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On the Determination of Suspended Sediment Concentration in the Estuary Using ADCP

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ABSTRACT

Using Backscatter intensity data from Acoustic Doppler current profilers (ADCPs) to estimate the suspended sediment flux in coastal regions can be effective and efficient. In order to improve the accuracy of suspended sediment concentration (SSC) estimation, we propose a method based on the theory of acoustic backscattering of sediment in the homogeneous field. Given the known probability distribution of the grain size according to the samples or historical in-situ data, as well as the temperature and salinity, the SSC in the water column can be calculated. Unlike using the empirical constants from regression, the SSC in the present method is dependent to the environments. Finally, the SSC from present method and previous method are inter-compared.

KEY WORDS: Acoustic backscattering; ADCPs; suspended sediment concentration (SSC).

INTRODUCTION

In coastal waters such as estuarine environment, the suspended sediment concentration (SSC) varies rapidly both in space and time in response to riverine discharge, tidal variation and the channel geometry. Traditional methods for SSC observation, i.e. the filtering of water samples, optical sensors (transmissimetry, backscatterance) and acoustical backscatterance sensor (ABS) provide only single point data in time and space. Alternatively, Acoustic Doppler Current Profiler (ADCP) can provide the SSC along the acoustic beam from the bottom to the surface layer using its echo intensity. The data from the transactions of shipboard ADCP could thus be very useful for the sediment flux estimation. Its advantage could greatly improve the efficiency and reduce the cost in the field survey. Many studies have shown the validity of utilize ADCP for SSC measurement (Deines, 1999; Garnet 2004, Poerbandono, 2004, Wall et. al., 2006; Kim and Voulgaris, 2008, Gostiaux and Haren, 2010; Moore et. al, 2013, Jourdin et. al., 2014). Deines (1999) first established the calibration procedure, which yielded the relationship between SSC and echo intensity. After that, some improvements were developed by Garnet (2004), Poerbandono (2004) and Kim et, al (2008). To use the method, one should conduct enough calibrations of ADCP with in-situ SSC data to obtain empirical constants. Moreover, the SSC results are independent to the variations of water properties (salinity, temperature and pH) and the grain size distribution, as their influences were not considered.

Based on the fundamental acoustic theory for acoustic backscattering of sediment in the homogeneous field (Sheng and Hay, 1988), the convertsion of mass concentration from echo intensity is a complex process. The results of SSC calculation depends on multiple factors including the suspended material features (particles size, grain size distribution), water properties (salinity, temperature, pH, pressure) and instrument characteristics (transmit power, transducer size, frequency and other parameters). Over the past decades there have been increased laboratory experiments to determine these factors (Ahuja and Hendee, 1978; Francois et. al., 1982; Hay, 1991; Hay and Sheng 1992; Downing et. al., 1995; Thorne and Hanes, 2002; Thorne and Meral, 2008; Gostiaux and Haren, 2010). More recent studies that consider these factors are Moore et. al, 2013, Baranya and Józsa, 2013; Topping et. al., 2015.

In this study, we carried out the sensitivity studies of the environmental factors to the 600 kHz ADCP applications to evaluate the effect of water properties (Salinity) and particle size distribution to the value of attenuation coefficient, then proposed a modified procedure for estimating SSC using ADCP echo intensity data.

THEORETICAL BACKGROUND

The applications of ADCP for suspended concentration measurement are based on the incoherent scattering theory, where the root mean square backscattered voltage V_{rms} is written as (Sheng and Hay, 1988; Thorne and Hanes, 2002):

$$V_{rms} = \frac{k_s k_t}{\psi \ r} M^{1/2} e^{-2r(\alpha_w + \alpha_s)} \tag{1}$$

$$k_t = P_0 r_0 \Re T_\upsilon \left\{ \frac{3c\tau}{16} \right\}^{1/2} \int_0^{\pi/2} \left(\frac{2J_1(ka_t \sin\theta)}{ka_t \sin\theta} \right)^4 \sin\theta d\theta \tag{2}$$

where k_s is the sediment backscattering function; k_t is the system constant of the monostatic piston transducer of ADCPs (Downing et al. 1995); r is the range from the transducer to the insonified volume; ψ is the near field correction factor; M is the concentration of suspended sediment; α_w is the attenuation due to water; α_s is the attenuation due to suspended sediment. P_0 is the sources level at range r_0 = 1 m; $\Re$ is the receive sensitivity; T_υ is the voltage transfer function for the system; c is the sound velocity; τc is the pulse length; $k = 2\pi f/c$, is the incident wavenumber; f is frequency of ADCPs; c is sound speed; a_t is the radius of the transducer; J_1 is the first-order Bessel function; θ is the angle subtended to the acoustic axis.

From Eq. 1 and Eq. 2, the square of root mean square backscattered pressure is presented:

$$P_{rms}{}^2 = P_0{}^2 r_0{}^2 \frac{k_s^2 k_t'^2}{\psi^2 r^2} M e^{-4r(\alpha_w+\alpha_s)} \qquad (3)$$

The Eq. 3 can be rewritten in decibel form:

$$RL = SL - 2TL + 10\log_{10}\left(k_s^2\right) + 10\log_{10}\left(k_t'^2\right) + 10\log_{10}(M) \qquad (4)$$

Where, RL is the measurement of reverberation level pressure (in dB); SL is the sources-level pressure (in dB) at reference distance r_0 = 1m from the transducer face. 2TL is the two way transmission loss that includes the attenuations due to water and sediment and the spherical spreading loss. k_t' is the new system constant.

Meanwhile, the active-sonar equation form from Urick (1975) is:

$$TS = RL + 2TL - SL + DT \qquad (5)$$

Where, TS is the Target Strength, DT is the Detection Threshold (in dB). Comparing Eq. 4 and Eq. 5, Eq. 5 can be rewritten as:

$$10\log_{10}(M) = RL + 2TL + DT - 10\log_{10}\left(k_s^2\right) - SL - 10\log_{10}\left(k_t'^2\right) \qquad (6)$$

SL of the ADCPs used in this study ranges from 217 to 219 dB. The reverberation level (RL) is converted directly from echo intensity data (in counts) in ADCPs using the formula of Gostiaux and Haren (2010):

$$RL = 10\log_{10}\left(10^{\frac{k_c E}{10}} - 10^{\frac{k_c E_{noise}}{10}}\right) \qquad (7)$$

where, E is the echo intensity (in count), E_{noise} is the ambient noise, k_c is the count to decibel conversion factor that depends on the temperature at transducer T_e (°C), and $k_c = 127.3/(T_e+273)$ (RDI, 2009).
The value of two-way transmission loss is:

$$2TL = 2r(\alpha_w + \alpha_s) + 10\log_{10}\left(\psi^2 r^2\right) \qquad (8)$$

The acoustic attenuation coefficient

Herein we assumed that the acoustic attenuation due to air bubbles is negligible. Therefore, the acoustic attenuation coefficient, α, is the sum of attenuation coefficient due to water, α_w, and attenuation coefficient due to suspended sediment, α_s. The attenuation coefficient due to water is a function of frequency and water temperature, salinity, pH, and pressure. Various empirical equations for calculating attenuation coefficient due to water absorption can be found from literatures (Shulkin and Marsh, 1962; Thorp, 1967; Fisher and Simmons, 1977; Francois and Garrison, 1982; Ainslie and McColm, 1998). The water absorption coefficient increases with salinity. In addition, the correlation slope is proportional to temperature. In high temperature environments, the variation of salinity in the estuaries will have strong effects of attenuation coefficient. In our case study, as the temperature was 30^0C, the change of salinity 1‰ will lead to the over-estimation of SSC by 4.5% at water depth 20 m. The change of salinity should be considered.

The attenuation coefficient due to suspended particles α_s is distinguished in two components, i.e. the viscous loss and scattering loss (Flammer, 1962). The viscous attenuation coefficient is a function of the kinematic viscosity of water, υ, sound frequency and the characteristic of suspended particles (particle density, particle size, the shape of particle, grain size distribution, the concentration of suspended sediment) (Urick, 1948; Ahuja and Hendee, 1978; Richards et al. 2003). The scattering loss component is the scattering of sound due to particles and it a function of acoustic frequency, the normalized total scattering cross section, particles distribution and suspended sediment concentration.

From the sensitivity study, the viscous attenuation coefficient will be decreased as the mean grain size increases. In contract, the value of scattering attenuation coefficient is proportional with the increase of particle size. In present study, the grain size distributions are the normal, lognormal and nonlinear-Weibull distributions. We adopted these three distributions for the calculation of the attenuation coefficient used the formula proposed by Ahuja and Hendee (1978) as shown in table 1.

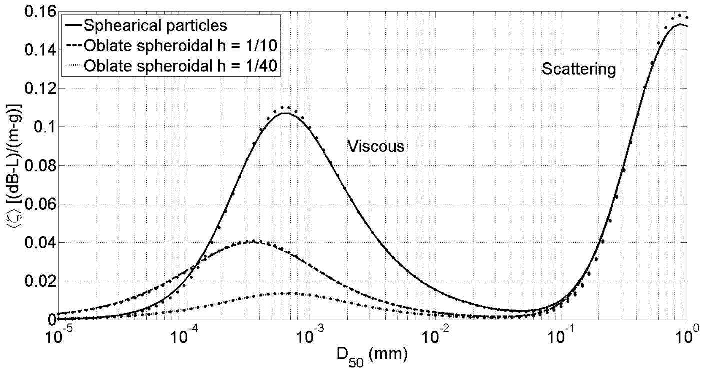

Fig. 1 The effects of the change of particles size, the shape of particles and particles size distribution to the value of total attenuation coefficient due to sediment; f = 600 kHz, ρ_s = 2.65 gcm^{-3}; $\sigma = 0.4a_0$, $\upsilon = 0.83\times10^{-6}$ at 30^0C.

Table 1 the total sediment attenuation coefficient

$\langle\zeta_\upsilon\rangle + \langle\zeta_s\rangle$ (dB L m^{-1}g^{-1})			
Distribution	Lognormal	Nonlinear Wei-bull	Normal
Spherical	0.0632	0.0542	0.0076
Oblate Spheroidal, h=1/10	0.0626	0.0536	0.0019
Oblate Spheroidal, h=1/40	0.0625	0.0535	0.0012
Prolate Spheroidal, h=10	0.0668	0.0572	0.0360
Prolate Spheroidal, h=40	0.0787	0.0678	0.1028

The result pointed out the shape of particle affects the value of the total attenuation coefficient due to sediment. In table 1, the difference of total attenuation coefficient that were calculated for spherical and oblate spheroidal with aspect ratios of h = 1/10 and 1/40 models is quite small. The shape of particle is negligible in this study. In table 1, the difference of the total attenuation coefficient value due to sediment between two distributions, which are the lognormal and nonlinear-Weibull distributions using spherical and oblate spheroidal with aspect ratios of h = 1/10 and 1/40 models, is about 0.009 dB L $m^{-1}g^{-1}$. These values are close to the results by Moore et al. (2013). It indicated that the lognormal and nonlinear-Weibull distribution are good agreement with the particles size distribution from in-situ data in this study.

The value of sediment absorption coefficient is proportional with the increase of SSC as shown in Fig. 2. The sediment attenuation should also be considered in the case of high SSC. In addition, the different impact of attenuation coefficient due to sediment, which is used the lognormal and nonlinear-Weibull distribution, is quite small, which reaches only 2% at water depth 20 m and 300 mg/L of SSC.

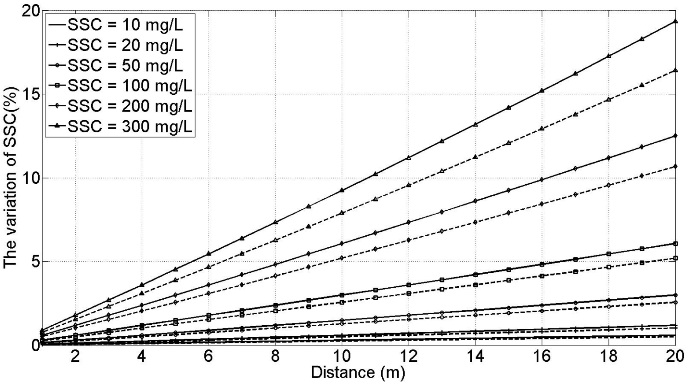

Fig. 2 The effect of attenuation coefficient due to sediment to the change of SSC; the value of the total attenuation coefficient is presented in table 1 for spherical particles. The value of SSC is taken over the range from 10~300 mg/L. The solid line showed that the value of total attenuation coefficient due to sediment is calculated using lognormal distribution; the dot line showed the total attenuation coefficient due to sediment is calculated using nonlinear-Weibull distribution.

Sediment backscattering function

According to Thorne and Hanes (2002), the sediment backscattering function can be calculated as follows:

$$k_s^{\,2} = \frac{\int_0^\infty a^2 f_\infty^{\,2} n(a)da}{\rho_s \int_0^\infty a^3 n(a)da} \tag{9}$$

Where, f∞ is the backscatter form function that describes the scattering properties of the particle; ρ_s is the particle density, 2.65 g/cm^3. The empirical equation of the backscatter form function is used in this study as (Thorne and Meral, 2008):

$$|f_\infty| = \frac{x^2(1-0.35e^{-[(x-1.5)/0.7]^2})(1+0.5e^{-[(x-1.8)/2.2]^2})}{1+0.9x^2} \tag{10}$$

To describe the size distribution of particles in suspensions, the normal and log-normal distributions are often used (Thorne and Meral, 2008). By previous investigation in the same estuary, we found the good agreement between nonlinear-Weibull model to the particles distribution. The sediment backscattering functions using the normal and lognormal distributions at ADCP frequency of 300 kHz, 600 kHz, and 1200 kHz are shown in figure 3. The sediment backscattering function is proportional to the mean of particles size and frequency. The difference of the sediment backscattering function for the two grain size distribution cases are small.

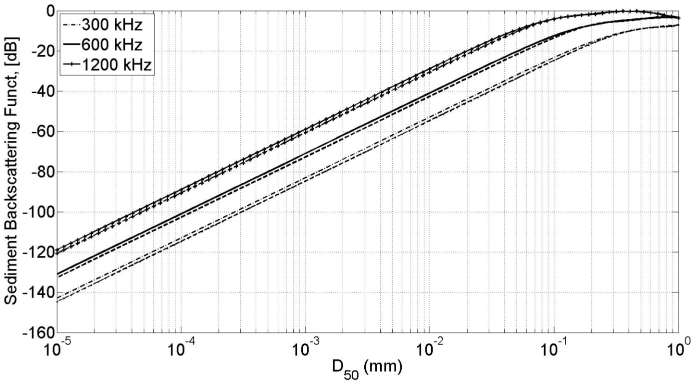

Fig. 3 The sediment backscattering function for a suspension of particles having normal distribution (--) and lognormal distribution (–) by number, as a function of the media grain size, D_{50}, from operating frequencies of RDI-ADCPs.

The most popular method for field survey can be Poerbandono (2004). He found the good relationship between the relative acoustic backscatter value (RB or IE) and direct sample concentration that were obtained at the same time and depth of a measuring column. The relationship was represented by a regression line, which is presented by the regression slope (A) parameter and regression intercept (B) parameter (Poerbandono, 2004) with high correlation coefficient (Lu, 2003; Poerbandono, 2004). It indicated that the SSC of profiler can be estimated from a calibration of backscatter data using direct the sample concentrations from in-situ data. From this viewpoint, it is not necessary to calibrate system parameters (transmit power, transmit pulse length, detection threshold) nor use the characteristic of suspended sediment (grain size distribution, backscattering form function model) (Garnet, 2004).

The formula, which was proposed by Garnet (2004) and (Poerbandono, 2004), is presented as:

$$10\log_{10}(M) = A \times RB + B \tag{15}$$
$$RB = SL + 2(\alpha_w + \alpha_s)r.$$

In comparison between Eq. 15 and Eq. 6, the theoretical parameters are presented as:

$A = 1;$
$B = F_{(SL,k_S,k_t',DT)}$

However, from the above discussed, it is clear that the A and B should not be constants, instead, they should be functions of oceanic environments. Moreover, the cost may increase rapidly with the sample size for regression. In present study, we used theoretical approach to determine the values of A and B from field experiment data and discuss the discrepancies with Eq. 15 method to estimation SSC from backscatter intensity data in ADCPs.

Field experiments

The sediment yield from ChoShui estuary is 42 million ton per year, which is the greatest in Taiwan. The present method for the estimate of SSC from acoustic backscatter data in an ADCP was applied to the data acquired around the reclamation area of Yun-lin industrial district, the south of ChuShui estuary, in July 27, 2015. The ADCPs that mounted on vessels were 600 kHz RDI workhorse ADCP in bottom tracking mode. The bin size was 0.2 m, the water depths ranged from 5 m~ 25 m. The vessel The area of study site is about 4 km^2 including 4 lines with the length of each line more than 2 km. the perimeter of study site is about 10km. During the experiment, water samples were taken at 6 positions covering study site. The LISST was used to determine particle size distribution from in-situ samples in the laboratory.

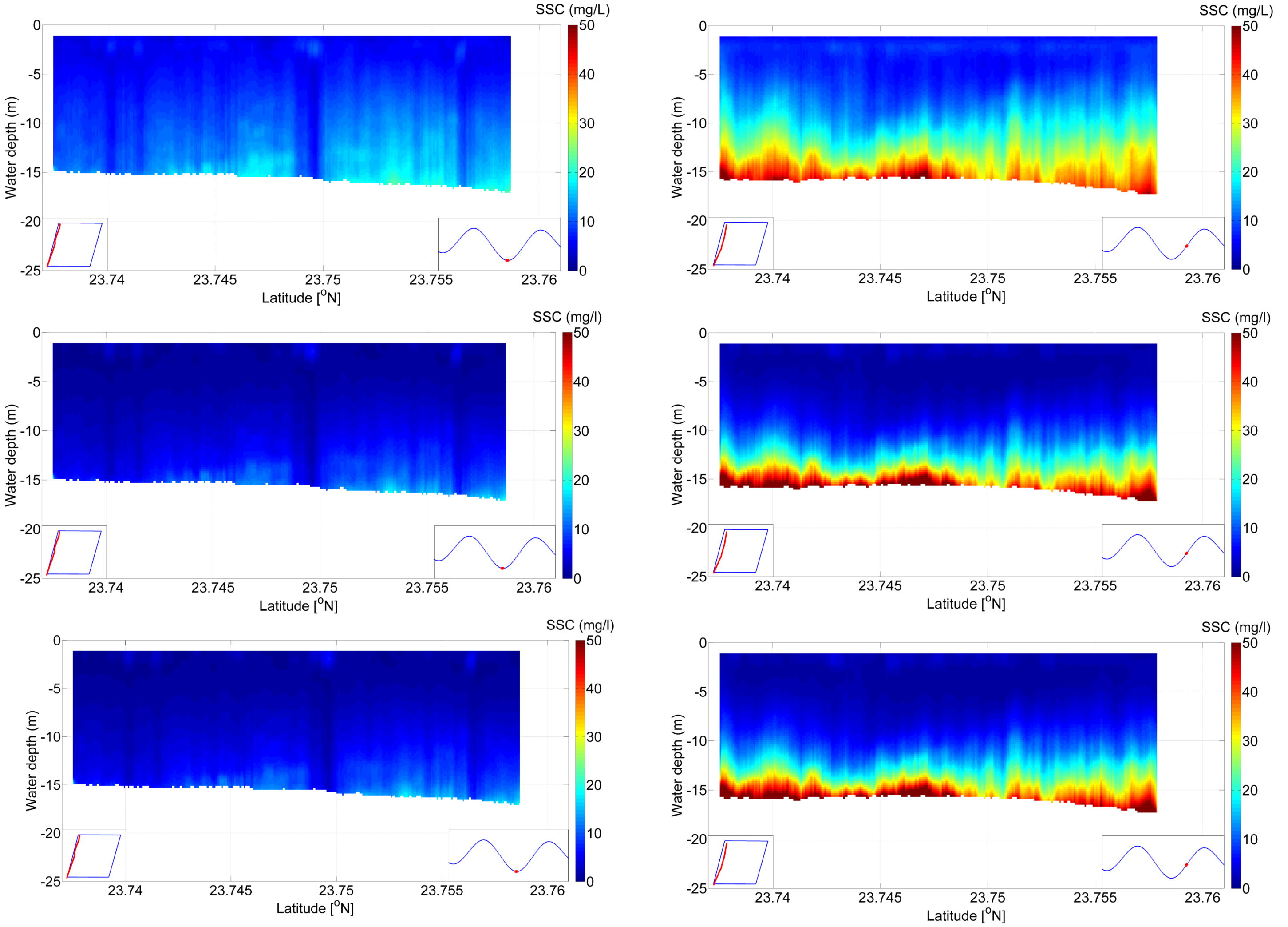

Fig. 4a, b show the results of SSC estimation that were estimated from Echo intensity data using empirical formula; 4c, d show SSC results using theoretical equation that was used the lognormal distribution; 4e, f show the SSC results using theoretical equation, which was used the nonliner-Weibull distribution.

To estimates SSC from backscatter intensity measurements in ADCPs, the theoretical method was used based on procedures outlined in Section 2. Time series of temperature was used to calculate a time series of the attenuation due to water. In addition, due to strong mixing in the study site, the value of Salinity and pH is 35‰ and 8.0 respectively. The pressure was estimated belong to the depth in each position. The voltage and system parameters were exploited to calculate sources level. Assuming the environment of field experiment is homogeneous, we estimated the value of parameters of the normal, lognormal and nonlinear-Weibull distributions using particle size distribution from in-situ data; these models were used to calculate the value of sediment backscattering function and the sediment attenuation coefficient. The reverberation level (in dB) was determined progressively at each bin of every profile of suspended solids from

ADCP backscatter strength by Eq. 8, and converted Echo units to dB utilizing RSSI scale factor, k_c, following (RDI, 2009), the normal value of k_c is 0.42 (dB/count). To calculate reverberation level, the ADCP echo intensity should be used the average of backscatter measured by four acoustic beams. The attenuation coefficient due to sediment was determined by the iterative method, which was introduced by Thorne and Hanse (2002). In the previous study, the values of two parameters of empirical formula were obtained from regression analysis (A = 0.598, B = -27.2).

RESULTS AND DISCUSSION

Comparisons are shown in Fig. 4. According to the sensitivity study, the difference of SSC between using lognormal distribution and nonlinear-Weibull distributions is neglected. It can be found that the SSC from empirical formula were higher than those from theoretical method in most of the water layer except the layer near the bottom. This is due to the under-estimation of the constants A and B in the empirical formula, which were obtained using linear regression between sampled SSC and relative backscattered according to Deines' expression (1999). In the present method, the attenuation due to sediment, salinity and temperature are considered and thus gave different values of A and B.

The SSC result in Fig. 4 reflected the effect of the tide to the change of SSC value. During ebb tide, the low current speed limit the re-suspension over the study site (Fig. 4a, c, e). The value of SSC increased as the tidal current intensified.

CONCLUSION

The echo intensity from ADCP can be used to infer the SSC. In the conversion formulation, the parameters A and B could be determined by either regression as empirical constants or from theoretical approach. Concerning the theoretical approach, we carried out sensitivity studies. The value of attenuation coefficient due to sediment may effect to the SSC estimation result, and the value of SSC is higher that lead to the influence is greater. In this study, the value of total attenuation coefficient due to sediment is 0.063 dB-g.$m^{-1}L^{-1}$ and 0.054 dB-g.$m^{-1}L^{-1}$ using the lognormal and nonlinear-Weibull distributions respectively. These results are similar to the parameters that were calculated by Moore et. al.,(2013). It is suggested to consider water temperature, salinity and grain size distribution as inputs to estimate the SSC.

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