ESTIMATION OF SUSPENDED SOLIDS CONCENTRATIONS BASED ON ACOUSTIC BACKSCATTER INTENSITY: THEORETICAL BACKGROUND

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ABSTRACT

Widespread use of acoustic instruments to measure current velocity has led to interest in the technique of using acoustic sensors to estimate suspended solids concentration (SSC) from acoustic backscatter intensity (ABS). These measurements are non-intrusive, much less susceptible to biological fouling than are measurements from optical instruments, and provide time series of ABS (profile) for improved temporal resolution of SSC estimates. Successful estimates of SSC from ABS provides promise that this technique might be appropriate and useful for determining SSC from commercially available instruments such as acoustic Doppler current profilers (ADCPs). In spite of significant advantages to the method, users must be aware of important limitations to the technique

Introduction: The transport, deposition, and suspension of sediments in rivers, estuaries, and bays are of critical importance to understanding overall condition and health of these complex systems. Sediments carry nutrients and potentially toxic materials; transport of sediments is the mechanism to re-distribute these materials within the system. High concentration of suspended materials may limit light transmission and thus inhibit photosynthesis. In addition, deposition of suspended sediments in shipping channels requires periodic dredging to maintain navigable waterways. While knowledge of SSC is needed to begin to understand these processes, quantitative measurement of this highly variable property is difficult at best. Use of in-situ optical instruments such as optical backscatterance sensors and transmissometers has provided estimates of SSC, but they do not measure SSC directly and are subject to biological fouling in highly productive waters. Collection and analysis of water samples provides direct measurement SSC and is not subject to biological fouling; however, this procedure is extremely labor intensive and tends to under sample in most cases because of the variable nature of suspended material.

Acoustic sensors that are routinely used to measure time series of water velocity overcome some of these difficulties and hold promise as a means of quantitatively estimating SSC from ABS intensity, a by-product of velocity measurements. An additional advantage of acoustic techniques is that backscattered signal is range-gated to provide time series of data profiles rather than single point measurements. Initial studies utilizing the acoustic technique provided qualitative results, for example, Schott and Johns (1987), Flagg and Smith (1989), and Heywood et al (1991). Laboratory experiments designed to calibrate ABS to sand concentration were conducted by Thorne et al (1991) and Lohrmann and Huhta (1994). Hanes et al (1988) used a 3 mHz acoustic source to estimate suspended sand concentration near Prince Edward Island and Thevenot et al (1992) developed calibration parameters as part of a study to monitor dredged material near Tylers Beach, Virginia using Broadband-ADCPs (BB-ADCPs). Hamilton et al (1998) provided comparison of optical and acoustic methods in a study describing measurements of cohesive sediments using an acoustic suspended sediment monitor and Thevenot and Kraus (1993) compared optical and acoustic methods using a 2400 kHz BB-ADCP in the Chesapeake Estuary. This is only a partial list of research in the field; however, in general, previous studies have been qualitative in nature or limited to large (sand-size) particles. Some studies used non-commercial, specially designed acoustic sensors. Many required extensive laboratory calibrations or were used for short duration (hours). Others did not account for acoustic losses in the near field of the acoustic transducer. Recently, Byrne and Patino (2001), Land and Jones (2001) and Gartner and Cheng (2001) described techniques to estimate time series of SSC utilizing standard commercial ADCPs. Theoretical background and some limitations of the technique are described, however the present discussion deals only with use of acoustic sensors to estimate SSC. Potential for using multi-frequency acoustic sensors to estimate size distribution of suspended solids is beyond the scope of this discussion.

Acoustic Method: The method of estimating SSC from ABS is based on application of the sonar equation for sound scattering from small particles. In its simplified form for reverberation level, the sonar equation (Urick, 1975) contains terms for the ensonified volume, volume scattering strength (a function of particle shape, diameter, density, rigidity, compressibility, and acoustic wavelength), source level (intensity of emitted signal, known or measurable), and two-way transmission loss. The transmission loss is a function of range to ensonified volume, and absorption coefficient for the water; it contains terms for losses due to spreading and absorption. Attenuation due to sediment must also be accounted for if it is shown to be significant at ranges and levels encountered during a study. The absorption coefficient for water is a function of acoustic frequency, salinity, temperature, and pressure and can be found using equations from Schulkin and Marsh (1962). Spreading loss is different in near and far transducer fields. The transition between near and far transducer fields is a function of transducer radius and acoustic wavelength. The correction for spreading loss in the transducer near field can be calculated from the formula in Downing et al (1995). From a practical standpoint, it is not possible to measure all the characteristics of the suspended material and the acoustic source that are required to directly estimate SSC from ABS. The approach described here involves casting the sonar equation in an exponential or log form by relating the SSC to a relative backscatter utilizing calibration parameters and single particle theory following the technique of Thevenot et al (1992). In exponential form, the estimation equation is

$$SSC_{(estimated)}=10^{(A+B*RB)}. \tag{1}$$

The exponent of Eq. 1 contains a term for the measured relative acoustic backscatter, *RB*, as well as terms for an intercept, *A* and slope, *B* that are determined by regression of concurrent ABS with known SSC on a semi-log plane in the form of $log(SSC_{measured})=A+B*RB$. The procedure to estimate a profile of SSC from a measured profile of ABS (say from ADCP) is a multi-step process that includes: 1) calculating transmission loss from spreading and absorption as a function of range and absorption coefficient including the near field transducer correction for spreading loss; 2) determining relative backscatter as a function of range by removing reference level (baseline), correcting for transmission loss and converting backscatter units to dB utilizing an (instrument dependent) scale factor; and 3) determining slope and intercept for a regression between logarithm of measured SSC and relative backscatter. Eq. 1 can then be used to estimate a profile of SSC.

Theoretical Limitations: There are two practical limitations to the method of predicting SSC from ABS. The first is a limitation common to any single frequency (optical or acoustical) instrument. Since single frequency instruments cannot differentiate between changes in concentration and changes in particle size distribution, a change in size distribution will be interpreted as a change in concentration unless independent particle size distribution measurements indicate need for additional calibrations. In addition, acoustic and optical methods respond differently to particle size with acoustic sensors more sensitive to large particles (proportional to volume) and optical sensors more sensitive to small particles (proportional to cross sectional area).

The second limitation is associated with the relation between instrument frequency and particle size distribution. The theoretical basis for acoustic analysis is Rayleigh (long wavelength) scattering model that is restricted to particles whose ratio of circumference to wavelength is less than unity. For a fixed frequency acoustic instrument, this condition restricts the maximum particle size for which the method is appropriate, beyond which estimates of SSC can be expected to have increasing errors. In addition, attenuation falls off significantly below circumference to wavelength ratios near 0.01-0.1 a situation that may create errors at small particle sizes. This limits the approach to a range of particle sizes beyond which estimates of SSC would be expected to display increasing errors in addition to errors from changes in particle size distribution. For a 1200 kHz acoustic source, particle diameters of 400, 40, and 4 μm correspond to circumference/wavelength ratios of 1.00, 0.10, and 0.01 respectively. Thus, the acoustic method is most appropriate for particle size distributions on the order of tens to hundreds of microns. Because of the inherent mismatch of frequency versus particle size, acoustic sensors are more appropriate for suspended material that is larger than that for which optical instruments are optimized. At very high frequencies (10-20 mHz) necessary for wavelengths to match un-aggregated clay particle sizes, sound attenuation is very high and acoustic range is unacceptably low for instruments designed primarily to measuring velocity profiles.

Summary: The technique of using ABS may provide reasonably accurate estimates of SSC under favorable circumstances. The method has some advantages over other methods but suffers from the same limitation as any single frequency sensor as far as being unable to differentiate between changes in size distribution and concentration. Although optical and acoustical instruments react differently to grain size, ABS measured by velocity sensors such as ADCPs provides SSC estimates concurrent with velocity measurements without the use of an additional sensor. It overcomes the problem of biological fouling, a major limitation of optical instruments. Another significant feature is that when utilizing acoustic measurements from ADCPs for estimates of SSC they are in the form of profiles rather than single point measurements. This method may be an extremely useful research tool if additional tests show that it can provide consistent and reasonably accurate results (within theoretical limitations), in spite of some minor changes in particle size distribution.

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