# MODELLING DOPPLER SONAR MEASUREMENT OF BEDLOAD TRANSPORT: WHAT EXACTLY ARE WE LOOKING AT?

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## 1 INTRODUCTION

Measurement of bedload transport in a field setting is challenging. Direct measurements are typically made using pressure-difference traps or pits requiring frequent user interactions or which will only provide time integrated measurements. Acoustic methods for sampling in the bottom boundary layer environment have significant advantages being non-invasive, robust and highly resolved in time. However, measurements close to the bed are challenging for acoustic systems because of transducer beam sidelobe interactions and large concentration gradients. Despite these potential issues, there have been several reports indicating that bedload transport can be measured using Doppler sonar systems[1,2,3]. Potential for this technique is further supported by several laboratory measurements[4,5].

Despite the demonstrations of correlation between acoustic measurements of bedload and independent measures (or estimates), it is not clear what is providing the signal or why this signal should in general correlate with bedload transport. This paper reports on efforts to model the acoustic backscatter from the bed with the goal of understanding the origins of those acoustic bedload measurements and of determining what exactly the signal represents.

## 2 ACOUSTIC MODEL

The acoustic model used in this study was developed to explore performance of Doppler sonar systems for near-shore sediment transport studies[6]. The model simulates acoustic targets (such as suspended sediment) as a distribution of discrete scatterers with the backscattered signal determined by summing over the contributions from the individual scatterers. The scatterers are moved through the model domain using a velocity structure that is defined in time and space. The concentration and target strength of the scatterers can be controlled to simulate particle concentration gradients and/or size differences. The model allows for a fairly general choice of acoustic sampling geometries including both monostatic and bistatic. For the present application, a single acoustic beam inclined at 20 degrees to the vertical is simulated as shown in Figure 1.

### 2.1 Acoustic Backscatter

The coherent backscatter model was originally developed for simulating velocity measurements and backscatter intensity was not a primary consideration. However, for the modelling of sediment transport (as opposed to simply particle velocities), backscatter becomes an essential component and there is then the need to validate the reconstructed signals.

The model determines backscatter intensity as:

$$B^2 = A^2 \int_r \int_\theta \int_\phi N\, D(\theta,\phi)^4\, \frac{e^{-4\alpha r}}{r^2} \sin\phi\, d\phi\, d\theta\, dr \quad (1)$$

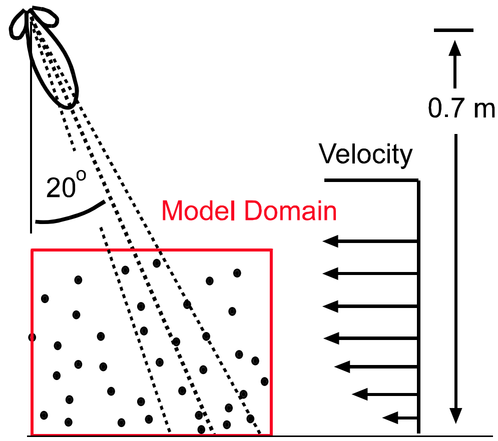


**Figure 1.** *Geometry of acoustic model.*

where, $A$ is the target strength accounting for target size, form factor, transmit strength and receiver sensitivity, $N$ is the number density of scatterers, $D$ is the transducer directivity, $\alpha$ the (range independent) attenuation coefficient, and $r, \theta$ and $\phi$ are spherical polar coordinates referenced to the acoustic beam axis.

For a given model configuration, there are two ways that backscatter intensity can be adjusted: the number of scatterers can change, or the backscatter contribution from each scatterer can change. Normally both concentration and size distribution will change with height above the bed with much higher concentrations close to the bed. For the model, this large increase in concentration introduces a problem because the simulation of large numbers of scatterers requires large amounts of computer processing time. Instead, the depth dependent target strength has been adjusted with a uniform concentration of scatterers. Figure 2 shows that at medium to high target concentrations there is an equivalence between these two approaches. However, when the concentration falls below that level where there is (on average) less than one scatterer present in a sample volume, the intensity response becomes effectively coherent and the two calibrations curves diverge. Target strength can be used to simulate changes in concentration so long as scatterer concentrations are adequately high so that this coherent response domain is avoided.

# 3 SEDIMENT MODEL

The acoustic model does not incorporate any fluid dynamic simulation and therefore requires a parametric description to generate concentration and velocity profiles. For this purpose, a combined bedload and suspended load model is adopted in which concentration and velocity above a defined bedload level ($z > h$), are given as[7]:

$$C(z) = C_h \left[\frac{(H-z)h}{(H-h)z}\right]^{w/\kappa u_*} \tag{2}$$

And

$$u(z) = \frac{u_*}{\kappa} \ln\left[\frac{z}{z_0}\right], \tag{3}$$

where, $C(z)$ is the concentration, $C_h = 0.05$ is the volumetric concentration at the top of the bedload layer at height $z = h$, $H$ is the height at which the concentration goes to 0, $w$ is the settling velocity of the sediment, $\kappa$ is the von Karman constant, $u_*$ is the friction velocity and $z_0$ is the bottom hydrodynamic roughness.

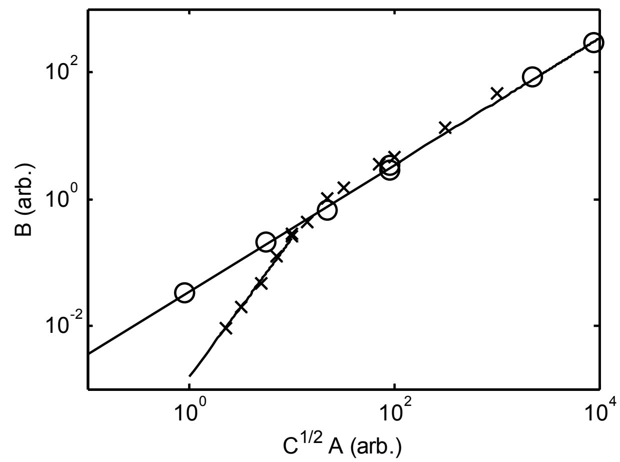


**Figure 2.** *Plot of modelled backscatter amplitude (B) against input concentration (C) and individual target strength (A), O's indicates data generated by varying target strength (A), and X's indicate results when varying concentration (C).*

Below the bedload level ($z < h$), concentration and velocity are given by[7]:

$$C(z) = C_0 - (C_0 - C_h)\frac{z}{h} \tag{4}$$

and

$$u(z) = u_h\sqrt{\frac{z}{h}}\,, \tag{5}$$

Where $C_0 = 0.65$ is the volumetric concentration at the bottom, and $u_h$ is the velocity at the top of the bedload layer set to match $u(h)$ in the suspended load (Equation 3) for a continuous profile.

The parameters available in the sediment model provide significant freedom to create representative profiles; not all possibilities are explored in this paper. The focus in this study is to understand how an acoustic system will respond to changes in the bedload thickness $h$, and for this purpose, the other parameters have been fixed with $z_0$ = 0.001 m, $u_*$ = 0.016 m/s, and $H$ = 2 m. An example of model profiles with a bedload layer of $h$ = 0.3 cm is shown in Figure 3. Also shown in Figure 3b are field observations of concentration that demonstrate the sediment model profile is reasonable.

## 3.1 Acoustic Sampling

At some distance above the bottom interface we anticipate that the (simulated) acoustic sampling should provide good representations of velocity and concentration profiles. Figure 4 shows profiles of velocity, concentration, and sediment flux determined from the model for the case of a 1-cm thick boundary layer sampled using a 10 µs acoustic pulse (providing a 7.5 mm range resolution). In the remainder of this paper, these and other model outputs are designated as acoustically "measured", or "measured", the quotation marks indicating that they are the values extracted from an acoustic scattering simulator. As expected, "measured" concentration and velocity (red x's) both match the model input values (blue line) beyond 2 cm above the bottom; flux here is also well measured. Details of the velocity and backscatter within 2 cm of the bottom are not resolved. It is important to note that the acoustic return provides values for both velocity and concentration at ranges beyond the bottom location. These values are clearly artifacts but they do contain information about the boundary and are included in subsequent transport calculations.

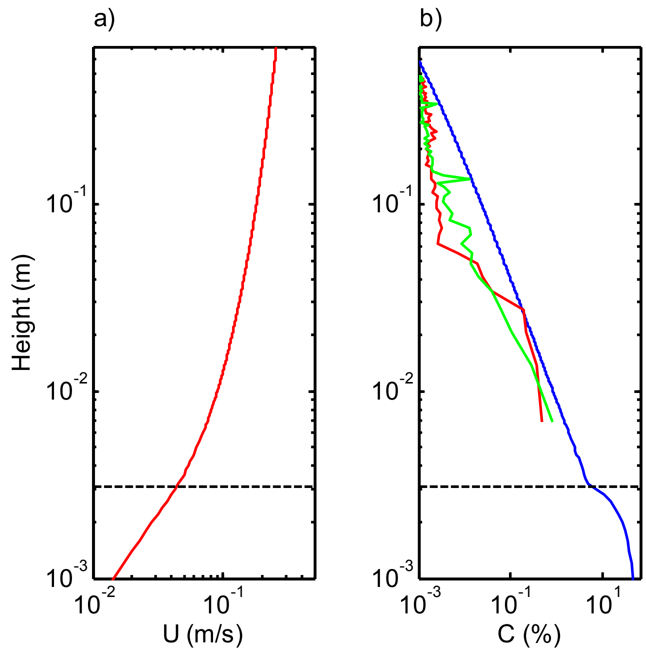


**Figure 3.** *Example velocity a) and volumetric concentration b) profiles. The dashed horizontal line identifies the top boundary of the bedload region ($z = h$). Example profiles of acoustically derived concentration from field trials (red and green lines in b) are included to demonstrate that the model profiles are reasonable.*

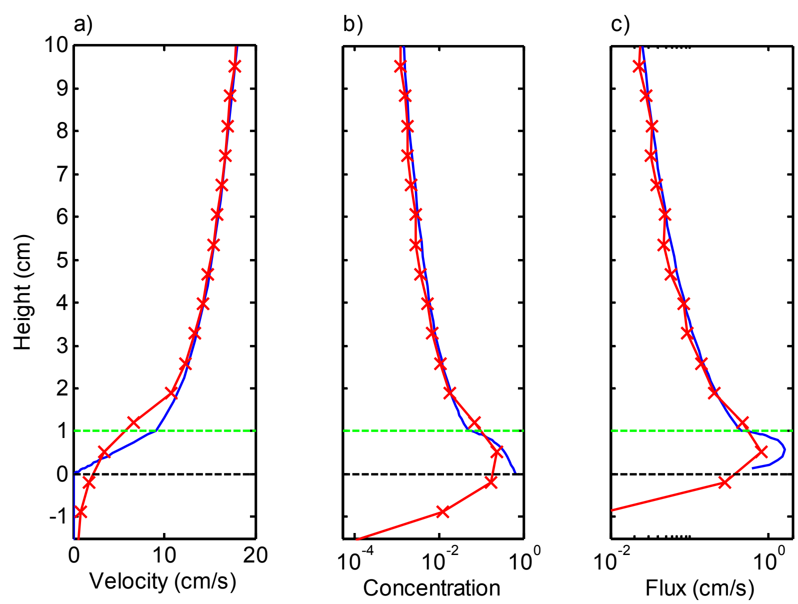


**Figure 4.** *Modeled profiles of a) velocity, b) volumetric concentration, and c) flux. Red x's are acoustically "measured" values, blue lines are input values, the dashed green line identifies the top of the bedload region and the dashed black line is the bottom (z=0 in the model).*

# 4 "MEASURED" TRANSPORT

"Measured" net transport was calculated by integrating over the simulated flux profiles. The acoustically "measured" values were compared to the input profiles of concentration and velocity. Trials were made for various free stream velocities using bedload thicknesses of 0.1, 0.3. 0.6, 1.0 and 2.0 cm. When measuring combined bedload and suspended load transport, the comparisons indicate excellent agreement as shown by the blue symbols in Figure 5.

For the total (bedload and suspended load) transport being modeled, suspended load constitutes between 15% and 50% of the total transport (depending on bedload thickness). At these relative contributions, even if the bedload were not measured at all, the agreement with total transport would appear reasonable on a logarithmic scale. The suspended load transport was removed from the model by setting concentration above the bedload to near 0 (some backscatter is required to retain velocity measurements). The same trials were repeated and results are shown using green symbols in Figure 5. Again, on a logarithmic scale the agreement is still very good.

## 4.1 Backscatter saturation

In practice, acoustic systems are limited in dynamic range and acoustic backscatter from high sediment concentrations are confounded by multiple scattering effects and high levels of attenuation. These factors inevitably impose a limit on the maximum sediment concentrations that can be measured acoustically. A simplistic way to simulate this limitation in the model is by clipping backscatter levels at concentrations greater than 3%. An example of how such an adjustment modifies the "measured" velocity is shown in Figure 6 for the case of the 1 cm thick bedload only model.

Figure 6a shows that when there is no suspended load, velocity "measurements" become biased toward zero to a height of about 5 cm (that is 6% of the depth below the transducer for the 20 degree transducer tilt angle considered); this bias is due to sidelobe effects. In models where there is (significant) suspended load, volume backscatter will provide a signal that will partially mask this contamination but it is never totally absent. For sediment transport measurements when there is little suspended load, this bias is not an issue because the bedload velocity itself is not contaminated. Note as well that clipping does not affect mean velocities far from the bed.

Concentration in the bedload layer is localized within the resolution of the transmitted pulse (x's in Figure 6b). As expected, the effect of clipping is to limit the maximum reported concentrations (o's in Figure 6b). The reduced concentrations result in flux profiles that substantially underestimate the true values (x's and o's respectively in Figure 6c). Despite this bias to low values, when profiles are integrated to estimate transport, the results retain a linear response: red and black symbols in Figure 5 show results for combined transport and bedload only transport when clipping has been applied.

## 4.2 Effective attenuation

The method of limiting signal levels to simulate limitations of backscatter "measurements" is rather artificial. A more accurate representation is to introduce an effective attenuation factor for the term $\alpha$ in Equation 1. This term can combine the effects of the frequency dependent sound absorption and the attenuation due to multiple scattering along the path length. This approach accounts for energy lost due to multiple scattering in high concentration sediment layers, without the computational burden of calculating the contribution of higher order scattering to the simulated return signal. In the simulations, a linear relationship between the mass concentration of the sediment and the attenuation coefficient was estimated[8] and combined with the sound absorption due to sea water along the path to give an effective attenuation for each scatterer.

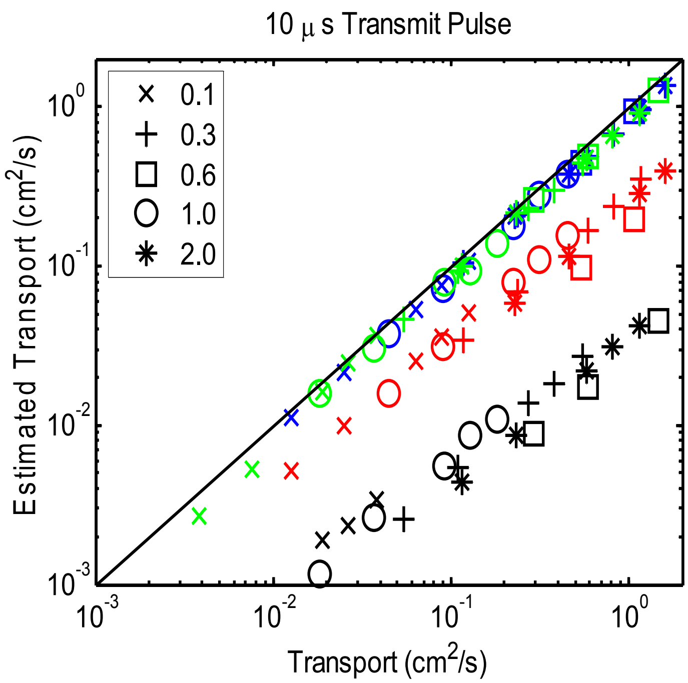


**Figure 5.** *Bedload thickness between 0.1 and 2.0 cm is indicated by symbols shown in legend. Blue, combined transport; green, bedload only; red combined transport with clipping; black, bedload only with clipping.*

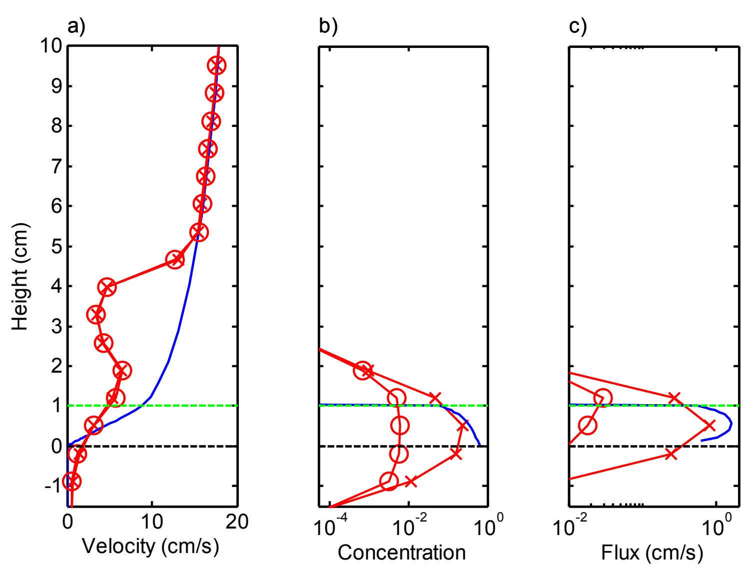


**Figure 6.** *Modeled profiles of a) velocity, b) volumetric concentration, and c) flux. Red x's and o's are acoustically "measured" values without and with clipping respectively. Blue lines are input values, the dashed green line identifies the top of the bedload region and the dashed black line is the bottom.*

### 4.3 Dual Frequency, bistatic mass transport estimate

A trial of the model using an effective attenuation term was run adding a dual frequency (1.7 and 3.4 MHz) simulation that allowed inversion of the mass concentration from the backscatter amplitudes using a dual frequency inversion scheme[9]. The advantage of this dual frequency inversion technique is that the mass concentration estimate at a given range is not dependent on an estimate at any other range, thereby removing the instability of an iterative single-frequency implicit inversion, which must simultaneously estimate the mass concentration and the effective attenuation at each range step before moving to the next. The results of the dual frequency inversion applied to the model's synthetic data are shown in Figure 7 as the red line with blue indicating the input concentration profile. In both the combined bed and suspended load case and the bedload-only case, the inversion does a reasonable job of returning the input mass concentration profile.

## 5 CONCLUSIONS

A model of suspended sediment concentration has been incorporated with a coherent Doppler sonar model and has been used to simulate "measurements" of suspended sediment and bedload transport. The model shows that for both combined bedload and suspended load or for bedload alone, accurate measurements are possible. Importantly, transducer sidelobe contamination which is clearly present in the model simulations does not appear to be a problem for the bedload measurement itself.

When a limit to the maximum measurable concentration is introduced, flux "measurements" become biased low but a linear response between "measured" and actual transport is still observed. This last result indicates that it would be possible to calibrate a system to overcome the limitation; however, any such calibration would depend on details of the sediment in question. Building on the simple approach of introducing a limit to measurable backscatter, the model was enhanced by using an effective attenuation coefficient combining both acoustic attenuation and multiple scattering contributions to acoustic energy loss. Simulated concentration profiles can reasonably be recovered from model backscatter using a two frequency inversion scheme.

The positive results from the present simulations are consistent with laboratory experiments[4,5] and field observations[2,3]. Future work will focus on understanding instrument specific limitations and sensitivities to the details of the velocity and concentration profiles.

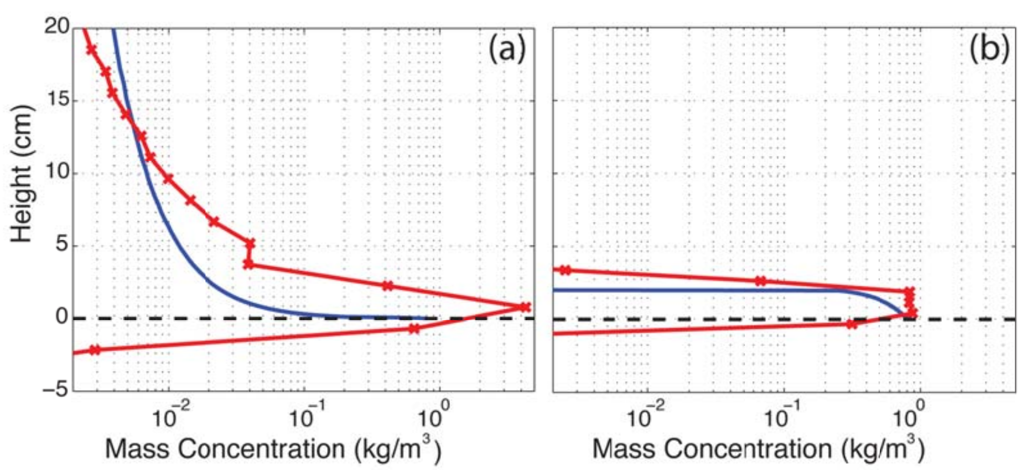


**Figure 7.** *Comparison of the model's input mass concentration profile (blue line) and the estimated mass concentration profile (red line) from a dual frequency (1.7 & 3.4 MHz) inversion for a) a suspended and bedload and b) bedload-only, above the bottom (dashed black line).*

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