Coherent Flow Structures over Alluvial Sand Dunes revealed by Multibeam Echo Sounding

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ABSTRACT: The topology, magnitude and sediment transport capabilities of large-scale turbulence generated over alluvial sand dunes has been reasoned to be influential in creating and maintaining dune morphology, and in dominating both flow field and the transport of suspended sediment above dune beds. Much past laboratory and numerical research has illustrated the origin and structure of such dune-related turbulence, and this turbulence has also been measured using both at-a-point and multipoint (aDcp) measurements within natural channels. However, all of these past field techniques have been unable to examine the holistic structure of such turbulence and examine how this may related to smaller-scale laboratory studies and numerical simulations. This paper examines the novel application of multibeam echo sounding (MBES) to examine flow above a series of sand dunes in the Mississippi and Missouri rivers, USA. A RESON 7125 MBES system was deployed from a small survey boat and used to map the detailed three-dimensional topography of sand dunes on the beds of both rivers. Once this bathymetric surveying had been completed, the boat was then moored at-a-point and the MBES head aligned so that is captured a flow parallel swath. The backscatter signal from the multibeam swath was then utilized to visualize the structure of turbulence as picked out by the clouds of suspended sediment. Image sequences were taken in the trough and near the crests of a large sand dune and reveal the presence and advection of large coherent flow structures, with superimposed smaller vortices, that translate through the measurement volume. These images are the first such whole flow field visualizations of dune-related macroturbulence ever collected from a natural alluvial channel and reveal a complex flow structure, which bears many similarities to that modelled in past laboratory and numerical experiments. This paper will present images and animations of the flow structure and compare this to past modeling of coherent vorticity within both smooth and dune-covered beds.

1 INTRODUCTION

Sand dunes are the dominant bedforms in many alluvial channels in forming appreciable elements of resistance to flow, dictating the routing of bedload transport, being key elements for the construction of larger bar and bed topography, and in producing flow fields that may dominate the entire channel depth. As such, the flow fields associated with dunes have fascinated scientists for many years and much progress has been made in unraveling the processes of dune form, flow and migration, utilizing theory, laboratory experimentation and field study (see review in ASCE, 2000; Best, 2005). Recent years have seen a growth in our ability to study the dynamics of sand dunes within large alluvial channels, and acoustic Doppler profiling has enabled study of flow fields through the entire flow depth. Additionally, multibeam echo sounding (MBES) has begun to enable us to examine, in exquisite detail, the morphology of sand dunes (Parsons et al., 2005), and address issues of dune morphology, bedform superimposition, and dune migration. What we ideally require is a methodology to link the detailed form of the dune bed, with study of the flow field associated with alluvial sand dunes, which can reveal details of the form of dune-related macroturbulence and its advection within the flow. This paper will present details and results of the application of MBES for examining both the form and flow field associated with large sand dunes in the Mississippi and Missouri rivers. We will outline details of using the MBES backscatter signal from the water column that allows us to visualize the structure of sediment suspension and turbulence associated with large alluvial sand dunes, and we detail how MBES and allied aDcp measurements can also quantify the flow field.

2 FIELD SITE

The field site detailed herein is located at the confluence of the Mississippi and Missouri rivers, near St Louis, USA. Field surveys employed a RESON SeaBat 7125 system, which is a dual-frequency, digital beam-forming system with 512 beams in a 130º swath coverage, with a very small (0.5º by 1º) beamwidth that can be used with either a 200 or 400 kHz frequency projector. The pulse length can vary between 10 to 300 µs, which gives the SeaBat 7125 the highest resolution available on the market, with range resolutions of 3 mm & ping rates approaching 50 Hz. The MBES was linked to a Leica dGPS to enable precise positioning, with tilt, roll and pitch sensors being used to adjust for boat movement. We surveyed the confluence of the river, and used this morphological map to select several sites at which we moored at-a-point and oriented the MBES swath parallel to flow, thus enabling us to document the downstream flow structure. This paper will present results from these at-a-point surveys that reveal the first whole-flow field visualizations of large-scale dune-related turbulence and the associated flow field. We will also use aDcp measurements to characterize the flow field at these sites and compare this with our MBES visualizations.

3 VISUALIZATION

Results from this study reveal that the backscatter signal from the MBES can be used to provide qualitative and quantitative visualizations of suspended sediment and macroturbulence associated with large sand dunes (Figure 1). These visualizations reveal the presence of large, depth-scale, coherent motions that have an upstream surface that slopes upstream and appears to also possess superimposed smaller-scale vorticity. These large-scale coherent flow structures are seen to originate in the dune leeside and the larger ones may reach the flow surface, confirming the patterns revealed in the pioneering work of Kostaschuk and Church (1993). However, MBES can produce flow field visualization of the form and growth of these structures as they advect downstream. Furthermore, we will illustrate the first attempts to use the backscatter signal from the MBES swath to estimate downstream-vertical velocities within part of the swath and that are capable of revealing the flow velocity field associated with the fluid upwellings (details in section 4). We will illustrate the methodology of this approach and first results of this MBES velocity field quantification.

These results will be compared with mean flow and turbulence data collected by aDcp at the same field site. This new MBES methodology holds huge potential for quantifying the morphodynamics of sand dunes within a range of sedimentary environments.

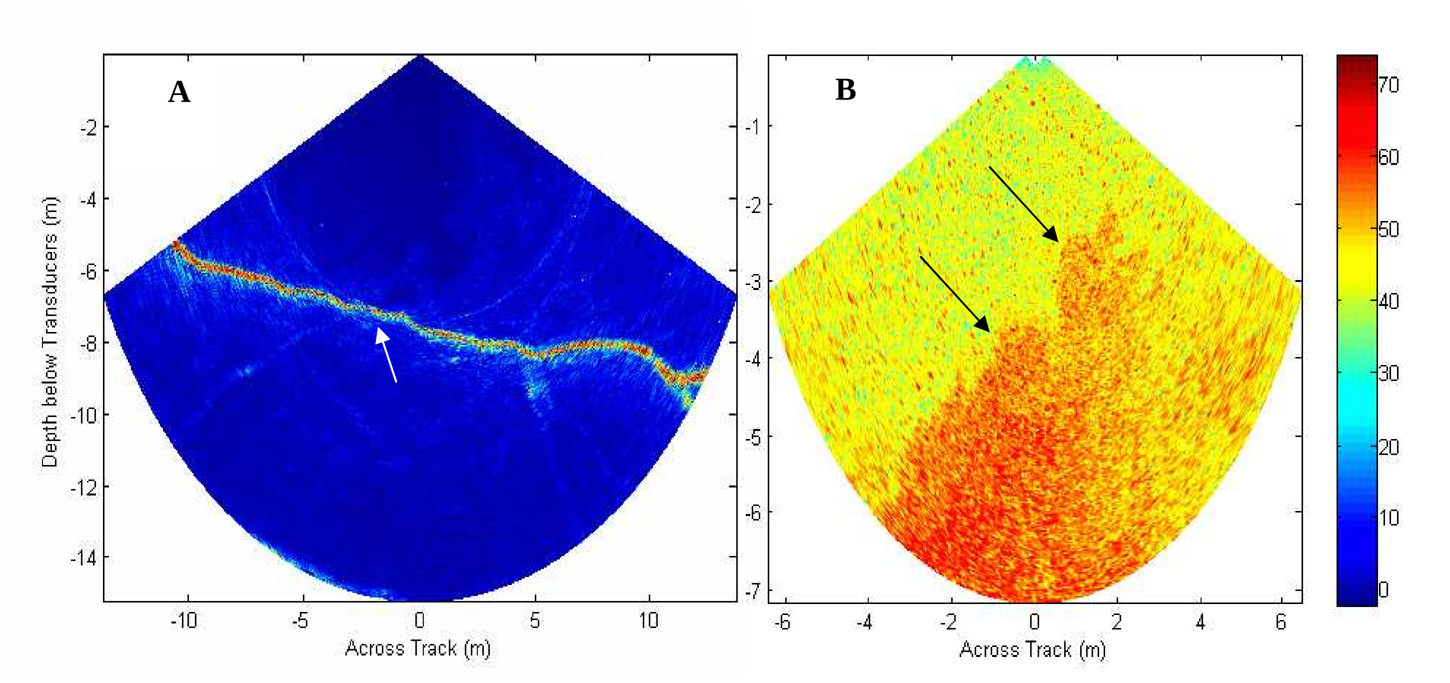


Figure 1: At-a-point MBES imaging of bed & suspended sediment flow structure in the leeside of a sand dune, Mississippi River, St Louis, with swath parallel to flow. Flow left to right. A) MBES swath showing low-angle dune leeside slope (arrowed) with flow left-right; B) Backscatter magnitude plot for part of swath showing high magnitude values that depict a coherent flow structure that contains higher concentrations of suspended sediment. Note presence of smaller-scale vorticity (arrowed) on the back of the larger, upstream-sloping, flow structure.

4 BACKSCATTER PROCESSING

4.1 *Concentration*

The objective of the post-processing routines is to derive an estimate for the Mass Concentration (mg/l) of suspended sediment from the strength of the back-scattered acoustic pressure recorded at the receiver interface. The 7125 MBES produces a two-dimensional fan of either 256 or 512 digitally formed beams sampled approximately every 2.1cm along each beam. The magnitude data along with the phase information is recorded in s7k files along with other sonar parameters.

For a fixed grain size distribution the scattering volume, Sv, is proportional to the Mass Concentration. Sv is derived as a function of the mean acoustic back-scatter voltage, the volume of the range cell, the spreading and absorption losses and the sonar settings such as power, gain, pulse length, and time-varying gain. It is therefore possible to estimate the suspended sediment concentration values with a single frequency sonar system, provided the grain size distribution remains the same throughout the ensonified volume and a system calibration is known either in absolute terms or by physically taking concentration samples and matching them to recorded back-scatter levels.

The sonar equation is used to estimate the values of Sv, which is defined as the ratio of the radiated acoustic intensity to the incident acoustic intensity per unit volume.

$$\mathbf{Sv(r,\theta) = RL(r,\theta,\psi) - SL(\theta) - S_p \log_{10} r + 40\log_{10} r ...}$$
$$\mathbf{- 10\log_{10} V(r,\theta) + 2\alpha r}$$

where:

RL = Receive level in dB – sound intensity level derived by squaring the raw magnitude data.
SL = Source level in dB – sound intensity level at 1m from the projector, relative to 1μPa
Sp = Spreading coefficient for time-varying gain
A = Spreading coefficient (dB/m)
V = Volume of range cell. Approximate volume (portion of shell calculated by subtracting volumes of two concentric spheres) is:

$$\mathbf{V = \frac{4}{3}\pi(R_2 - R_1)^3 \frac{\theta\phi}{(2\pi)^2}}$$

where R_2 and R_1 are the radial limits of the cell, Φ is the along-track 3dB beamwidth and θ is the across track 3dB beamwidth, which approximates to (as a consequence of the beamforming process):

$$\theta = \frac{\theta_n}{\cos(\lambda)}$$

where θ_n is the nadir beamwidth and λ is the angle from the nadir.

The processing routine takes the position of an individual sample in a beam and determines the positions of all other samples within a specified spatial radius of that sample. Two values, corresponding to the median and the mean of all the samples within the radius, are then assigned to that point. The process is then repeated for all samples within all the beams of the multibeam fan. Hence, the process performs a two-dimensional spatial-averaging algorithm for the full swath for an individual ping. Averaging can also take place between successive pings. This level of data averaging is required because of the nature of the Rayleigh-scattering regime for uniformly distributed spherical-scatterers for a radius corresponding to (2π/λ)*a << 1, where λ is the wavelength of the incident sound wave and a is the radius of the scatterers. The standard error for n samples of a Rayleigh distribution is approximated by the following:

$$\sigma_e \approx \frac{V_{rms}}{2\sqrt{n}}$$

where V_{rms} is the backscatter voltage sample. Hence it can be seen 100 samples are required for a 5% error.

4.2 *Velocity*

Work is ongoing to extract velocity information simultaneously with the concentration estimates. Methods are being developed to estimate velocity data the raw amplitude data and in the fullness of time from Doppler estimation using recordings complex baseband-equivalent data. The preliminary results obtained from correlating the magnitude data are detailed and presented in this section.

The correlation method works in a similar manner to Particle Image Velocimetry (PIV) methods, which are now, the most commonly used velocity measurement technique in fluid mechanics. PIV methods are popular and successful owing to the simple concepts that underlie the methods, the accuracy and low-intrusiveness. The method used to obtain the results presented in this paper simply consists of replotting the averaged reverberation levels, obtained using the method outlined in the previous section, onto a rectangular grid. This provides a rectangular grid of concentration data. Rectangular areas within one ping are then correlated to the surrounding areas within the next ping. A velocity vector is then simply estimated by joining the centre of the first rectangular area with the centre of the rectangular area within the next ping with the highest correlation to the first. The process is then repeated across a grid of different area in the first ping to produce a two-dimensional matrix of velocity estimates.

5. RESULTS

Figure 2, shows the results obtained from the Mississippi/Missouri river field site close to St Louis during October 2007. The position of the MBES is the same as is described in Figure 1. The flow is from left to right and the coloured scale shows the linear values of the spatially averaged reverberation levels across the swath, replotted on a rectangular grid with 0.025m spacing. The scale is simply normalized to the maximum and minimum reverberation within the swath. Concentration samples taken within the water column at the site are currently being analysed to enable a calibration. The arrows on the grid in the centre of the swath are the velocity vector estimates derived using the correlation method. The estimates show vectors that are aligned with the expected direction of flow from left to right with a smaller average downwards component of vertical velocity. The magnitude of the velocity components correlates well with the aDcp measurements taken at the site and also with the visual observations of the flow structures advecting downstream.

Figure 3. shows the magnitude of the velocity vectors in the last plot show in Figure 2. The mean value of downstream velocity is around 1.3ms^{-1}. It can be seen that the suspended sediment structures appear to advect downstream at a greater velocity with greater height from the bed.

Figure 4 shows the variation with time of the mean value of the downstream components of velocity across the two-dimensional rectangular grid. The mean was calculated for thirty successive pings over a period of 3s. The mean value over the 3s is 1.33ms^{-1}.

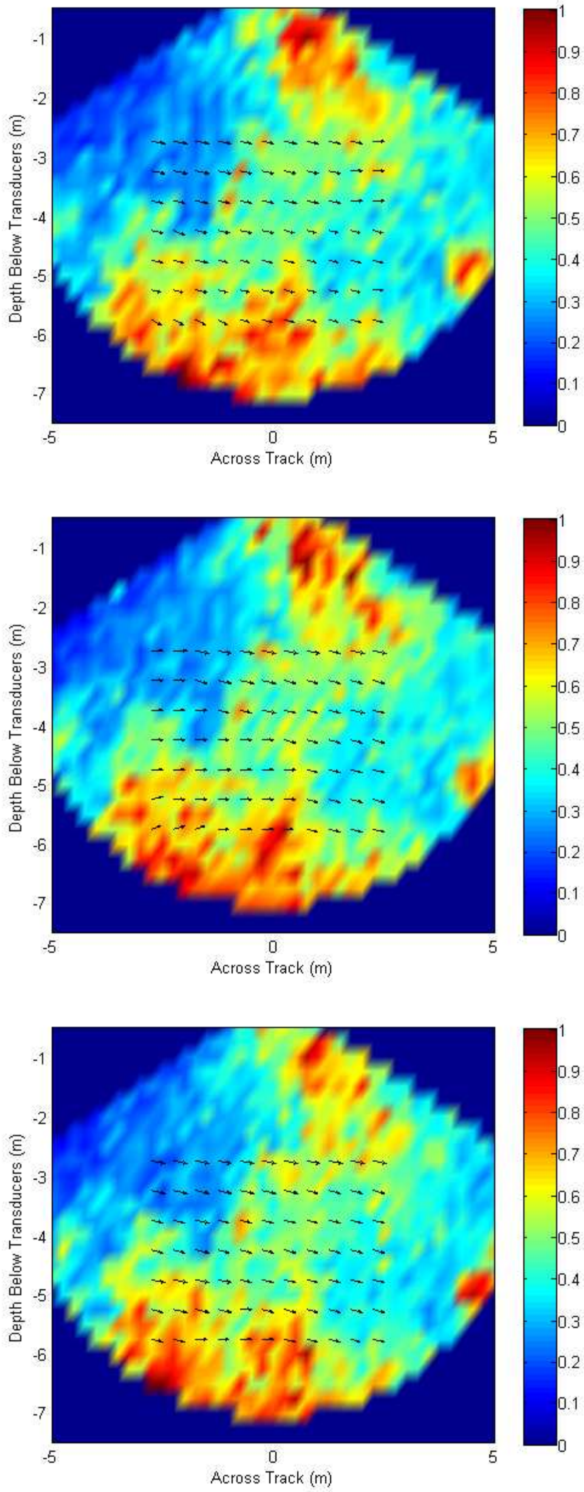
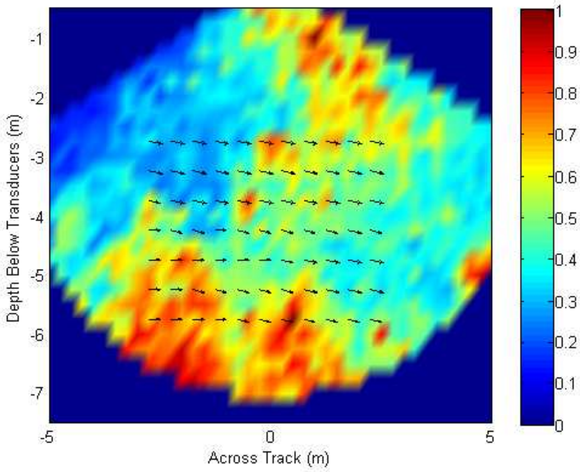


Figure 2: Mean reverberation levels calculated for each sample using a two-dimensional circular window with a radius of 0.13m plotted on a colour scale. The arrows represent the velocity vectors calculated using the correlation method between successive pings with a 0.1Hz repetition rate. The four figures represent the velocities between five successive pings over a period of 0.4s.



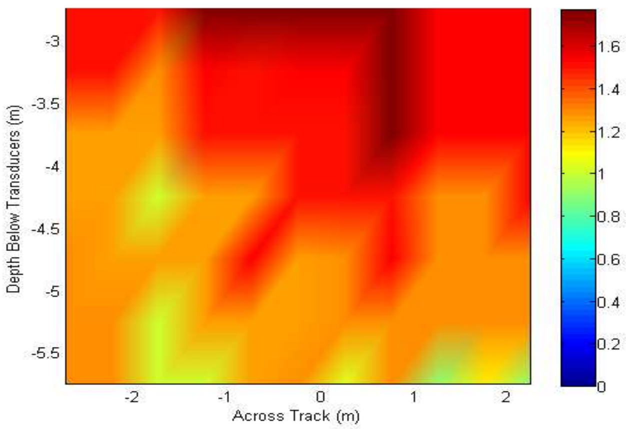


Figure 3: Velocity magnitudes corresponding to the rectangular area of velocities show in the bottom panel of Figure 2.

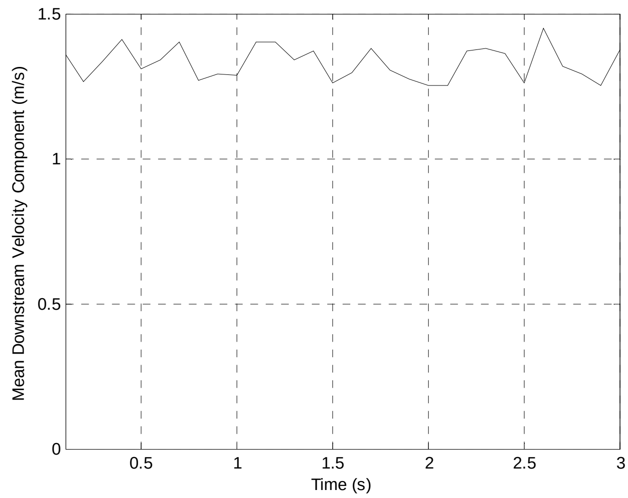


Figure 4: Mean component of downstream velocity over 30 successive pings.

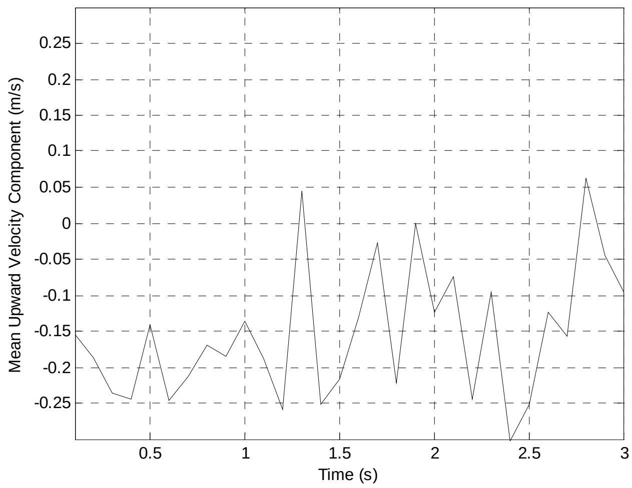


Figure 5: Mean component of vertical velocity over 30 successive pings.

Figure 5 shows the variation of the mean vertical component of velocity over the same 30 pings as Figure 4. The plot shows that the mean velocity is mostly towards the bed and has a 3s mean of -0.15ms^{-1}.

5 CONCLUSIONS

This paper has demonstrated the huge potential of new MBES systems for examining the fluid and sediment dynamics of river dunes and marine sandwaves concurrent to bathymetric mapping investigations. Further developments and refinements in this holistic approach hold the key to gaining better understanding of the interactions of turbulent flow and sediment suspension over bedforms and will enable us to better monitor, model and manage environmental systems.

6 REFERENCES

ASCE Task Force, 2002 Flow and transport over dunes, *J. Hydraulic Engineering*, 127, 726-728.

Best, J. 2005 The fluid dynamics of river dunes: a review and some future research directions. *J. Geophysical Research, Earth Surface*, 110, F04S02, doi:10.1029/2004JF000218.

Kostaschuk, R.A. and Church, M.A. 1993 Macroturbulence generated by dunes: Fraser River, Canada. *Sedimentary Geology*, 85, pp. 25-37, 1993.

Parsons, D.R., Best, J.L., Hardy, R.J., Kostaschuk, R., Lane, S.N. and Orfeo, O., 2005 The morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: results from simultaneous multibeam echo sounding and acoustic Doppler current profiling, *J. Geophysical Research, Earth Surface*, 110, F04S03, doi:10.1029/2004JF000231.