

Observing Bedload/Suspended Load Using Multi-Frequency-Acoustic Backscatter

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Abstract

This paper describes the application of acoustic backscatter from multiple probes (1, 2 and 4 MHz) to investigate the spatial and temporal distribution of bedload and suspended load concentration in a small-scale laboratory flume experiment with a mobile sand-bed. The acoustic backscatter data are normalized to show the spatial pattern of suspended sediment concentration in relation to changes in the bed morphology as the bedforms migrate past the fixed measurement point. Each probe operates at a different acoustic frequency which results in different responses to near-bed sediment transport and suspended sediment transport. Results show a significant increase in sediment concentration upstream from each crest and reduction in sediment transport towards the trough. This pattern of sediment concentration suggests that sediment may be transported from the crest of the bedform into the main body of the flow, whilst periodic increases in transport near the base of the lee slope may reflect fluctuations in the reattachment point of the separation zone. The arrangement of multiple probes in a streamwise direction allows morphological data to be used to calculate the bedload transport rate which shows a strong correlation with the near-bed acoustic backscatter response from the highest frequency (4 MHz) probe. A single acoustic probe could be calibrated to quantify sediment concentration, but the spatial and temporal variability of the sediment transport observed at this scale means that multiple probes are unlikely to be suitable for measuring sediment size.

Introduction

Acoustics can be used to measure sediment transport at high spatial and temporal resolutions allowing the detailed structure of bedload and suspended load dynamics to be mapped (e.g. Crawford and Hay, 1993; Thorne and Hardcastle, 1997; Thorne and Hanes, 2002). This offers the potential to give an improved understanding of how bedload and suspended load transport mechanisms vary spatially and how these spatial differences relate to changes in bed morphology and flow structure. The basic principle of acoustic backscatter is to transmit a pulse of acoustic energy (typically in the range 0.5-5 MHz) from one or more directional sound transducer(s) mounted at a distance above the bed. As the pulse spreads away from the transducer, it insonifies any suspended material in the water column which scatters sound energy leading to attenuation of the signal. Some of the sound energy is reflected by particles and this reflected sound energy is detected by the transducer which also acts as a receiver.

If the speed of sound is known, the received signal can be gated so that the distance of the received signal from the transducer can be calculated. The scattering strength of the suspended material and the sound propagation characteristics of the sediment can then be used to develop relationships between the intensity of the received echoes and the characteristics of the sediment producing the reflected signal.

This paper explores how acoustics may be used to distinguish the spatial distribution of suspended sediment concentration over mobile bedforms in a small-scale flume experiment. Although it is possible to use the acoustic backscatter data to measure sediment concentration and particle size when using multiple acoustic frequencies, this approach is not adopted since the spatial separation of the probes is large compared to the spatial variability of the suspended sediment concentration. However, the use of multiple probes arranged in a streamwise direction does allow the migration rate of bedforms to be measured, which can be used to calculate the transport rate from the morphological data collected. This paper will also investigate how the different frequencies respond to sediment transport to evaluate the spatial and temporal changes in sediment transport dynamics for both bedload and suspended load over a number of migrating bedforms.

Methodology

Experimental set-up

Experiments were conducted in a recirculating flume in the Department of Geography, University of Hull. The flume is 0.3 m wide and the average flow depth was 0.15 m. The flow rate was set to give an average flow velocity of 0.5 ms^{-1} with a mean bed shear stress of $\sim 2 \text{ Nm}^{-2}$ and average water surface slope of 0.0025. The working section is approximately 7 m long and measurements were taken from the centre of the working section. Washed sand was used as sediment with a mean grain diameter of 0.48 mm and a standard deviation of 0.12 mm. Water and sediment were recirculated and the flume was operated continuously for several days before measurements were taken allowing the bed to equilibrate.

For this study, the three transducers were oriented vertically and located in a line parallel to the streamwise direction. The probes were mounted immediately below the water surface ($\sim 5 \text{ mm}$) facing towards the bed of the flume and close to each other (with a separation of 0.03 m between each probe in the streamwise direction – see Figure 1). The probes were operated with a gain of 9dB to avoid saturation of the signal due to the strong acoustic reflections from the bed surface, which is relatively close to the transducers.



Figure 1. Picture showing the probe set-up in the flume. The three transducers are mounted linearly as close as physically possible.

The system described in this paper is a commercially available device known as the *AquascatTM*, manufactured by *Aquatec Group Ltd, UK* (<http://www.aquatecgroup.com>). The device consists of three transducers, each operating at a different frequency, with a control module that incorporates the signal processing system and a data logger. To minimize the effects on water flow in the vicinity of the measurement area, the acoustic transducers are mounted remotely from the main instrument housing and attached by 4 m cables to the controller module. The three-frequencies of this system are 1, 2 and 4 MHz and each transducer operates both as a transmitter and as a receiver. The signal from each transducer is processed using a tuned amplifier and transformer and can be operated with variable gain

over distance to compensate for the decrease in received signal intensity due to geometrical spreading losses and attenuation due to absorption. The received signal is detected and filtered to attenuate high frequencies and to avoid aliasing of the signal when sampled by the controller (Smerdon et al. 2004). Table 1 gives details of the system costs.

Table 1. Approximate costs of system components in (excluding taxes) in 2004 (UK pounds).

Component	Cost
Aquascat system	18,000
Transducers	900 (each)
High resolution firmware	500
Temperature probe	500

A 12-bit analogue-to-digital converter is used for data acquisition (Smerdon et al. 2004). Acoustic transmission is triggered in a sequence that commences by setting the first transmission frequency, then in rapid succession, initiating transmissions on each of the three frequencies. Following each acoustic transmission, the received signal (reflected sound) is sampled at up to 128 range gates which have a vertical resolution of at least 2.5 mm allowing the device to measure a profile of 0.32 m or longer. Profiles can be sampled at rates of either 80, 64, 40 or 32 Hz by varying the ping rate (frequency of acoustic pulse transmissions) and these profiles can be averaged to reduce measurement uncertainty. The system settings and logging operation are controlled by proprietary software that runs on a separate computer and communicates with the controller/logger via USB. The entire system is field portable and can be operated with a 12V power supply.

Data Processing

The purpose of this paper is to evaluate the ability of the acoustic backscatter technique to determine the spatial and temporal distribution of bedload and suspended sediment transport dynamics. The data have not been calibrated to quantify either sediment concentration and/or size. The data will therefore be analyzed in terms of the root mean square voltage (V) response which is proportional to the concentration and/or size of the sediment. However the acoustic signal is also affected by attenuation both due to water and transported sediment and by beam spreading which would be relatively small over the short distances involved. The output (V) is proportional to the rms of the backscatter pressure amplitude (Lee and Hanes, 1995). Thorne and Hardcastle (1997) show that:

$$V = \frac{K_s K_t}{r \psi(r)} S_c^{\frac{1}{2}} e^{-2\alpha r} \quad \text{Equation 1}$$

where

$$K_s = \frac{f}{\sqrt{\rho_s a}} \quad \text{Equation 2}$$

K_t is a system calibration constant, r is the distance from the transducer, $\psi(r)$ is a range modification factor accounting for non-spherical spreading close to the transducer, S_c is sediment concentration and α is the attenuation due to water and sediment. K_s relates to the properties of the scattering particles where f is the form factor which is related to particle size, ρ_s is the sediment size and a is the mean particle radius.

Data were collected using a system sampling rate of 64 Hz with an internal averaging of 32 samples such that the output data were collected at 2 Hz. Samples were taken in 2.5 mm bins starting 0.06 m from the transducer head. Samples were taken for a period of 120 minutes. These data were thereafter processed in two stages. First the bed height is identified from the maximum V measured which corresponds to the highest intensity of backscatter representing the bed surface. Second, in order to remove the effects of attenuation and beam spreading the complete time series (of n measurements) was used to calculate the average root mean square voltage (\bar{V}_z) for a given distance (z) above the bed surface

$$\bar{V}_z = \frac{\sum_1^n V_z}{n} \quad \text{Equation 3}$$

This yields the average acoustic signal for a given distance from the bed and then for each measurement, the fluctuation in root mean square voltage (V_z') relative to the mean at that height above was then normalized by dividing by the average at that height:

$$V_z' = \frac{V_z - \bar{V}_z}{\bar{V}_z} \quad \text{Equation 4}$$

This removes the effect of attenuation and beam spreading, but also removes all information about the variation with depth of particle size and concentration, retaining the variation over time. V_z' therefore shows the fluctuations in the concentration and/or size of sediment over time at a given height above the bed. However, since the sediment used was well-sorted (see above) with a narrow grain size distribution it is expected that variations in concentration are likely to be more significant than variations in sediment size. Due to the passage of bedforms below it is, therefore, possible to identify the temporal fluctuations of bedload material and suspended sediment concentration associated with changes in bed elevation over each bedform.

Libicki et al. (1989) identified the need to consider configurational noise due to the random distribution of phase returns from a homogeneous suspension. Thorne and Hardcastle (1997) suggest that to obtain 5% standard error in the measurement of V requires approximately 100 independent measurements, i.e.

$$\sigma(V) = \frac{V_{RMS}}{2\sqrt{n}} \quad \text{Equation 5}$$

Normally this requires further averaging in addition to the temporal averaging undertaken at the time of logging (Thorne and Hardcastle, 1997). For the 32 independent measurements obtained at 2Hz, the standard error of the collected raw data is approximately 11% therefore further temporal averaging is necessary to reduce the noise of the data.

Results

Bed morphology

The bed elevation is measured as the bin that returns the maximum V . Since the spacing between the transducers is known, it is possible to correlate the lagged bed height measurement between probes to calculate the average rate of bedform migration. Table 2 shows the lag time that gives the

maximum correlation coefficient for three different probe combinations. From this, the equivalent bedform migration rate is calculated, giving an average bedform migration of $4.6 \times 10^{-4} \text{ ms}^{-1}$.

Table 2. Bedform migration rates calculated from lagged data.

Probes	Distance between probes (m)	Lag Time (s)	Correlation coefficient (r^2)	Migration rate ($\times 10^{-4} \text{ ms}^{-1}$)
Probe 3 to Probe 1	0.06	133	0.8672	4.5
Probe 3 to Probe 2	0.03	61	0.9495	4.9
Probe 2 to Probe 1	0.03	67.5	0.8857	4.6

For a single measurement, the bed elevation is given to the nearest 2.5 mm which is the vertical extent of the measurement bins. To analyze the data, bed elevations were averaged over a period equivalent to a distance traveled of approximately 0.01m which is equivalent to averaging over 21.5 seconds. Figure 2 shows the bed profiles with the mean bedform migration rate being used to shift the time series to measure co-incident points of the bedform. The average bedform height measured using probe 1 is approximately 5 mm lower than for probes 2 and 3 (Table 3). Experiments carried out in still water with no sediment transport show that the different frequency probes show no more than a 0.5 mm difference in average bed elevation. This suggests that either the higher frequency transducers (probes 2 and 3) are not able to detect the true bed level due to higher sediment concentrations in a layer above the bed or that the lower frequency transducer (probe 1) penetrates the bed when sediment is being transported and measures below the true bed level.

Table 3. Bed elevation statistics for each probe. The average error range is the average of 95% confidence interval for the prediction of the mean bed height for each 1 cm unit of the bed.

Probes	Average bed elevation (mm)	Average Error range (mm)
Probe 1 (1 MHz)	60.46	± 0.98
Probe 2 (2 MHz)	65.13	± 0.47
Probe 3 (4 MHz)	65.64	± 0.33

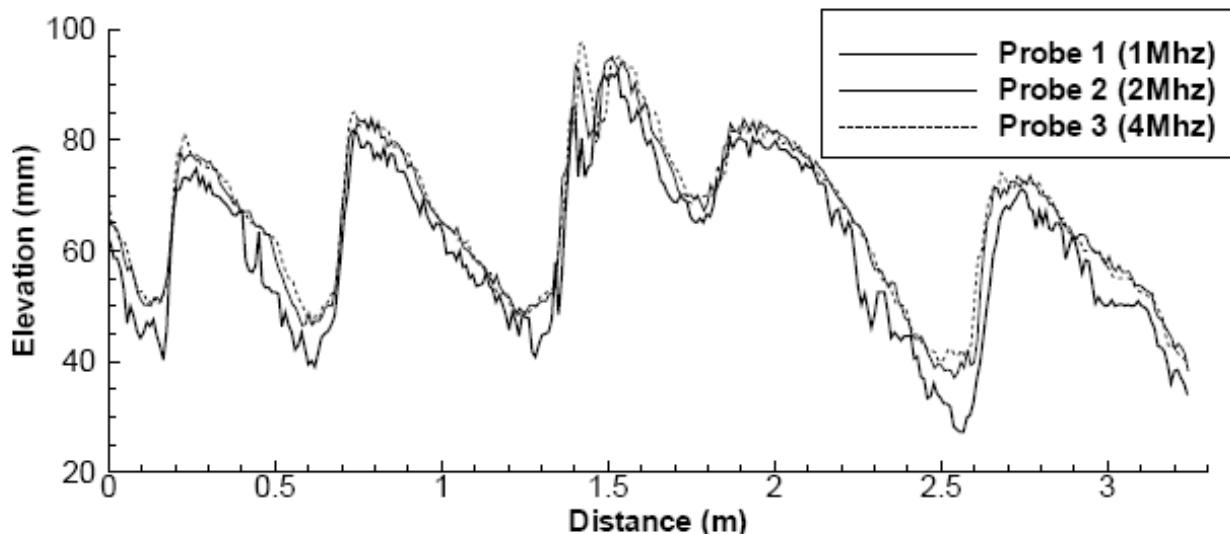


Figure 2. Bed profile measured by each probe. Data are averaged over a time period representing 1cm of movement and offset to account for the different probe positions

Spatial Distribution of Bedload Transport

If there is any variation in particle size, it is most likely to occur near the bed which may result in a different response from the higher and lower frequency transducers (the lowest frequency being more sensitive to larger sized sediment and *vice versa* for the higher frequency transducer). Hence, it can be assumed that the lower frequency probe will be most sensitive to the largest sediment which is likely to be transported as bedload and the first measurement bin above the bed should give the best representation of the variation of sediment concentration in the near-bed region, unless this probe returns measurements from below the bed surface. The acoustic data were averaged over the same period as the bed morphology data (21.5 seconds) which gives an estimated standard error of 1.3% from Equation 5. Figure 3 shows the distribution of sediment concentration detected by probe 1 in the layer immediately above the bed (the measurement bin immediately above the bin in which the maximum V is measured). There is considerable temporal fluctuation in the acoustic signal and the fluctuations above and below the mean value show limited correlation ($r^2 = 0.13$) to the bed topography. The most notable feature is that for most bedforms the sediment concentration peaks before the crest of that bedform and then shows a significant decrease towards the base of the lee slope of the bedform. Given the poor correlation between the bed morphology and the sediment concentration measurements it suggests that these measurements are potentially of limited use for understanding bedload transport and that they may be dominated by erroneous surface or sub-surface acoustic reflections.

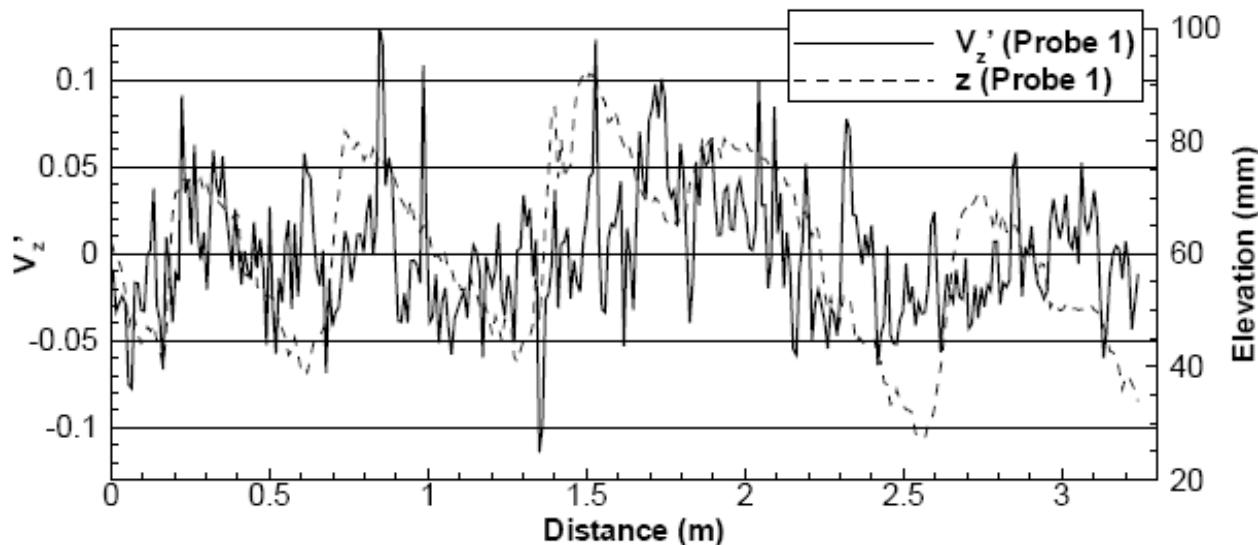


Figure 3. Sediment transport measured by probe 1 in the bin immediately above the detected bed surface. The bed profile measured by probe 1 is also shown.

Probe 3 uses the highest acoustic frequency and detects the bed with an elevation 5 mm greater than probe 1 (as described above). Figure 4 shows the variation in sediment concentration detected by probe 3 at the height where the maximum V is measured by probe 3. This is approximately 5 mm above the bed height detected by probe 1. There is a very noticeable correlation ($r^2 = 0.72$) between the bed elevation and the sediment concentration with concentrations that are greater than the mean occurring towards the crest of the bedform and concentrations that are lower than the mean in the troughs of the bedforms.

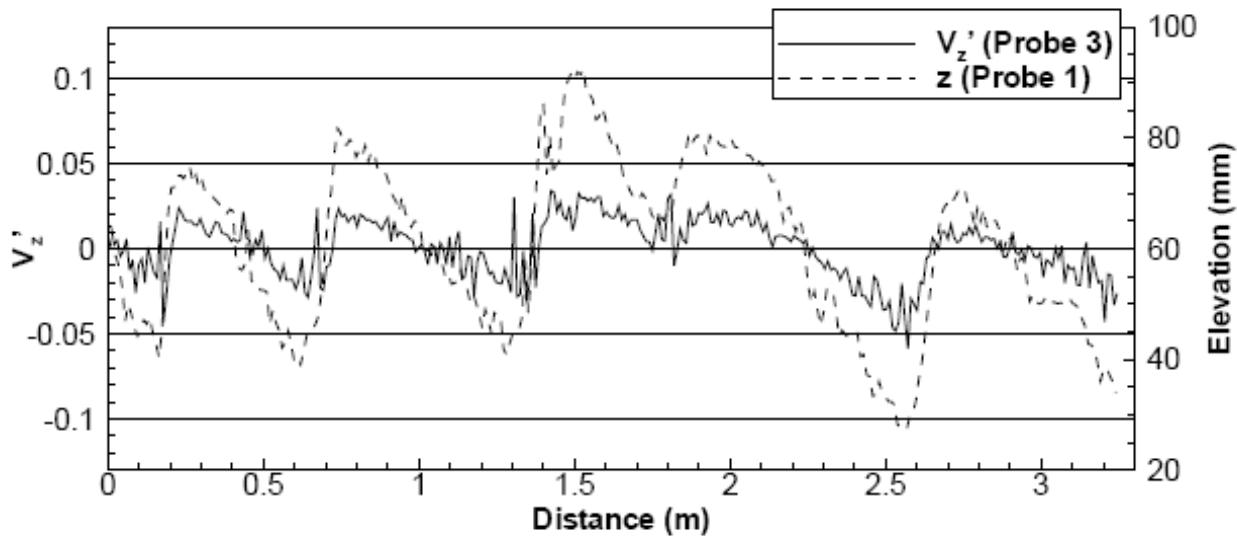


Figure 4. Sediment transport measured by probe 3 in the lowest measured bin. The bed profile measured by probe 1 is also shown.

The instantaneous bedload transport rate at a specific point ($q_b(x,t)$) can be estimated from the bedform morphology using the following equation:

$$q_b(x,t) = c(z(x,t) - z_0) \quad \text{Equation 6}$$

where c is the migration rate of the bedform $z(x,t)$ is the bed elevation and z_0 is the height of the bedform where $q_b(x,t) = 0$ (e.g. Hoekstra et al., 2004; Engel and Lau, 1980). It can be assumed that z_0 is the average bed height. Figures 5A and B shows the relationship between $q_b(x,t)$ and the sediment concentration measured by probes 1 and 3. There is a poor fit between the instantaneous bedload transport calculated from the bedform morphology and the sediment concentration detected by probe 1 (Figure 5A) which suggests that this frequency is not well-suited to measurement of the transport rate near the bed. In contrast there is a strong relationship between the sediment concentration measured by probe 3 and the morphological estimate of the bedload transport rate (Figure 5B), indicating that either it is measuring the concentration of the bedload transport layer or that the near-bed suspended sediment concentration shows a strong correlation to the bedload transport rate.

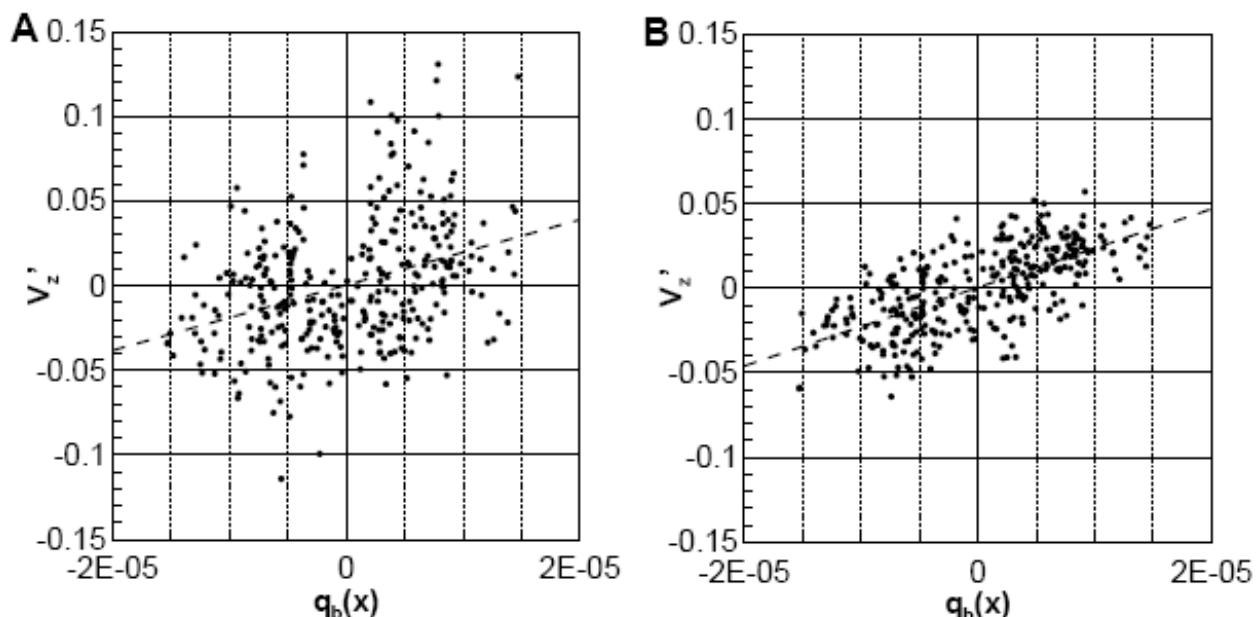


Figure 5A & B. Comparison of sediment transport rate calculated using morphological data ($q_b(x)$) with sediment transport measured by (a) probe 1 and (b) probe 3. The lines shown are calculated from linear regression and have an r^2 of 0.13 and 0.72 for probes 1 and 3 respectively. Data from probes 1 and 3 are taken from same location relative to bed as shown in Figures 3 and 4 respectively.

Spatial distribution of Suspended Sediment Concentration

Figures 6A, B and C show the temporal and spatial distribution of backscatter deviation for each of the three probes. It would appear that probe 1 is most sensitive to changes near the bed and clearly shows pulses of higher sediment concentration near the bed. There is a noticeable increase in concentration immediately on the lee slope of each bedform. Probes 2 and 3 appear to show higher sediment concentration above the crests and lower sediment transport in the trough regions. Sediment concentration detected by probe 3 in the lee of the bedforms is noticeably different from that shown by

probe 1. The data from probe 3 show that an area of higher sediment concentration separates from the bed and is carried some distance downstream from the bedform crest, whilst the increase in sediment concentration detected by probe 1 remains close to the bed surface. There are smaller fluctuations in suspended sediment concentrations over the last bedform measured compared to the earlier bedforms. Figure 7 shows the first three bedforms in more detail with the measurements taken by probe 3. This clearly shows a significant increase in concentration in the lee of the bedform crest which appears to show pulses of higher sediment transport downstream from the dune crest and a significant reduction in concentration towards the base of the trough.

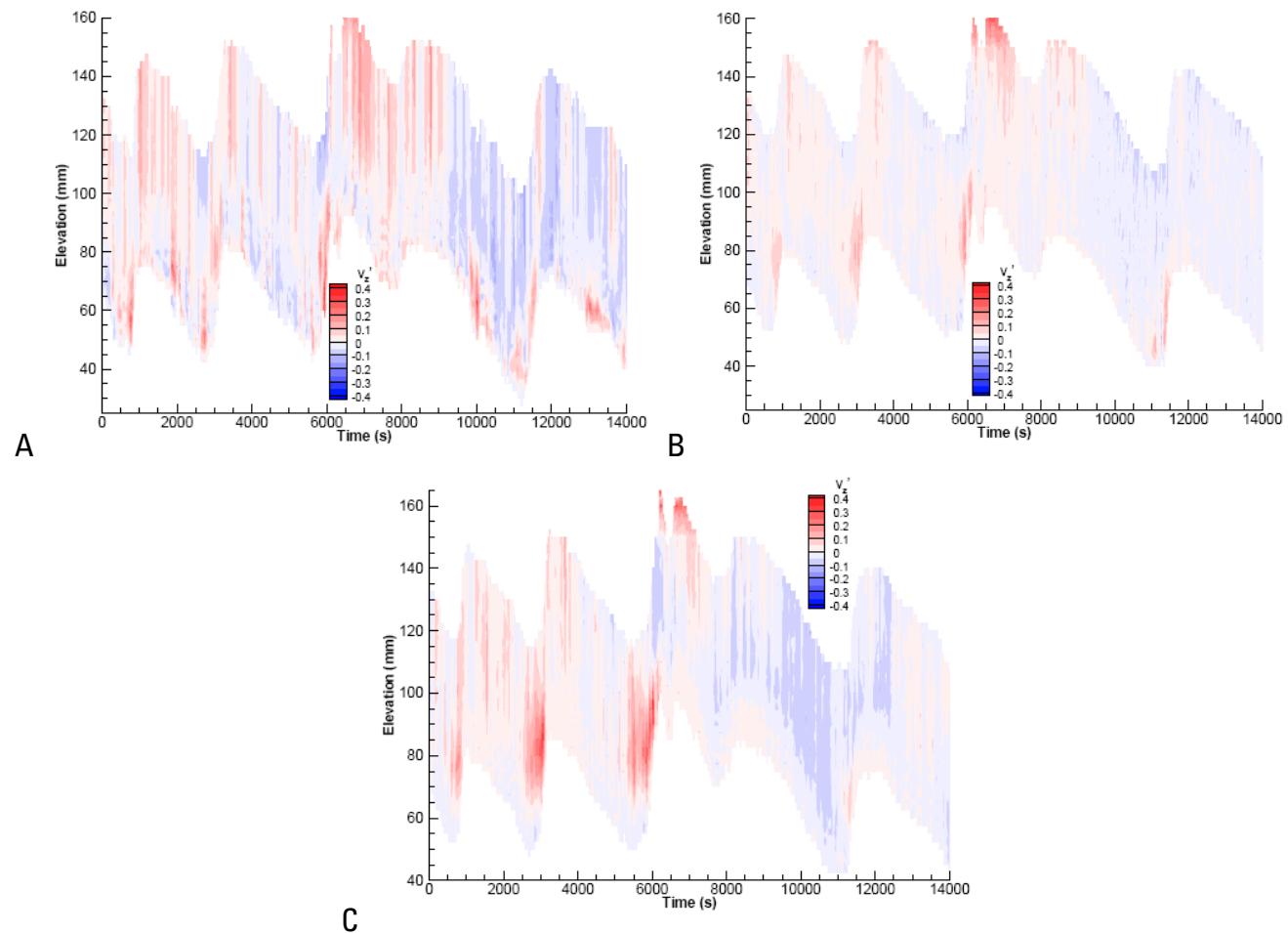


Figure 6 A, B & C. Contour plots showing sediment transport measured by probe 1 (A), probe 2 (B) and probe 3 (C). Data are shown only for the bins where there is a complete record through the entire time series. Bedform is shown by grey shaded area. Note that the fluctuations are normalized such that variations in sediment transport with height are removed.

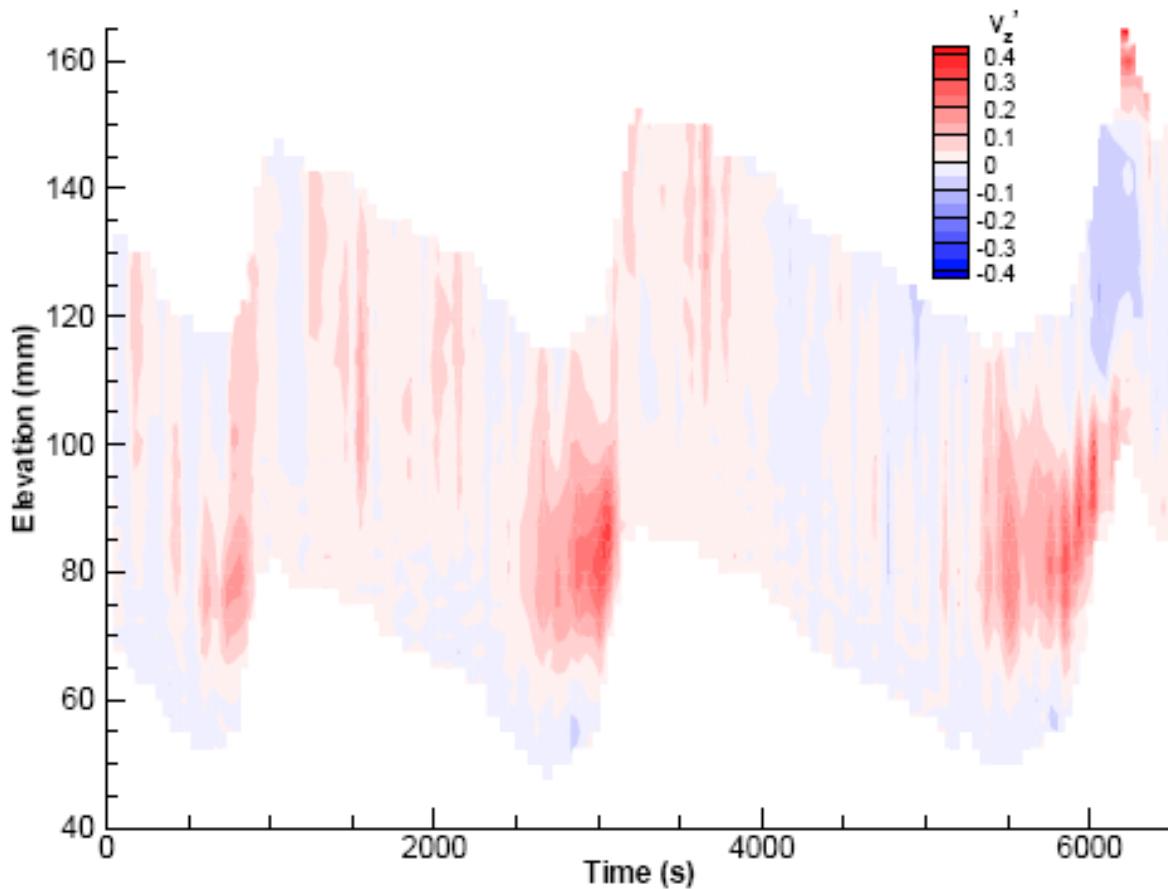


Figure 7. Detail showing the first three bedforms shown in Figure 6C.

Discussion and Summary of Technique

Acoustic backscatter profiling appears to have considerable potential for identifying spatial and temporal fluctuations in sediment concentration over bedforms. The morphological data that are obtained show the detailed structure of the passage of bedforms which can be used to obtain the bedform migration rate from multiple probes. This allows the bedload transport rate to be calculated based on the rate of sediment transport per unit width of the flume. Indeed, this shows very good correlation with the higher frequency measurement of the sediment transport in the near-bed layer which may have some potential for calibrating the results. There is not a clear relationship between the sediment transport detected just above the bed by the lowest frequency probe suggesting that either this signal is affected by noise from surface or below-bed acoustic reflections or that sediment transport in this region is discontinuous and is affected by short-time scale variations in flow properties such as turbulent events. Significant peaks in sediment transport occur ‘upstream’ from each crest and there is a marked decrease towards the trough. Downstream from the base of the lee slope there are periodic increases in transport which may reflect fluctuations in the reattachment point (e.g. Bennett and Best, 1996, Ha and Chough, 2003).

The spatial distribution of the acoustic response shows the structure of sediment concentration over several bedforms (Figure 6). The spatial distribution of the fluctuations in the acoustic signal show greater sediment concentration over the stoss slopes where flow is accelerated and reduced sediment concentrations in the trough regions which is similar to the pattern of sediment concentration measured by Kostaschuk and Villard (1999) using a pump sampling system. Regions of higher sediment concentrations in the lee of the bedform are detected by the high frequency probe; these regions are detached from the bed as shown by the relatively low sediment concentrations towards the base of the bedform trough (Figure 7). This suggests that sediment may be transported from the crest of the bedform into the main body of the flow. This may reflect the detachment of particles from the bed at the bedform crest, in a process similar to that shown by Ha and Cough (2003) based on motion picture analysis. Kostaschuk and Villard (1999) also demonstrated the presence of strongly intermittent suspension events using an acoustic profiler, which is similar to the fluctuations in higher sediment concentration downstream from the crest of the bedform. The latter also show some periodicity that may reflect turbulent fluctuations in the shear layer development. These suspension structures and intermittent increases in sediment entrainment have been associated with turbulent ejections forming at the bedform crest (e.g. Kostachuk and Villard, 1999). The near-bed sediment transport shown by the high frequency probe also shows a significant increase in transport on the stoss slope (Figure 4) which may reflect the entrainment of sediment at the point of reattachment of the separation zone (e.g. Bennett and Best, 1996, Kostaschuk and Villard, 1999, Ha and Chough, 2003).

The use of multiple probes allows rapid calculation of morphologically-based transport rate. However, further work needs to be carried out to calibrate the system to quantify the spatial and temporal characteristics of suspended sediment transport. This is likely to be possible in terms of calculating sediment concentration which can be quantified using a single frequency; however the spatial separation of the probes means that it is unlikely to be suitable for determining sediment size variations at this scale. Due to the small distance of the bed surface from the probe, the acoustic signal returned from the bed is very strong. Therefore to avoid saturation of the signal, very low gains need to be used when collecting the data which may lead to problems detecting the true bed level.

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