave emitted from ADCP to the water column, and the moving particles scattered the acoustic wave back to the instrument equal to echo intensity (EI). In this case, the average of acoustic backscatter data from four transducers in ADCP was used as a base data. The backscatter value was then converted into suspended sediment concentration based on many processes: transmission losses, conversion factor, calibration,
and verification. The echo intensity, EI (counts) was then converted into scattering volume, SV (dB) [4] and with the equation from calibration process; the SV will convert into suspended sediment concentration (mg L\(^{-1}\)) [5]. This is determined using the sonar equation, and the calibration was conducted using simple linear equations [6].

There are two types of ADCP, static and mobile. Many studies use static ADCP for estimating SSC, because this method provides time series data. In such cases, static ADCP still cannot cover larger areas, due to only take one-point data at one time [7]. Conversely, in order to improve the spatial resolution of ADCP data, the use of mobile ADCP can be reduced the error, and this is the subject of this paper. The advantages of ADCP as a tool for estimating the suspended sediment concentration was having very broad temporal scales, compared with conventional methods using water sampling.

Mobile ADCP use signal processing software that samples the vertical backscatter intensity profile by calculating moving particle in numerous range-gated sample volumes (bin) along a beam path [8]. Suspended sediment concentration can be computed as the product of the strait’s cross-section at the point of measurement. This paper describes a study of suspended sediment concentration in Lembeh Strait at 307.2 kHz frequency of mobile ADCP. The measurements were then compared with direct measurement SSC within 30 samples at different tidal condition. The aims of the present study are as follows: (1) to assess acoustic technology using mobile ADCP to estimating suspended sediment concentration in different site (near and far from the port), (2) to estimates SSC in a large spatial data, and (3) to compare SSC from mobile ADCP with in-situ SSC measurement.

2. Materials and methods

2.1. Research location

This research was conducted in 10-12 April 2016 at Lembeh Strait, North Sulawesi, Indonesia. The research vessel was crossed into three different areas: one location was near the Port of Bitung and two locations were away from the port; shipping lanes and dive spot (Fig. 1).

![Figure 1. Map of the study area. The red lines correspond to the position of the research vessel in (a) near the port, (b) shipping lanes, and (c) dive spot.](image-url)
2.2. Equipment

Equipment used in this study was mobile ADCP WorkHorse Mariner by Teledyne RD Instruments and operates at 307.2 kHz, four-beam, convex configuration with a beam angle of 20°. Water samples were collected using van Dorn water sampler from 30 sampling at different site. Other equipment used was Horiba U-50 water quality checker for temperature, salinity, and pH data loggers.

2.3. Experimental setup

The strait’s cross-section is split into $N$ horizontal subsection of equal width and area. The part of the cross-section where mobile ADCP measured backscatter intensity was actually used corresponds to a distance range of $1.5-40$ m from the transducer; approximately 30 subsections depend on bathymetry. The setting of mobile ADCP were $100$ cm bin size, $60$ m maximum profiling depth, transducer placed at $0.65$ m depth below surface water, blanking zone $1.5$ m below transducer depth. Heading, roll, and pitch data were corrected using gyro. The ship velocity was calculated from position fixes obtained by C-Nav Differential Global Positioning System (DGPS).

2.4. Data analysis

2.4.1. Transmission losses and absorption. Sound signal strength from ADCP determined as echo intensity in counts. Before conversion process to suspended sediment concentration, this signal required transmission losses and absorption correction. Transmission losses (dB) were calculated as follows [5]:

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

where $R$ is distance between each transducer in ADCP to measured layer or bin (m) and $\alpha$ is sound absorption coefficient (dB m$^{-1}$). The $R$ can be measured by:

$$R = r + \frac{D}{4}$$

where $r$ is a half size of bin size and $D$ is distance from each bin (m). The parameters were including temperature ($T$), salinity ($S$), pH, and material absorbing the sound signal; they were boric acid ($f_1$) and magnesium sulphate ($f_2$). Absorption by chemicals where $f_1$ and $f_2$ consist at the equation, are two principal components in the ocean. Beside those factors, $\alpha$ also depends on frequency used [9] in ADCP. Absorption coefficient can be calculated using [10] formula as follow:

$$\alpha = 0.106 \frac{f_1 f_2^2}{f_1^2 + f_2^2} e^{(pH-8)/0.56} + 0.52 \left(1 + \frac{T}{43}\right) \left(\frac{S}{35}\right) \frac{f_2 f_2^2}{f_1^2 + f_2^2} e^{-D/6} + 0.00049 f_2 e^{-\frac{T}{127} + \frac{D}{17}}$$

2.4.2. Counts to dB conversion. Since transmission losses were calculated, echo intensity needed to be corrected. The Doppler-shift frequency in ADCP is not based strictly on the continuous Doppler frequency shift, but is estimated using a discrete phase change on a pulse to another pulse in each transducer. Echo intensity in counts was converted to reverberation level ($RL$). In the sonar equation, all terms are in dB. When measuring with an ADCP, the $RL$ comes as stated on equation:

$$RL = K_c (E - Er)$$

where $K_c$ is echo intensity scale for conversion to decibels unit, $E$ is echo intensity received signal strength indicator (RSSI), $Er$ is echo intensity at the reference level (both in counts) [4]. A typical value for $Er$ is 40 counts. Relative acoustic backscatter ($RB$) which is echo level measured at transducer plus two-way transmission losses were calculated as follow:

$$RB = RL + 2 TL$$
2.4.3. Estimation of suspended sediments concentration. To estimate suspended sediment concentration from RB time series data, the following approaches were used including calibration process. By utilizing SSC laboratory result in different layer of depth [11], a simplified equation can be derived for estimating SSC. RB values can change due to particle move. Empirical formula was used by simple linear regression by calibration process. From this analysis, the regression line should be correlated direct sample and echo intensity data from ADCP. Simple regression analysis was used to find the regression slope and intercept. These relations are based on sonar equation by:

$$SSC_{ADCP} = 10^{(\text{Intercept} + \text{Slope} \times \text{RB})}$$

(6)

3. Results and discussion

3.1. Conversion of echo intensity in counts to dB
Calibration curve was built to relate echo intensity values to SSC. Data from direct measurement of suspended sediment concentration were then matched with echo intensity in same layer or bin to obtain information of calibration [12]. It was found that the best-fit values for slope and intercept values are 0.0202 and 1.6121, respectively. Suspended sediment concentration profiles have an acceptable fit of $r = 0.9197$. Measured echo intensity compared with calculation show a fairly good agreement. Despite that the introduced method is calibrated against detailed field measurement, there might be different coefficient of slope and intercept due to location which have to be considered in different area of survey. First, the effect of grain size distribution at one location will be different to other location and it will affect acoustic signal detected by ADCP [13]. One of limitations of using ADCP to measure suspended sediment concentration is acoustic sensors in ADCP is dependence on sediment properties such as particle size and more sensitive to large particle [14]. Second, measurement of direct sampling was lack of data for calibration because it has only 30 data pairs. This calibration data were then used for estimating suspended sediment concentration (Fig. 2).

Figure 2. Echogram of suspended sediment concentration at three observation location. Vertical axes indicate water depth in meters, and horizontal axes is ensemble number of track.
For the analysis, we choose an averaged data of the surveyed cross-section and extracted echo intensity data for each tidal condition. The result has been recently investigated with detailed various echo intensity. Because of many factors affecting acoustic signal transmission in natural water column environment such as transmission loss and absorption, raw echo intensity (EI) measured by ADCP were filtered by transmission losses correction to reducing error. Field investigations were performed during both high and low tidal, and also flood and ebb tide cycles in all area. Spatial distributions of averaged suspended sediment concentration were shown in Fig. 2. In echogram, the yellow-orange shades represent higher concentration. Over the cross-section the largest water depth is around 40 m. An important aspect of tidal condition of Lembeh Strait is that current usually flow from the southwest to northeast during ebb tide to low water; and vice versa during flood tide to high water. This area has an average tidal range of 1.2 m and the pattern of tide is a mixed semi-diurnal tide.

Suspended sediment concentration values along Lembeh Strait during the study period ranged from 45 to 80 mg L\(^{-1}\). The range increased during low tide ranged from 10 to 15 mg L\(^{-1}\) in all location. The measured SSC was found to be higher in the location near Port of Bitung compared to other location. Comparison between ebb and flood tide in SSC measurement show that the concentration will vary. But during the low water, the SSC values were significantly higher because of large amounts of suspended sediment are alternatingly eroded, resuspended, and deposited \[15, 16\]. This suggests that suspended sediment variation along Lembeh Strait was affected by tidal condition. During high tide water, the volume of water in Lembeh Strait increases, thus reducing the concentration of suspended sediments. One reason for the higher SSC obtained during low water measurement is probably higher sediment input through northwest current due to inlet from Bitung City.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Validation of estimated suspended sediment concentration from ADCP compared to direct sampling.}
\end{figure}

Figure 3 shows a distribution of suspended sediment concentration derived using the ADCP acoustic intensity and direct measurement. By comparing the 1:1 line with the best fit linear regression line, the ADCP-based SSC estimates are slightly lower than the estimates based on direct measurement. Results of the acoustic method shows a good qualitative agreement with statistical relationships between the SSC and direct SSC measurement method by \(r = 0.8483\). This results may be caused by several factors, for example there were differences of particle size distribution at various depths as well as differences in sampling intervals \[17\].


4. Conclusion
Mobile ADCP is one of promising acoustic instrument that reliable to estimate SSC in a more detailed temporal and spatial resolution. The acoustic parameter was calibrated against the in-situ data sets obtained. The concentration during the low water was higher than high water. Such a measurement method can support the sediment transport study as well as to the calibration process.

Acknowledgements
The authors would like to extend their gratitude to Marine Geological Institute, Indonesia for opportunity to join this research in Lembeh Island. This work also supported by Directorate General of Higher Education for financial support through PMDSU Grant (No. 330/SP2H/LT/DRPM/IX/2016).

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