On the possibility of single-frequency acoustic measurement of sand and clay concentrations in uniform suspensions, corrected version, by Daniel M. Hanes

Published originally: Hanes, D.M., On the possibility of single-frequency acoustic measurement of sand and clay concentrations in uniform suspensions, Continental Shelf Research, v. 46, doi: 10.1016/j.csr.2011.10.008, 2012.

Corrections incorporated into this paper were published alone as: Hanes, D.M., Erratum to ‘‘On the possibility of single-frequency acoustic measurement of sand and clay concentrations in uniform suspensions”, Continental Shelf Research, http://dx.doi.org/10.1016/j.csr.2012.10.003, 2012.

Abstract: There are fluvial, estuarine, and coastal environments in which the size distribution of suspended sediment is sometimes bi-modal, with one narrow peak in the size range of clay and the other narrow peak in the size range of sand. In such situations it is possible to exploit the acoustic scattering and dissipation properties of the water-sediment mixture to estimate the concentration of the two different size suspended sediment constituents using the measured backscatter from a single frequency transceiver. While it may seem counter-intuitive that the backscatter from a single frequency could be utilized to estimate the concentrations of two different size fractions, the dominance of the clay to sound attenuation and the sand to sound back-scattering can be usefully exploited under unusual conditions where the characteristic sizes of the two sediment fractions are approximately known, and the concentrations of the clay and sand are homogeneous along the acoustic sound path.

Introduction

Acoustic backscatter is a useful technique for measuring the size and concentration of suspended sediment in field applications (e.g. Thorne and Hanes, 2002). The underwater range and non-intrusive nature of underwater sound often renders acoustic methodologies preferable to optical methods. If the size distribution of the suspended sediment is narrow and known, then a single frequency backscatter system can be effectively utilized to measure the spatial and temporal structure of the concentration field along the acoustic beam path (e.g. Hanes et al. 1988). If the size distribution of the sediment is not known, then a multiple frequency system is generally required in order to invert the backscattered sound to estimate size and concentration fields (e.g. Crawford and Hay, 1993; Hay and Sheng, 1992; Thosteson and Hanes, 1998). It has generally been believed that a single frequency system is incapable of measuring concentration if either the size is unknown, or if there are multiple sizes of sediment. To be quite simplistic, sound scattering is a non-linear function of sediment size, so many smaller sediment grains could scatter the same amount of sound as fewer larger grains. The inversion of backscattered intensity is therefore not uniquely related to concentration but is also a function of sediment size (and also other less significant factors for typical field situations).

It is therefore quite fascinating that Wright et al. (2010), through largely empirical means, have successfully measured the concentrations of suspended silt and clay (combined) and suspended sand in the Colorado River using a single frequency backscatter system. Their success is probably due to conditions in which the clay-sized fraction dominated the viscous dissipation of sound energy and the sand-sized fraction dominated the back-scattering of sound. Their success probably also depended on the relatively stable size distribution over time, and the relatively homogeneous suspended sediment concentration along the acoustic beam path, which was directed approximately horizontally from the river bank toward the center of the river.

This work will demonstrate the theoretical possibility for a single frequency backscatter system to measure the concentration of suspensions of clay and sand under rather idealistic and simplified conditions. These conditions consist of narrow and separate size distributions characterized by two sizes, and homogeneous suspended sediment concentration.

Theoretical Background

The basic equation describing the backscattering of sound from a suspension of particles has been given in many forms, with the following form from Thorne and Hanes (2002):

$$P_{rms} = P_o r_o f \left[\frac{3M\tau c}{8D\rho_s} \right]^{1/2} \frac{0.96}{k a_t \psi r} \exp\{-2\alpha r\} \qquad (1)$$

P_{rms} is the backscattered pressure at the receiver, which is typically related to the voltage generated in response to the pressure. P_o is the reference pressure at range r_o, r is distance from the transducer along the acoustic travel path, D is the diameter of the suspended particles, a_t is transducer radius, τ is acoustic pulse duration, c is speed of sound, ρ_s is particle density, k is wave number, M is mass concentration, f is the form function that describes the back-scattering properties of the particles (e.g. Sheng and Hay, 1988), ψ accounts for departure from spherical spreading in the near-field (e.g. Downing et al, 1995), and α is the total attenuation coefficient that accounts for transmission losses due to the fluid and the suspended sediment.

The acoustic losses characterized by the attenuation coefficient result from a variety of processes, as summarized by Flammer (1962). The losses consist of the sum of viscous dissipation due to the motion of the fluid under the oscillating pressure field (α_w), viscous dissipation due to the relative motion between the particles and the fluid (α_{sv}), and scattering of sound by particles (α_{ss}).

Urick (1948) derived the following expression for the viscous dissipation, normalized by mass, due to the particles in fluid:

$$\alpha_{sv} = \left[\frac{k}{2\rho_s} (\sigma - 1)^2 \left(\frac{s}{s^2 + (\sigma + T)^2} \right) \right] \qquad (2)$$

where $\sigma = \rho_s / \rho_f$, ρ_f and ρ_s are fluid and sediment density, $s = \frac{9}{2\gamma D}\left(1 + \frac{2}{\gamma D}\right)$, $\gamma = \sqrt{\pi F / \nu}$, F is the frequency of the backscatter system, ν is kinematic viscosity of the fluid, and $T = \frac{1}{2} + \frac{9}{2\gamma D}$.

The scattering loss due to spheres was given by Urick (1948) as $\frac{M}{D\rho_s}\left(\frac{x^4}{96}\right)$, where $x = kD/2$, and was modified for sand based upon empirical measurements, and normalized by mass, by Thorne and Meral (2007):

$$\alpha_{ss} = \left[\frac{1.5}{D\rho_s} \left(\frac{0.29x^4}{0.95 + 1.28x^2 + 0.25x^4} \right) \right] \quad (3)$$

Equations 2 and 3 are plotted in Figure 1 (upper panel) as a function of sediment size for frequencies of 200 Khz, 1 Mhz, and 5 Mhz.

The backscatter form function, *f*, has also been estimated experimentally by several researchers (e.g. Thorne and Hanes, 2002):

$$f = 1.1 \left\{ 1 - 0.25 \exp\left[-\left(\frac{x - 1.4}{0.5} \right)^2 \right] \right\} \left\{ 1 + 0.37 \exp\left[-\left(\frac{x - 2.8}{2.2} \right)^2 \right] \right\} \left\{ \frac{1.1x^2}{1 + 1.1x^2} \right\} (4)$$

The backscatter form function (equation 4) is shown in Figure 1 (lower panel) for the same frequencies.

Solution Technique

Equation 1 is recast below for an idealized mixture of two sediment sizes, and constant concentration along the acoustic path range:

$$rP_{rms} = P_o r_o \left[\frac{3\tau c}{8}\right]^{1/2} \frac{0.96}{k a_t \psi}\left[f_1^2 \frac{M_1}{D_1\rho_{s1}} + f_2^2 \frac{M_2}{D_2\rho_{s2}}\right]^{1/2} \exp\left\{-2r(\alpha_w + \left(\alpha_{ss1}+\alpha_{sv1}\right)M_1 + \left(\alpha_{ss2}+\alpha_{sv2}\right)M_2)\right\}$$

(5)

where the dissipation terms consist of viscous dissipation due to water, sound scattering due to sediment, and viscous dissipation due to sediment for each sediment component, and the subscripts 1 and 2 indicate sediment one (clay) and sediment two (sand), respectively. Taking the natural logarithm of equation 5 and differentiating with respect to range yields:

$$P^{-1}\partial P/\partial r = -r^{-1} - 2(\alpha_w + \left(\alpha_{ss1}+\alpha_{sv1}\right)M_1 + \left(\alpha_{ss2}+\alpha_{sv2}\right)M_2) \quad (6)$$

If the attenuation due to sediment 1 dominates the attenuation due to sediment 2 then

$$\left(\alpha_{ss1}+\alpha_{sv1}\right)M_1 \succ\succ \left(\alpha_{ss2}+\alpha_{sv2}\right)M_2 \quad (7)$$

and the concentration of sediment 1 is given approximately by:

$$M_1 = -\left[P^{-1}\partial P/\partial r + r^{-1} + 2\alpha_w\right]/\,2\left(\alpha_{ss1}+\alpha_{sv1}\right) \qquad (8)$$

With the additional assumption that sediment 2 dominates the backscatter,

$$f_1\left[\frac{M_1}{D_1\rho_{s1}}\right]^{1/2} \prec\prec f_2\left[\frac{M_2}{D_2\rho_{s2}}\right]^{1/2} \quad (9)$$

equation 5 can be recast for an approximation of M_2 by:

$$\left[f_2 \left[\frac{M_2}{D_2 \rho_{s2}} \right]^{1/2} \right] = r P_{rms} \left[\left[\frac{3\tau c}{8} \right]^{1/2} \frac{0.96}{k a_t \psi} P_o r_0 \right]^{-1} \exp\left\{ 2r(\alpha_w + \left(\alpha_{ss1} + \alpha_{sv1}\right) M_1 + \left(\alpha_{ss2} + \alpha_{sv2}\right) M_2) \right\} \quad (10)$$

In combination with equation 8, equation 10 can either be solved implicitly for M_2 or if the small term involving M_2 on the r.h.s. is ignored then equation 10 can be solved explicitly. Note that for particular sediment sizes and acoustic frequencies, equation 7 provides limits to the ratio of the sand-to-clay concentrations for which the technique is applicable.

Discussion

While the assumptions inherent in the development above are at best only approximate in field applications, they are sometimes sufficiently satisfied such that single frequency backscatter data can be usefully interpreted with regard to sediment dynamics in the system. Similar methods to that presented above could be useful in developing qualitative descriptions of the suspended sediment field even when the assumptions are somewhat relaxed. For example, even when the size distributions are broad and the concentrations field varies spatially, a qualitative suspended clay to sand index could probably developed for particular sites based upon the single frequency acoustic backscatter. Long term monitoring of a “clay to sand” index and relating it to other environmental conditions could help inform managers regarding various aspects of flow and sediment regulation for their particular site or system.

For example, Topping et al. (2007) and Wright et al. (2010) describe the suspended sediment in the Colorado River downstream of Glen Canyon Dam often consists of clay, silt, and sand in various combinations of concentration and size. By assuming that two characteristic sizes, one for clay/silt and one for sand, represent the full size distribution (which in reality is a broad distribution over the clay to medium sand size classes) and by measuring the acoustic backscatter along a path pointed approximately horizontally across the river, they obtain useful estimates of the variations in clay/silt and sand concentrations over time. Even though there are surely gradients in suspended concentration across the river, this deployment orientation probably helps average over the gradients in an effective manner. Note that an acoustic path pointed along the axis of the river would probably be most ideal in applying the above techniques, but it would be less meaningful in terms of average conditions over the river cross-section.

Applying and expanding the concepts developed above to multiple frequency systems under field conditions would expand the usefulness, accuracy, and applicability of the technique. For example, the sand size could be measured from the multi-frequency backscatter using standard techniques, then techniques such as those presented above could be applied to estimate the clay concentration in some limited cases, or a clay to sand index more generally. Also, it is relatively straight forward to apply the developments presented above to narrow bimodal size distributions (rather than just two characteristic sizes).

An important caveat to this discussion is that under conditions in which the fine sediment flocculates, the dissipation and backscatter formula presented above no longer apply, and the technique is not directly applicable. This is often the case in estuarine or coastal applications where large salinity gradients are common.

Conclusion

A theoretical analysis demonstrates it is possible to estimate suspended clay and sand concentrations from a single-frequency backscatter system in situations where the attenuation of sound is dominated by clay particles and the backscatter of sound is dominated by sand grains for the sound frequency employed. The specific technique presented above is limited in application because it assumes that the two distinct sediment sizes are known and that the size and concentration fields are uniform along the acoustic path, which is a rare occurrence in nature. However, the general phenomena of clay dominating the dissipation and sand dominating the backscatter may be usefully exploited under more common conditions.

Acknowledgements

The author would like to thank Chris Vincent and Peter Thorne for numerous related collaborations over the years, and also thank Scott Wright and David Topping for discovering the basic idea behind this work and demonstrating it to a non-believer. This work was initiated with the support of the U.S. Geologic Survey Coastal and Marine Geology program. The author appreciates the constructive review comments of Curt Storlazzi, Jingping Xu, Yogi Agrawal, and Peter Thorne.

References

Crawford, A.M. and Hay, A.E., 1993. “Determining suspended sand size and concentration from multifrequency acoustic backscatter”, J. Acoust. Soc. Am. 94(6), 3312-3324.

Flammer, G.H., 1962. “Ultrasonic measurement of suspended sediment”, U.S. Geological Survey Bulletin 1141-A. Government Printing Office, Washington, DC, 48 pages.

Downing, A., Thorne, P.D., Vincent, C.E., 1995. Backscattering from a suspension in the nearfield of a piston transducer. Journal of the Acoustical Society of America 97, 1614–1620.

Hanes, D. M., C. E. Vincent, D. A. Huntley, and T. L. Clarke (1988), Acoustic measurements of suspended sand concentration in the C2S2 experiment at Stanhope Lane, Prince Edward Island, *Mar. Geol., 81,* 185-196.

Hay, A. E. and J. Sheng (1992), Vertical profiles of suspended sand concentration and size from multi-frequency acoustic backscatter*, J. of Geo. Res., Vol. 97, No. C10,* 15,661-15,677.

Sheng, J. and A. E. Hay (1988), An examination of the spherical scatter approximation in aqueous suspensions of sand. *J. Acoust. Soc. Am. 83(2), February 1988*, 598-610.

Thorne, P. D., C. E. Vincent, P. J. Harcastle, S. Rehman, and N. Pearson (1991). Measuring suspended sediment concentrations using acoustic backscatter devices, *Mar. Geol., 98,* 7-16.

Thorne, P.D. and Hardcastle, P.J., 1997. "Acoustic measurement of suspended sediments in turbulent currents and comparison with in-situ samples", J. Acoust. Soc. Am. 101(5), 2603-2614.

Thorne, P.D., and Hanes, D.M., 2002, "A review of acoustic measurements of small-scale sediment processes", Continental Shelf Research 22, 603-632.

Thorne, P.D. and Meral, R., 2008, Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport processes, Continental Shelf Research, 28, 2, 309-317.

Thosteson, E.D. and D.M. Hanes, 1998, A simplified method for determining sediment size and concentration from multiple frequency acoustic backscatter measurements, Journal Acoustic Society of America, 104 (2), 820-830.

Topping, D.J., Wright, S.A., Melis, T.S., and Rubin, D.M., 2007, High-resolution measurements of suspended-sediment concentration and grain size in the Colorado River in Grand Canyon using a multi-frequency acoustic system, in Proceedings of the 10th International Symposium on River Sedimentation. August 1–4, Moscow, Russia.

Urick, R.J., 1948, “The absorption of sound in suspensions of irregular particles”, J. Acoust. Soc. Am. 20(3), 283-289.

Wright, S.A., Topping, D.T., and Williams, C.A., 2010. Discriminating silt-and-clay from suspended-sand in rivers using side-looking profilers, Proceedings of the 2nd Joint Federal Interagency Sedimentation Conference, June 2010, Las Vegas NV.

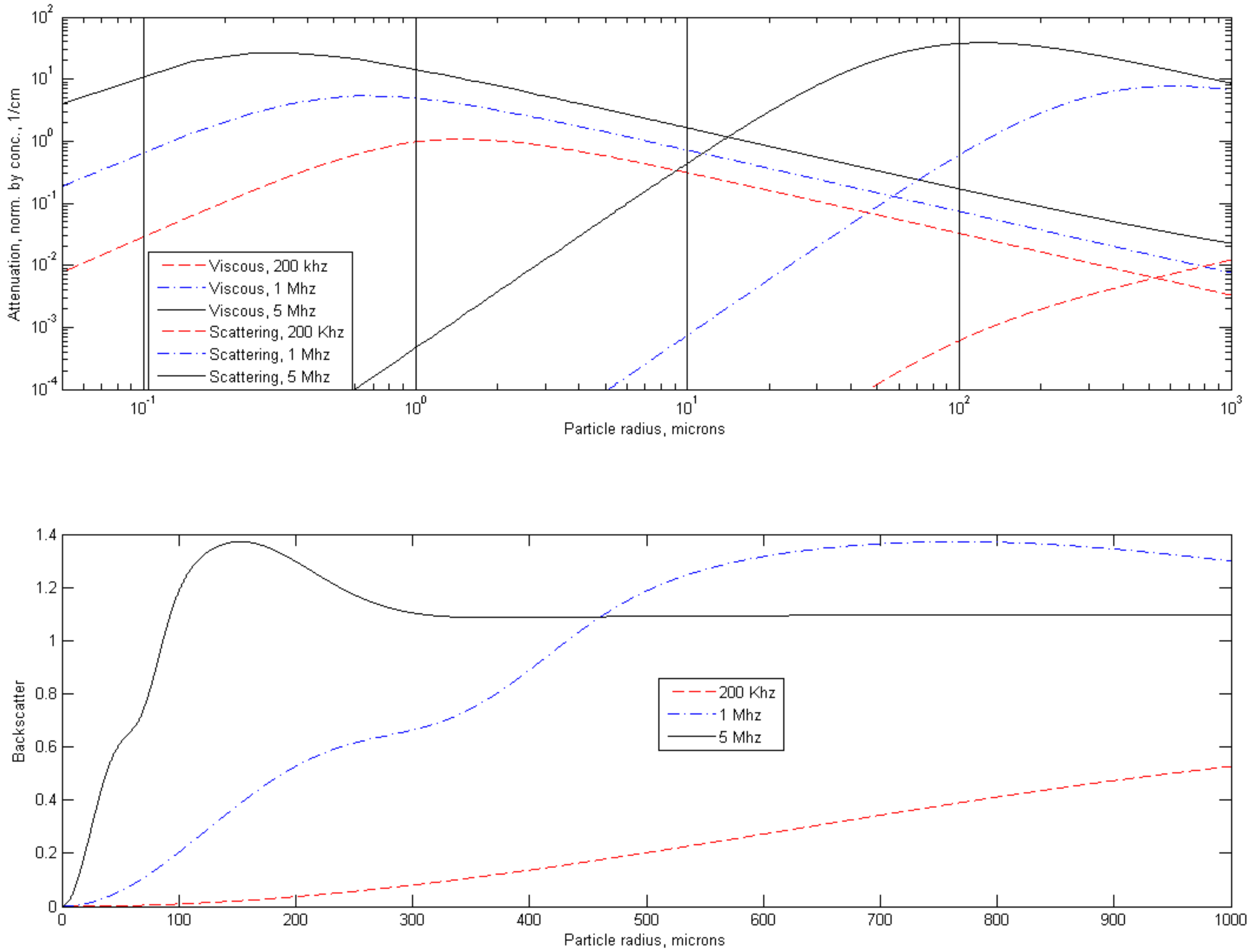

Figure 1: Upper: Normalized attenuation coefficients using Equations 2 and 3, as a function of particle radius. Lower: Backscatter form function (equation 4) as a function of particle size.