Project Report: Estimating the size of the measurement volume for passive acoustic monitoring of Self-Generated Noise (SGN)

USDA-ARS-National Sedimentation Laboratory:
Daniel G. Wren
J. R. Rigby
Roger Kuhnle

University of Mississippi, National Center for Physical Acoustics:
Bradley Goodwiller
Brian Carpenter
Jim Chambers

Daniel Wren contact:
Watershed Physical Processes Research Unit, National Sedimentation Laboratory (NSL), USDA-ARS, Oxford, Mississippi, (662) 232-2926; Daniel.Wren@ars.usda.gov

Introduction

Passive acoustic technology has the potential to allow continuous measurement of bed load moving through streams. The technology is relatively economical and is amenable to automated operation. While the magnitude of recorded sound has been shown to be well-correlated with bedload transport (e.g. Thorne, 1985 and 1986; Barton, 2006), there is still a good deal of work needed before the technique can be used reliably in a variety of environments. A key need for its advancement is a procedure for estimating the measurement volume from which sounds are received (Figure 1). Continued development of SGN methodology is well-aligned with the FISP goals of improving technology for sediment measurement and development of indirect methods for measuring sediment transport.

During previous efforts to aid in quantification of bedload transport using Self-Generated Noise (SGN), it was found that little information on underwater sound propagation over rough beds in rivers was available. Most of the work that has been done in depths of a few meters or less was in support of bioacoustics research (e.g. Forrest et al., 1993; Forrest, 1994). Since the measurements were made in suitable habitat for certain aquatic animals, the beds were soft mud, which has different sound propagation characteristics from hard or rough beds. At the present, we do not know how different the propagation will be over rough beds of gravel, cobbles, or boulders. Without this knowledge, it is not possible to arrive at a reasonable estimate of the measurement volume of a hydrophone submerged in a stream. The development of SGN measures that may be quantitatively compared across reaches and watersheds has been stymied by the lack of a technique for obtaining even a rough estimate of the distance or volume from which SGN can be detected. There are several reasons why an estimate of the measurement volume is important in SGN measurement:

- As a step towards development of a general approach to converting SGN data into bedload flux
- To determine how much of stream is being monitored
- For planning number of instruments to place in channel
- For quantification of uncertainty and data quality

Even though high amplitude sounds originating from longer ranges can produce the same amplitude at a receiver as lower amplitude sounds originating from short distances, sound propagation characteristics and instrument parameters may be used to establish a maximum range from which sounds can be received. There are limits to the amplitude of sound generated by particle collision, and these will be a related to the bed material size distribution. By starting with an estimate of the highest amplitudes that are likely and combining this information with sound propagation and instrument parameters, an estimate of the measurement footprint can be established. Some of the parameters that will affect the size of the measurement volume follow:

- SGN properties
    - Amplitude
    - frequency
- Physical location
    - Channel geometry and composition
    - Bed material size distribution
    - Water depth
    - Bed roughness
    - Position of hydrophone in stream channel (i.e., side vs. middle)
- Hydrophone parameters
    - Frequency response (also affected by recording system)
    - Directivity
    - Noise floor
- Recording system
    - Noise floor (also affected by hydrophone)
- Multi-source interference (constructive and destructive interference)

This report summarizes efforts to measure sound propagation over beds with different levels of roughness. A direction for continued research, based on the results presented here, is also included.

Methods

A series of experiments where sound was propagated over beds of varying roughness was performed in a laboratory flume. A remotely operated pneumatic impactor (Figure 2) was built to provide repeatable, broadband, short duration sound (Figure 3). Sound propagation experiments were performed over the following bed types: redwood lattice; 35 mm gravel; 15 cm cobbles; and a mixture of gravel and cobbles. The test section, which was 8.5 m in length, was lined with 3 layers of redwood lattice on both the bottom and sides. Water depths can be seen in Table 1. The impactor was flush with the

substrate on the bottom, and it's first position was at the vertical redwood placed at the upstream end of the test section. For the gravel bed data collection, the impactor was moved approximately 5 cm before each measurement. The range was identified in post processing based on known positions of transducers and the speed of sound based on measured water temperature. For all other runs, the impactor was moved 25 cm for each data point, resulting in the following positions relative to the redwood boundary: 25, 50, 75, 100, 125, 150, 175, 200, 225, 275, 300, 325, 350, 375, and 400 cm. The piston impactor was approximately 3 cm above the bottom of the apparatus, and the redwood lattice on the bottom of the flume was approximately 7 cm thick. The gravel thickness was approximately 7 cm and the cobble thickness was approximately 15 cm. The mixed gravel/cobble bed was the same thickness as the cobble bed, since the gravel was not above the elevation of the cobbles at any point. The hydrophones were mounted, relative to the end of the redwood lattice section at 1, 2, 4, and 8 meters and were centered in the flume channel at approximately 10 cm above the bed. All acoustic data was recorded with RESON TC4013 hydrophones amplified by RESON E6061 preamplifiers. This signal was digitized by a National Instruments 9215 data acquisition module and recorded with a Labview script.

High resolution bed measurements were collected using a Micro-Epsilon 2700 LLT profiling laser that collected 640 discrete points along a line that varied from 76 mm long at a range of 300 mm and 148 mm long at a range of 600 mm (Figure 4). The vertical resolution was 15 μm for a Micro-Epsilon standard metallic diffusely reflecting object. The resolution on natural materials was lower, but measurements indicate that the vertical resolution was in the 100-200 μm range. The resulting data were irregularly sampled, due to the variable width of the laser profile with distance from the laser profiler, so the data were gridded at a horizontal resolution of 1 mm^2 using the ScatteredInterpolant function in Matlab. Elevation points that shared the same x,y coordinate due to overlapping scans were averaged. The final dataset had 1 mm resolution in the X and Y directions and at least comparable resolution in the vertical direction (Z direction).

Rough beds were constructed by placing either gravel (Figure 4, left), cobbles+gravel (Figure 5), or cobbles (Figure 6) over the redwood lattice on the flume bottom. In each case, the bed was scanned with the Micro-Epsilon laser system, resulting in root mean square (rms) roughness measurements shown in Table 2.

Basic theory

Sound spreading

Sound waves spread out from their source, causing, for any given point along the path travelled by the wave, a rapid loss in energy per unit area. For an unbounded case, sound travels in all directions, which is described as spherical spreading. The apparent Transmission Loss (TL) for spherical spreading is TL=20 log R, where R is range (Urick, 1975). For a shallow layer of large lateral extent, the upper and lower boundaries prevent spreading, but spreading is possible parallel to the boundaries, resulting in cylindrical spreading: TL=10 log R (Urick, 1975). This relationship will be altered, based on the characteristics of the stream bottom and the water surface roughness.

Furthermore, since streams are bounded at the sides, the geometry of the boundaries will play a role in determining how sound will propagate in a stream channel.

Frequency cutoff
Transmission loss is frequency dependent:

$$f_c = \frac{c_w}{4D\sqrt{1 - c_w^2 / c_s^2}}$$

where f_c=cutoff frequency, c_w=sound speed in water, c_s=sound speed in sediment and D= depth (Au and Hastings, 2008). Frequencies below f_c are sharply attenuated and propagate only over very short distances (Figure 7).

Detection threshold
The detection threshold can be understood in terms of the passive sonar equation:

SL-TL=NL-(DI-DT)

Where SL=source level, TL=transmission loss, NL=noise level, DI=directivity index, and DT=detection threshold.

The source level for SGN is dependent on the medium from which the sound originates and the mechanics of local flow causing particle movement. The work described here does not encompass an analysis of SL; we focused on sound propagation only. The directivity index and detection threshold are also functions of the electronic system and transducer; DI and DT can be found from specifications provided by manufacturers of equipment and can also be measured in controlled conditions. The NL in the stream is also an important variable that is in need of continuing research. The quantity NL-(DI-DT) must be less than SL-TL for sound to be detectable. The smallest detectable sound will be just larger than NL-(DI-DT).

Regardless of the source of sound, transmission loss in a stream is dependent on numerous factors, which can be divided into signal characteristics and environmental characteristics. The primary signal characteristics are amplitude and frequency. Environment factors include water depth, bottom roughness, bottom composition, water surface roughness, and channel geometry. Noise level is also an important characteristic that may influenced by both environmental and acoustic factors; NL will not be addressed in detail. The primary focus of this work was on the definition of TL for sound propagating in a shallow water environment with a rough bed.

Results

The primary result of this study is a set of measurements of sound propagation over a range of surface roughness in a laboratory flume. The basic measurement technique was described above, and the results of the measurements are summarized in Figure 8,

where it can be observed that amplitudes for rougher beds are lower than for smoother beds. This effect is due to scattering of sound in directions other than the direction of primary propagation. Both the sidewalls and the bottom play a role. It is also readily apparent that, for the small cross-sectional geometries typical of flume experiments, the effect of geometrical spreading described by spherical and cylindrical spreading models is minor compared to the effects of multiple-scattering from rough boundaries. Additional information, a measure of bed roughness in the case, was needed. In Figure 9, the relationship between the log slope of the transmission losses shown in Figure 8 and the rms roughness of the flume bottom (Table 2) is shown. The equation in the figure allows calculation of the coefficient for a simple spreading model. For example: for cobbles, loss was 0.22*31+17~24, so TL=24*log(R).

Caution should be used in the extension of the relation shown in Figure 9 to other environments. The geometry of the channel (in this case a rectangular flume) and the roughness of the walls (redwood lattice) both played important roles in determining how sound propagated along the channel. In earlier iterations of this work, an unlined flume was found to create a sound field that was dominated by nodal interference, making amplitude a weak function of distance or location in the flume; amplitude was controlled by the reverberation of sound from the smooth bottom and sides of the flume. Roughening the walls and bottom helped to alleviate the situation and created a less coherent sound field, where changes in amplitude with distance were clearly the result of transmission losses rather than nodal interference patterns.

Conclusions and Future Work

The propagation of sound was measured for three different bottom materials in a laboratory flume: gravel, cobble, cobble+gravel. It was found that, due to sound scattering, rougher beds resulted in greater losses in amplitude with distance. Assuming a logarithmic model for transmission losses with range, a predictive equation was determined for the multiplier.

Our experience in measuring sound propagation in a flume environment revealed the need for field measurements of propagation in streams with a range of channel geometry. The flume walls, being straight and parallel, are not a good representation of a typical stream channel geometry, which will tend toward a more trapezoidal shape, with banks sloping away from the channel. The effect of bank geometry may play a large role in determining how sound will propagate in a given channel. Bank geometry, bottom roughness, ambient noise, and instrument parameters will all have to be considered in predicting sound propagation in a channel.

Among the most important results of this work was the confirmation of the complexity of the sound field in a bounded channel. Some of the difficulties of making measurements in tanks are also discussed in Au and Hastings (2008). The reverberant sound field created in a laboratory flume is not a useful analog to natural channels, and creating anechoic conditions for the frequencies of interest (~3k-20k) would be prohibitively expensive because of the large scale of elements that would be needed to absorb the sound.

Future research aimed at a better understanding of the fluvial sound field should focus on field work geared toward measuring the attenuation of sound over range for a variety of channel geometries, roughnesses, and flow strengths. Preliminary measurements in a nearly quiescent shallow sand-bedded stream and fast-moving mountain stream revealed dramatically different measurement volumes. Sound travelled approximately 100 m in the sand-bedded stream with little attenuation, but the same sound, from the same electronic system, was undetectable at 5 meters in the rocky, fast-flowing mountain stream. This early result, combined with the laboratory measurements presented here, emphasizes the need for more field measurements that can be used to build up a database of propagation environments that can lead to a predictive relationship for sound propagation in fluvial environments.

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Table 1. Water depths for propagation testing.

Bed Type	Depth Label	Gage Reading (ft)	Nominal Depth (cm) above redwood	Nominal Depth (cm) above bed
Gravel	1	2.465	35.6	30.6
	2	2.765	44.8	39.8
	3	2.611	40.1	35.1
	4	2.314	31.0	26.0
Cobble	2	2.43	34.6	23.6
	3	2.587	39.4	28.4
	4	2.762	44.7	33.7
Mix	1	2.485	36.2	25.2
	2	2.635	40.8	29.8
	3	2.797	45.8	34.8
Redwood	1	2.477	36.0	36.0
	2	2.646	41.2	41.2
	3	2.75	44.3	44.3

Table 2. Material roughness, measured by Micro-Epsilon laser system:

Material:	Approximate rms roughness (mm):
Gravel	13
Cobbles	31
Cobbles+gravel	18
Redwood lattic	8

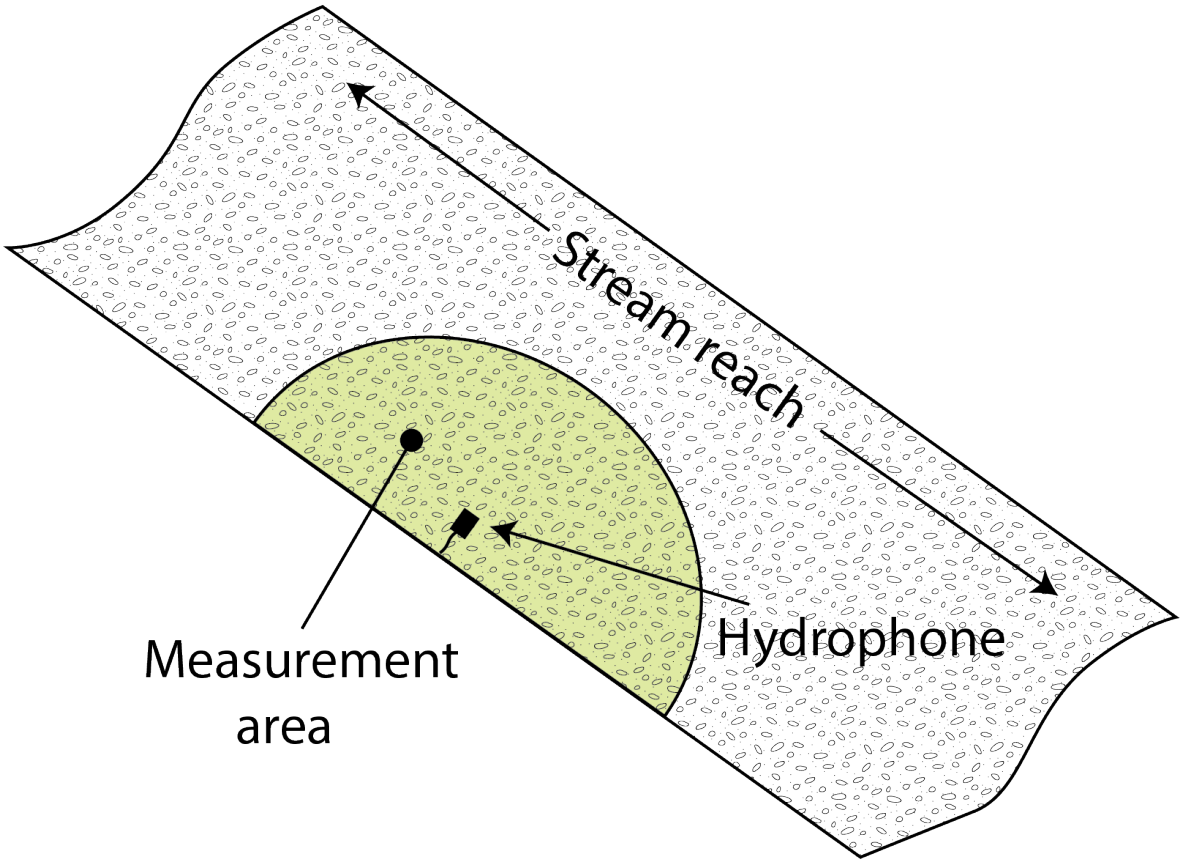

Figure 1. Schematic diagram of measurement area for a transducer deployed in a stream channel.

Figure 2. Piston impactor used in the propagation experiments.

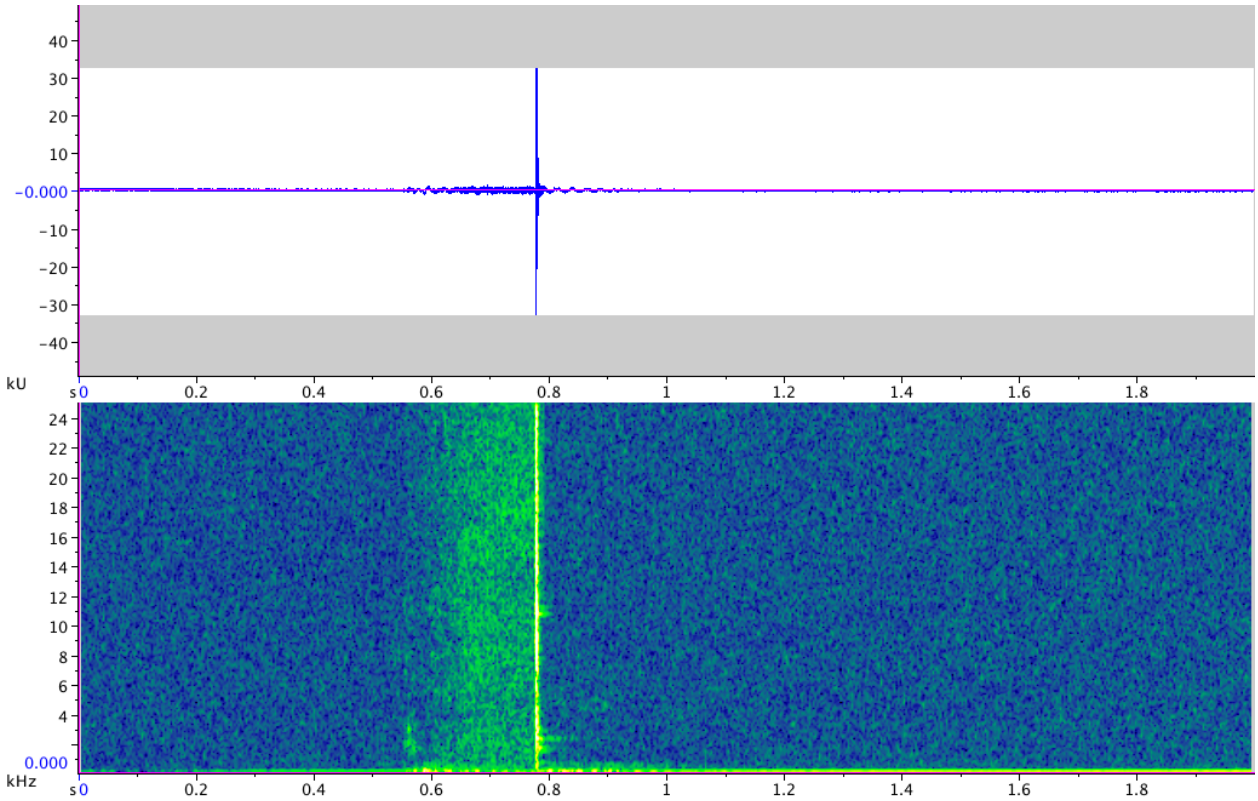

Figure 3. Signal (top) and spectrogram (bottom) of the acoustic impulse from the impactor used in the propagation experiments.

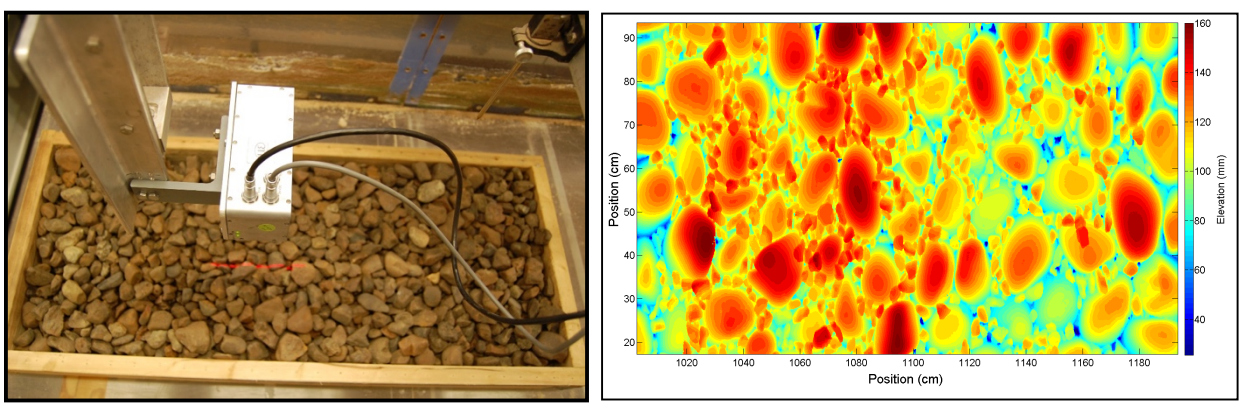

Figure 4. Micro-Epsilon laser (left) and an example of measured topopgraphy from the mixed cobble/gravel case (right).

Figure 5. Mixed cobble/gravel case.

Figure 6. Cobble bed, showing arrangement of hydrophones and redwood lattice.

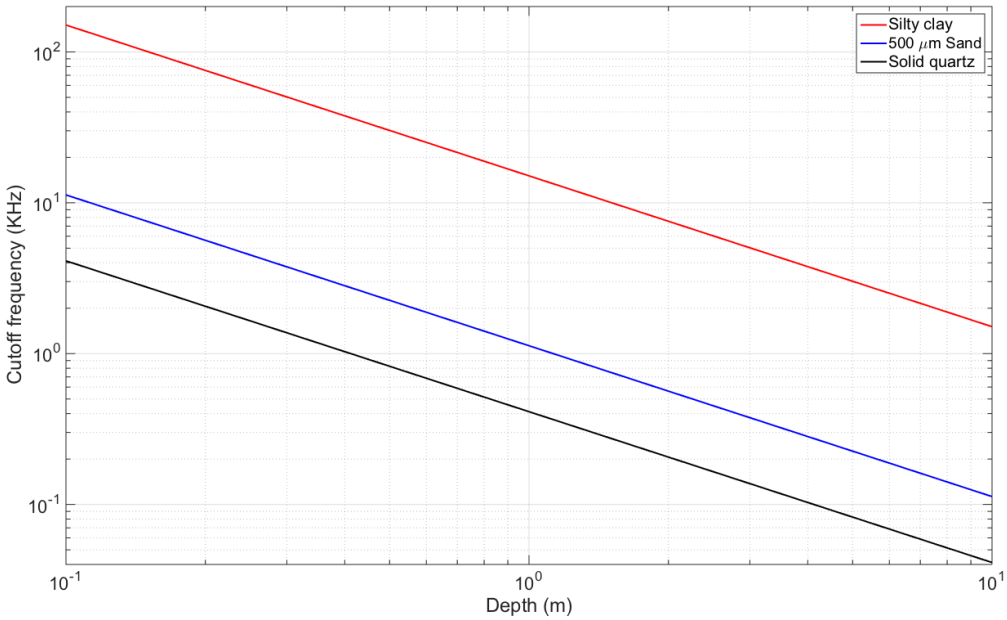

Figure 7. Cutoff frequency for sound propagating in water for three different bottom compositions.

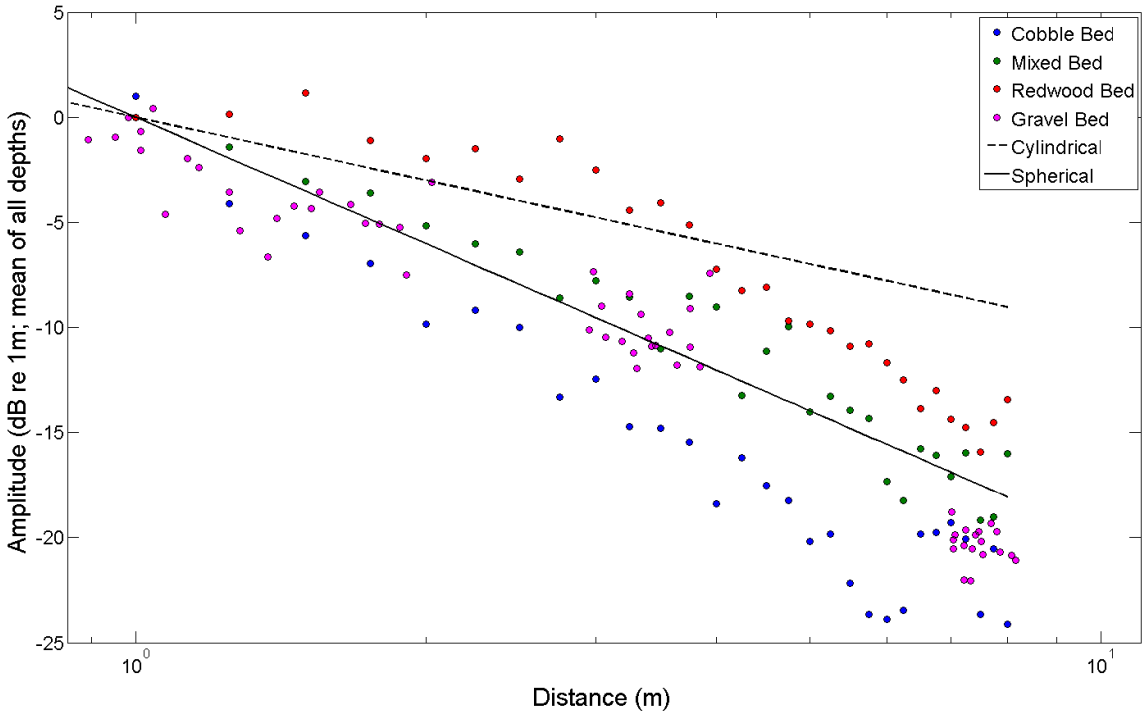

Figure 8. Sound propagation in a laboratory flume over beds with varying levels of roughness.

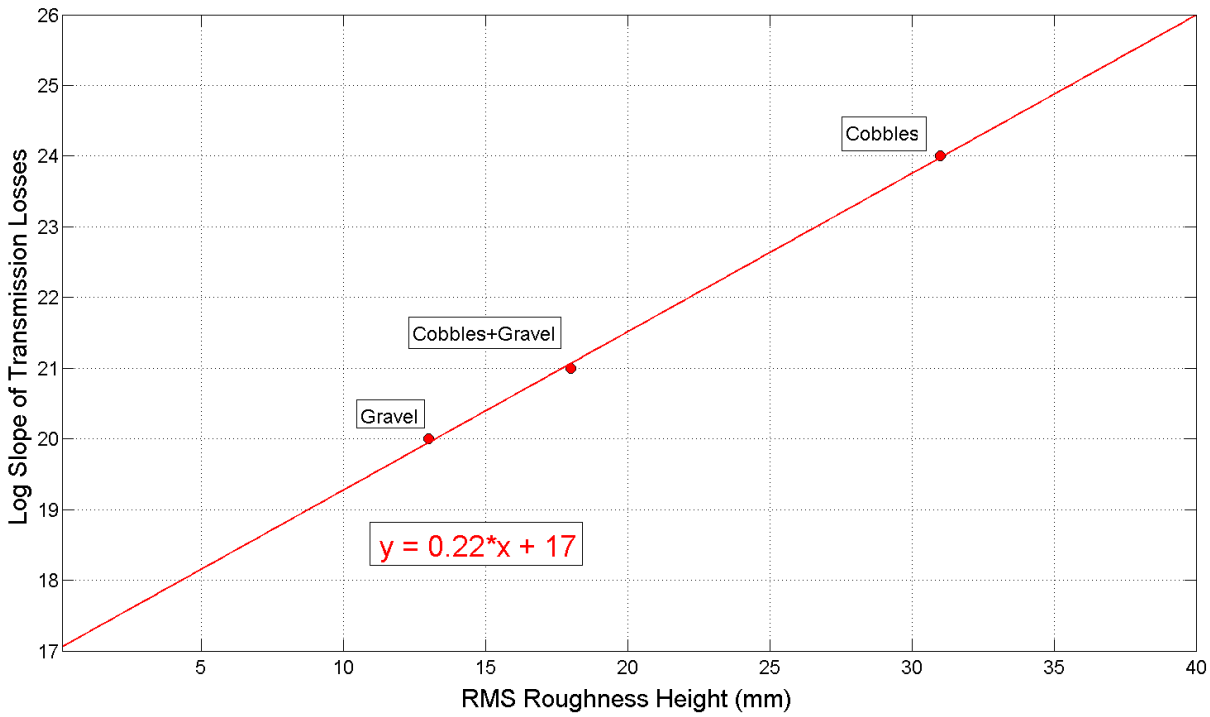

Figure 9. Relationship between the log slope of the transmission losses shown in Figure 8 and the rms roughness of the flume bottom.