Analysis of coherent flow structures over alluvial dunes revealed by multi-beam echo-sounder acoustic backscatter

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Abstract

Large-scale coherent flow structures, or macroturbulence, produced by alluvial sand dunes are reasoned to dominate the flow field and result in significant transport of suspended bed sediment. Macroturbulence, and its interaction with the free flow surface, is also thought to influence the creation and maintenance of the dune bed morphology. Recent physical and numerical modelling has demonstrated the structure and origin of such turbulence, and field data obtained along vertical profiles using acoustic Doppler current profilers have also recently enabled a quantification of such turbulence from within natural channels. We have recently developed a novel method, based upon acoustic backscatter from multibeam echo sounding systems, which allows for the simultaneous quantification of suspended sediment dynamics and estimates of flow velocity (see Simmons et al., 2010; Best et al., 2010). This paper presents a full application of this new technique to data collected over dune bedforms in two large rivers: the Rio Paraná and the Mississippi River. An analysis of the mean velocity components and turbulence intensity across the flow field and the quadrant analysis of the flow structures, together with a description of the temporal length scales revealed by wavelet analysis, are presented. These field results are compared with recent numerical modelling of coherent macroturbulence over dune-covered beds, allowing verification of our conceptual models of these key features of many river flows.

1. INTRODUCTION

Simultaneously quantifying, at sufficiently high resolutions, the interactions between turbulent flow, sediment transport and bed morphology has long been known to be key to improved understanding of the morphodynamics of bedforms. Recent advances in Multibeam Sonar (MBES) technology, which allow recording of the full water column acoustic backscatter data, have opened up this possibility (Simmons et al., 2010; Best et al., 2010). The theory relating the acoustic backscatter to sediment concentrations and flow velocities has been well developed and employed over the course of the last two decades (see Thorne and Hanes, 2002). Combining these theoretical and technological advances, Simmons et al. (2010) and Best et al. (2010) were able to advance a methodology based upon MBES that permitted quantification of the suspended sediment concentration and velocity vectors across the two-dimensional MBES swath fan, enabling the simultaneous measurement of these related sediment transport parameters across the flow field above a dune field in a large alluvial river.

2. FIELD SITES AND METHODS

The results presented herein were derived from data collected at two field locations: the Mississippi River near the confluence with the Missouri River, USA (38°48'N, 90°7'W) and the Rio Paraná near the confluence with the Rio Paraguay, Argentina (27°18'S, 58°35'E). Data were collected at both locations using a RESON 7125 SeaBat 396 kHz MBES deployed on a survey vessel that was moored at a single stationary location over the lee-side of a low-angled sand dune in the Mississippi and at three separate stationary locations along the streamwise axis of a sand dune in the Rio Paraná.

The MBES was mounted with the acoustic interrogation swath aligned parallel to the streamwise flow, enabling the two-dimensional imaging of the development of turbulence-related suspensions of sediment in the streamwise direction. Data were collected over 256 acoustic beams at the Mississippi site and 512 beams at the Paraná site, both over a swath of 128° with an acoustic frequency of 398 kHz and with a sample-spacing of ~2.1 cm. The MBES ping collection rate was set to 10Hz for the Mississippi and 30Hz for the Paraná. The distance to the river bed at the field sites locations varied between ~6.8 to ~9.0 m. Figure 1 shows the raw acoustic magnitude data for a single ping at Paraná Position 3 (furthest downstream). The strong acoustic reflection from the bed can be seen bisecting the swath approximately horizontally at *c.* 8 m depth below the transducers. The areas of the water-column near to the bed on both sides of the swath are dominated by an acoustic artifact known as sidelobe interference. The region of study herein is therefore the sector bounded by the arc of the nearest distance to the bed that is free from such interference. Suspended sediment bursts are discernible within this volume, advecting with streamwise flow from left to right. It should be noted that suspended sediment backscatter is a relatively weak signal and the data in the image has been clipped to a maximum of 2500 MBES counts to enhance the contrast with the strong bed echoes.

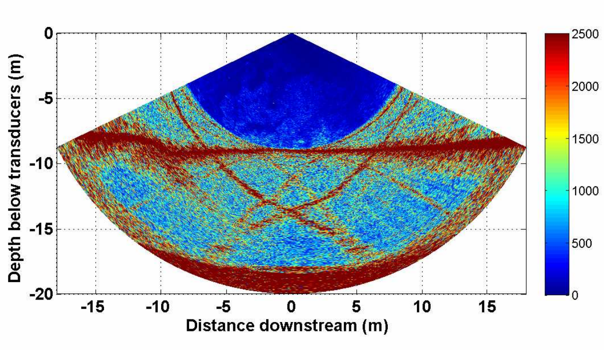

Figure 1. Raw data from a single ping obtained over the lee of a sand dune in the Paraná (Position 3).

The results presented herein were derived from flow field vectors obtained by using a method of comparing the mean quadratic difference (MQD) between two-dimensional areas of consecutive pings. The magnitude data were first adjusted for acoustic propagation losses and averaged over a local area to account for the random nature of acoustic backscatter from small particles. Details of the flow field velocity method are fully described by Best et al. (2010) and the spatial averaging and conversion to suspended sediment concentration by Simmons et al. (2010). In short, data were corrected for acoustic propagation losses, averaged with a circular spatial filter of radius 6.5cm and interpolated to Cartesian co-ordinates on a rectangular grid (cell size 2.5 x 2.5 cm) to allow the MQD between area windows in consecutive pings to be calculated. The flow field vectors were allocated to the position at the centre of the window in the first ping, with the streamwise and vertical velocity vector determined by considering the distance to the centre of the window with the lowest MQD in the next ping and the delay between the two pings. The MBES system at the Mississippi site recorded at a ping rate consistent with the set parameter of 10Hz; however the system used at the Paraná site recorded at a variable ping rate with delays between 0.03 - 0.5 s (typical mean of ~ 0.12 s) as the system lacked sufficient processing power to write the large quantities of data to the hard disk at the set ping rate parameter of 30Hz.

3. RESULTS AND DISCUSSION

3.1. Flow field time series analysis

The Mississippi data consists of a single recording over a period of 600 s. The mean flow field streamwise (*u*) and vertical (*w*) components of velocity for the entire period are displayed in Figure 2. *u* increases with height above the bed, rising to ~1.7 ms^{-1} high in the water column, and *w* decreases from ~0 - 0.01 ms^{-1}. The area shown is not as extensive as the full sector to the bed (transducer-to-bed range is 6.85 m) as the method is less accurate near the area boundaries where the window size decreases. Data were screened above a MQD quality threshold, although some artifacts can be seen near the boundaries, e.g. the far right-hand side of the *w* component. Figure 3 shows *u* and *w* along the vertical profile directly below the transducers.

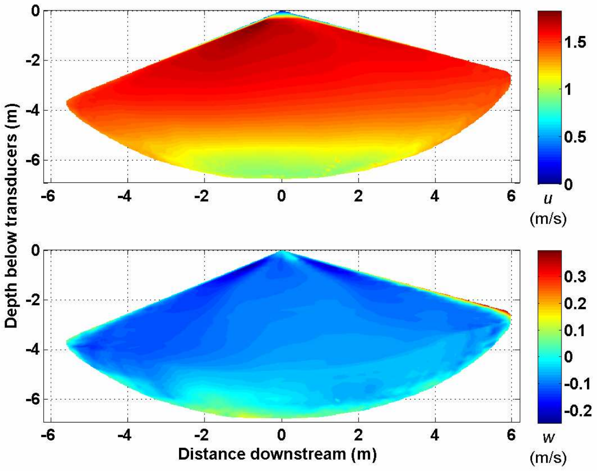

Figure 2. Mean *u* (top) and *w* (bottom) velocities across the analysis area of the multibeam swath at the Mississippi site.

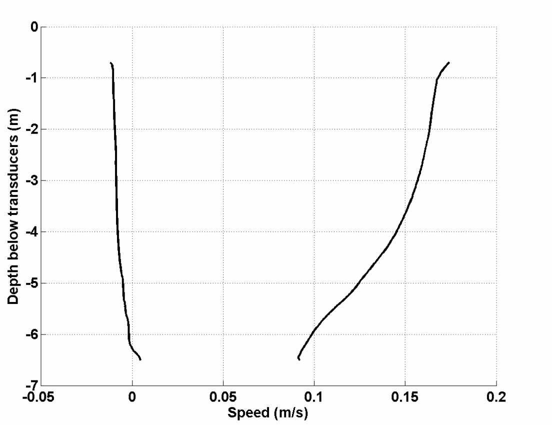

Figure 3. Mean vertical profile of *u* (right) and *w* (left) derived from the time series for the vertical profile beneath the MBES transducers at the Mississippi site.

Figures 4 & 5 display the time series for *u* & *w* respectively for three single points in the vertical profile below the transducers at heights above the bed, *z*, of 0.75, 0.5 and 0.25 of the flow depth, *h*. The RMS of the deviatoric components of velocity increase, with turbulence intensity, towards the bed: 1.37 cms^{-1} (*u*, 0.75 *z/h*), 1.59 cms^{-1} (*u*, 0.5 *z/h*), 2.21 cms^{-1} (*u*, 0.25 *z/h*) , 0.56 cms^{-1} (*w*, 0.75 *z/h*), 0.65 cms^{-1} (*w*, 0.5 *z/h*), 1.24 cms^{-1} (*w*, 0.25 *z/h*). Quadrant analysis has been previously utilized to discriminate turbulent events in the boundary layer (e.g. Lu and Willmarth, 1973; Bennett and Best, 1995). Four quadrants are defined for deviations from the mean: Quadrant 1 (positive *u* & *w*), Quadrant 2 (negative *u*, positive *w*), Quadrant 3 (negative *u* & *w*) and Quadrant 4 (positive *u*, negative *w*).

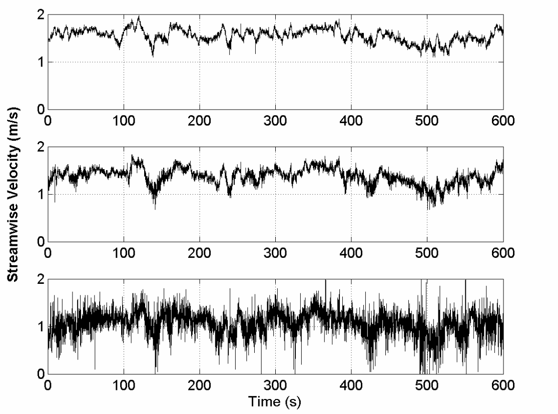

Figure 4. Time series of U at 0.25 *z/h* (bottom), 0.5 *z/h* (middle), 0.75 *z/h* (top) at the Mississippi site.

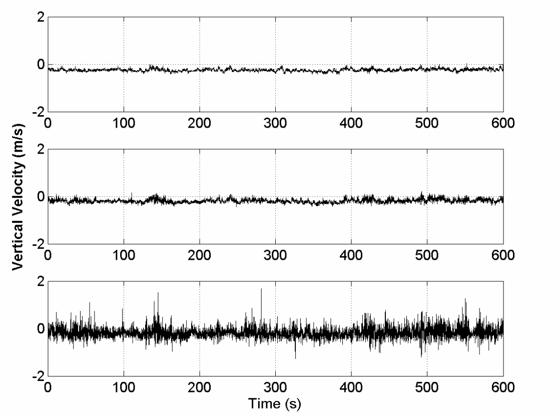

Figure 5. Time series of *w* at 0.25 *z/h* (bottom), 0.5 *z/h* (middle), 0.75 *z/h* (top) at the Mississippi site.

Figure 6 shows the result of quadrant analysis applied to the vertical profile below the MBES, showing the frequency of occurrence beyond a 'hole' size of one standard deviation. The results show how Q1 and Q3 events dominate lower in the water column, but that Q2 and Q4 events dominate away from the bed. Wavelet analysis was also applied to the time series shown in Figures 4 & 5 to examine how the scales of variability evolved temporally and spatially as a function of time. Wavelet analysis produces power values for a range of frequencies and a set of locations in time, and has been previously applied for the analysis of turbulence (e.g., Farge, 1992). The Morlet wavelet was applied to derive the results shown in Figures 7 & 8 for the *u* and *w* components respectively at the three heights above the bed. Distinct frequencies are apparent in both of the wavelet power spectra, with coherence between the streamwise and vertical components. Both spectra also show a trend of the filtering of higher frequencies with distance from the bed. Distinct clustering of events is also apparent in the time series, which is likely produced by shear layer flapping and vortex shedding.

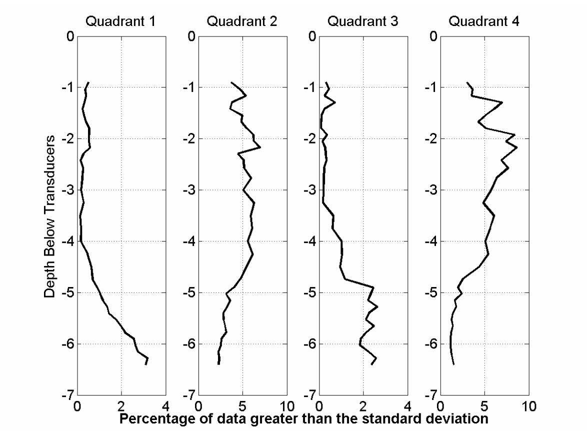

Figure 6. Quadrant analysis of the time series for the vertical profile beneath the MBES transducers at the Mississippi site.

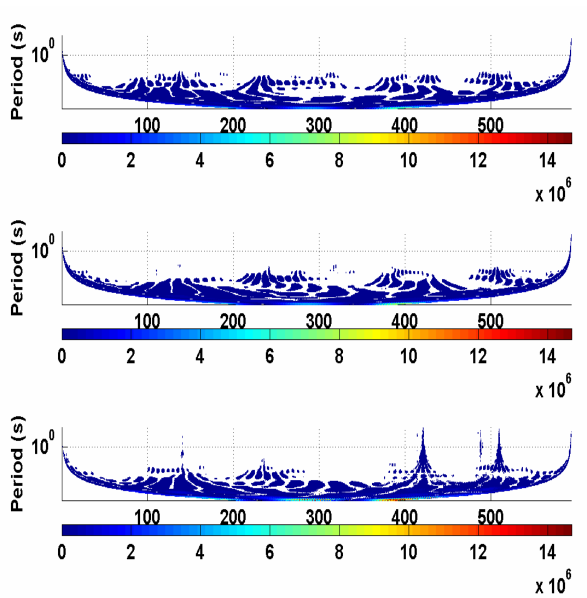

Figure 7. Wavelet analysis of the *u* time series for 0.75 *z*/*h* (top), 0.5 *z*/*h* (middle), 0.25 *z*/*h* (bottom).

3.2. Spatial Variability and Evolution

The data recorded at the Paraná site was obtained over a single sand dune at three stationary locations separated by increasing distance in the downstream direction from Position 1 to Position 3. The data from the Paraná site was found to be poorer in quality as the result of two factors related to the ping rate. Firstly, the processor was incapable of recording at 30Hz, which led to a variable delay between successive pings. Secondly, when the delay was small (usually less than 0.1 s) large and varying magnitudes of surface reverberation were observed across the swath. Heavily contaminated pings at less than 0.07 s delay were therefore rejected from the analysis, thus increasing the average delay between the remaining pings. A time series analysis of the data would require interpolation to a uniform temporal sampling rate. Reverberation was a particular problem at the edge of the swath, as was the presence of the mooring cable that can be seen on the left-hand side of Figure 1 Herein, we show the results for the mean *u* and *w* components of flow velocity across the central section of the swath sector from beams 165 to 348 that span 45.5°.

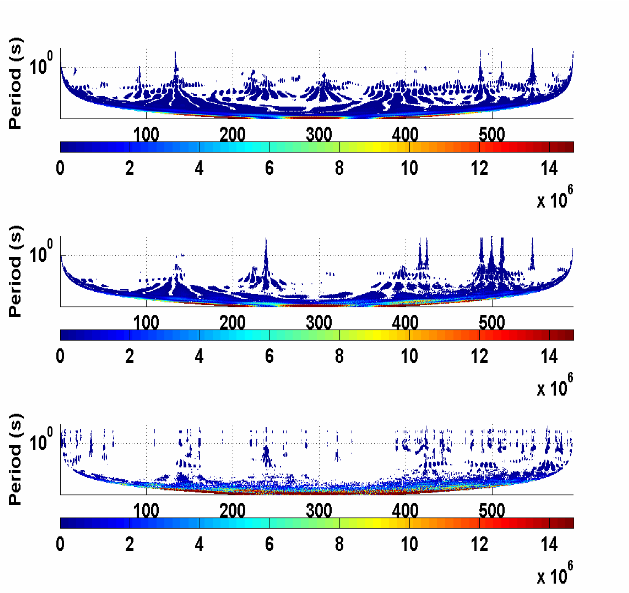

Figure 8. Wavelet analysis of the *u* time series for 0.75 *z*/*h* (top), 0.5 *z*/*h* (middle), 0.25 *z*/*h* (bottom)

Figure 9 shows the mean vertical *u* and *w* profiles for the three positions. The usable data were recorded over shorter time periods than for the

Mississippi site: Position 1 (181 s), Position 2 (52 s) and Position 3 (33 s). The three *w* profiles show a very similar variation with depth above the bed. The *u* profile shows a sharp gradient above the bed for the furthest upstream (near crest) and shallowest position, Position 1.

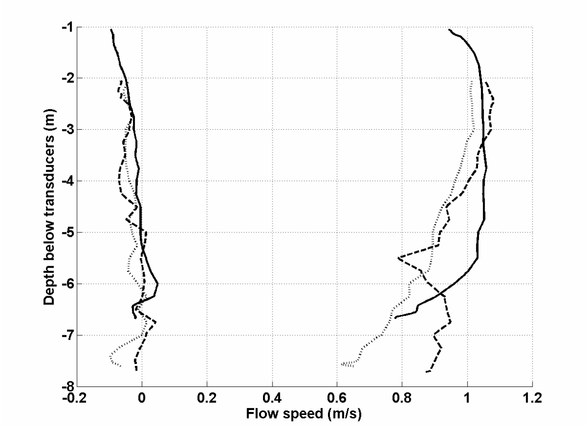

Figure 9. Mean vertical profile of *u* (right) and *w* (left) derived from the time series for the vertical profile

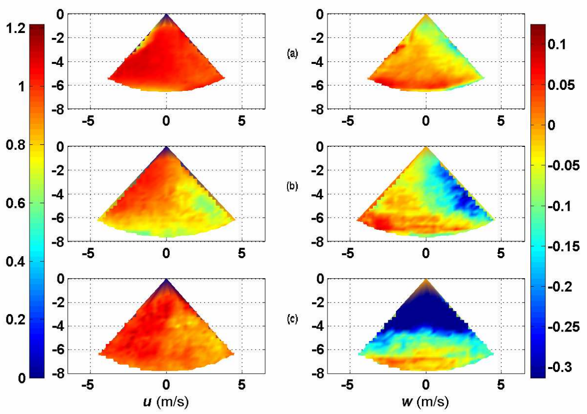

Figure 10. *u* (left) and *w* (right) flow fields obtained from the analysis of data collected at three locations in the lee of a sand dune in the Rio Paraná. Position 1 (a), Position 2 (b) and Position 3 (c)

The Position 2 profile shows a more gradual increase in flow speed with depth above the bed, while the Position 3 profile shows a similar gradient between ~ 2 - 5.5 m but with a notable increase in flow velocity in the lower two metres of the profile, perhaps related to a re-attachment point and/or intense turbulence that results in the incorporation of some temporal variation, particularly given the short length of the time series. Figure 10 shows the variation of mean *u* and *w* across the central region of the swath.

4. CONCLUSIONS

Methods for deriving the suspended sediment concentration and flow field velocity vectors across a two-dimensional flow field at a stationary position over a sand dune have previously been demonstrated by Best et al., (2010). The results in the present paper demonstrate how an analysis of the spatial and temporal variation of the flow field velocities obtained with this method can reveal insights into the turbulent behavior of flow over a dune. Work is ongoing to further characterize the variations in turbulent behavior, use the spatial richness of the MBES data to link the periodicities identified in the wavelet analysis to the structures responsible for the signals. Additionally, effort is been focused into further quantifying the uncertainties associated with this new and promising method, particularly with some of the technical issues encountered at the Rio Paraná site.

5. REFERENCES

Bennett, S.J., & Best, J.L. 1995. Mean flow and turbulence structure over fixed, two-dimensional dunes: Implications for sediment transport and dune stability, Sedimentology, 42: 491– 513, doi:10.1111/j.1365-3091.1995.tb00386.x.

Best, J., Simmons, S., Parsons, D., Oberg, K., Czuba, J. & Malzone, C. 2010. A new methodology for the quantitative visualization of coherent flow structures in alluvial channels using multibeam echo-sounding (MBES), Geophys. Res. Lett., 37. doi: 10.1029/2009GL041852.

Farge, M. 1992. Wavelet transforms and their application to turbulence. Ann. Rev. Fluid Mech., 24: 395– 457, doi:10.1146/ annurev.fl.24.010192.002143.

Lu, S.S. & Willmarth, W.W. 1973. Measurements of structure of Reynolds stress in a turbulent boundary layer, J. Fluid Mech., 60: 481–511, doi:10.1017/S0022112073000315.

Simmons, S.M., Parsons D.R., Best J.L., Orfeo, O., Lane, S.N., Kostaschuk, R., Hardy, R.J., West G., Malzone, C., Marcus, J. & Pocwiardowski, P. 2010. Monitoring Suspended Sediment Dynamics Using MBES, Journal of Hydraulic Engineering. Volume 136, Issue 1: 45-49.

Thorne, P.D., & Hanes, D.M., 2002. A review of acoustic measurement of small-scale sediment processes, Cont. Shelf Res. 22: 603–632.