Imaging of Large-Scale Sediment Transport Dynamics with Multibeam Sonar

Stephen Simmons[a], Dan Parsons[a], Jim Best[b], Chris Malzone[c] and Gareth Keevil[a]

[a]University of Leeds, School of Earth and Environment, University of Leeds, LS29JT Leeds, UK
[b]Departments of Geology and Geography and Ven Te Chow Hydrosystems Laboratory, 1301 W. Green St., University of Illinois, Urbana, IL 61801, USA
[c]Reson Inc., Goleta, Santa Barbara, CA 93117, USA
s.m.simmons@leeds.ac.uk

Multibeam Echo-Sounder (MBES) systems have developed rapidly over recent decades and are routinely deployed to provide high-resolution bathymetric surveys. Modern data handling and storage technologies have facilitated the logging of the back-scatter information previously discarded by these systems. This paper describes methodologies that exploit this logging capability to quantify the concentration and dynamics of suspended sediment within the water column. This development provides a multi-purpose tool for the holistic surveying of sediment transport by imaging suspended sediment concentration, associated flow structures and providing concurrent high-resolution bathymetry.

Results obtained from the tank testing and field deployment of a RESON 7125 MBES are presented. The capacity of MBES systems to image suspended sediment structures is demonstrated and a novel methodology for estimating flow velocities is introduced, based on cross-correlation methods similar to Particle Image Velocimetry. Results obtained from this analysis are presented using field data obtained over a dune in the Mississippi River.

The results demonstrate the capability of MBES systems to successfully resolve contrasts in suspended sediment concentrations. The large sets of data recorded in the two-dimensional MBES swath enables the real-time monitoring of suspended sediment transport and related flow processes on a scale previously unrealisable with single-beam acoustic systems.

1 Introduction

This paper describes the methodologies developed as part of a joint project between the University of Leeds and RESON Inc., concerning the development of MBES systems for the quantitative monitoring of suspended sediment dynamics in aquatic environments (funded by the Natural Environment Research Council, UK). Methods of data analysis have been developed that provide an estimate of suspended sediment concentration and flow velocities, derived from the back-scatter data obtained using RESON's 7125 MBES system. Results are presented that were obtained with the 7125 during the controlled testing at a large tank facility at Blyth in the North of England and from a field survey at the confluence of the Mississippi and Missouri rivers, USA, using the same system.

The research team at the School of Earth and Environment, University of Leeds has extensive experience of quantifying and modelling the links between flow and sediment dynamics in a wide range of environments using a variety of innovative approaches. The potential for using MBES to identify suspended sediment structures was identified by the group whilst collecting bedform bathymetry data in the Paraná fluvial system along the border of Argentina and Paraguay [1]. The objective of the current project is to extend the use of the MBES, from an instrument designed to produce high-resolution bathymetry data, to one that is simultaneously capable of providing information regarding the suspended sediment concentration and associated flow structures within the water column. The aim is thus to produce a methodology that will enable a wide range of scientists to exploit a single instrument, which is capable of providing holistic measurements of spatio-temporal bathymetry, sediment concentration and flow velocity. This will provide a powerful tool for the understanding, modelling and management of complex fluvial systems, as well as a range of other Earth-surface environments.

2 Methodology

The objective of the post-processing routines developed during the project is to derive estimates for the mass concentration and flow velocities of suspended sediment structures, by using the strength of the back-scattered acoustic pressure recorded at the MBES receiver interface, together with the various sonar and environmental variables. The 7125 MBES used to obtain the results presented in this paper, produces a fan of beams over a two-dimensional swath of 128^{o}. The beam-forming algorithm produces either 256 or 512 beams when operating at 400kHz or 256 beams at 200kHz. The angular spacing between the beams can be set to uniform or 'equi-distant' to produce approximately equal-spaced bathymetric samples along the bed. The transmit and receive beam-patterns combine to give approximate 3dB beam-widths at nadir of 0.5^{o} x 1.0^{o} at 400kHz and 1.0^{o} x 2.0^{o} at 200kHz. The magnitude and phase information is recorded along each beam with a sampling distance of approximately 0.0214m ($1500ms^{-1}$ sound speed).

Fig. 1 shows a visual representation of the back-scatter magnitudes for a single ping obtained from a vessel moored at a point over the lee-side of a dune on the Mississippi River. The MBES was operating on the 400kHz setting with 256 beams of equal angular spacing. The solid line is the bathymetric data obtained with the MBES bottom-finding algorithm. The depth of the bed at nadir is just over 7m and the data above the solid line shows the back-scatter from material within the water-column and also the side-lobe interference from the bed reflections. The area of interest for concentration and flow velocity estimation is defined by the area within the specular arc formed by the side-lobe component of the nearest bed reflection to the transducers. This area can be seen in Fig.1 where a flow structure transporting suspended sediment is observed. The structure is advecting with the flow of the river from the left to the right of the Figure.

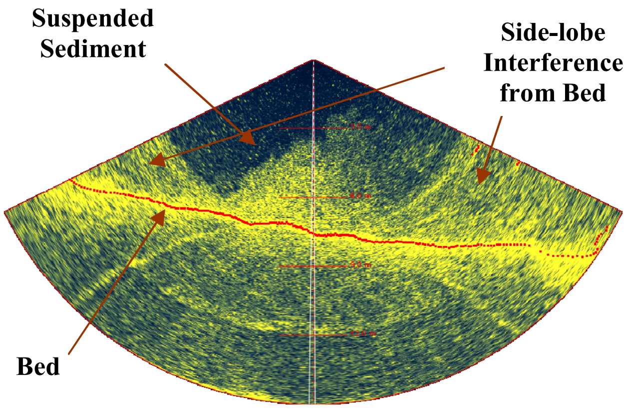

Fig. 1 Raw back-scatter magnitude data from a single ping. The orientation is parallel to the flow of the Mississippi river over the lee-side of a dune bedform.

2.1 Concentration Estimation

The aim of the post-processing is to form an estimate of mass concentration of suspended sediment (C, mg L^{-1}) across the two-dimensional area of the MBES swath. For a fixed distribution of grain properties and size, the reverberation level, Sv, is proportional to the mass concentration, C. 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. Sv (in terms of across-track polar co-ordinates, r, θ) is derived from the sonar equation as:

$$\begin{aligned} Sv(r,\theta) &= RL(r,\theta) - SL(\theta) - S_p \log_{10} r \ldots\ldots \\ &+ 40\log_{10} r - 10\log_{10} V(r,\theta) + 2\alpha .r \end{aligned} \quad (1)$$

where RL and SL are the receive and source level intensities in dB, S_p is the time-varying gain spreading coefficient, α is the absorption (dB/m) and V is the range cell volume, defined as:

$$V(r,\theta) = \frac{1}{3\pi}(r_2 - r_1)^3 \frac{\theta_{Nadir}}{\cos(\eta)}\phi \quad (2)$$

where r_2 and r_1 are the radial limits of the cell, ϕ is the along-track 3dB beam-width, θ_{Nadir} is the across-track 3dB beam-width at nadir and η 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 this radius, are then assigned to that point. The process is then repeated for all samples within all the beams of the two-dimensional 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. A large degree of averaging is required because of the nature of the Rayleigh-scattering regime for uniformly distributed spherical-scatterers [2]. To conform to the Rayleigh regime the following inequality must apply:

$$\frac{2\pi}{\lambda} a < 1 \quad (3)$$

where λ is the wavelength of the incident sound wave and a, is the radius of the scatterer. The standard error for n samples of a Rayleigh distribution is approximated by Eq.(4) [3]:

$$\sigma_e \approx \frac{V_{rms}}{2\sqrt{n}} \quad (4)$$

where V_{rms} is the expected back-scatter voltage and n is the number of samples . Hence it can be seen that 100 samples are required for a 5% error in the receive voltage. This equates to an error of approximately 10% in the acoustic intensity and hence concentration estimate.

2.2 Flow Velocity Estimation

Methods of estimating flow velocities have been developed using the cross-correlation of magnitude data between successive pings. The cross-correlation method works in a similar manner to standard Particle Image Velocimetry (PIV) methods. PIV is a commonly used velocity measurement technique in fluid mechanics and has become popular and successful owing to its simplicity, accuracy and low-intrusiveness.

The first step in the method is to convert the averaged reverberation levels (obtained using the method outlined in section 2.1) from polar to Cartesian co-ordinates by performing a two-dimensional interpolation. This allows rectangular windows of data in one ping to be cross-correlated with areas of data in another ping as follows [4]:

$$R(s,t) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} P_1^{i,j}(m,n) P_2^{i,j}(m-s,n-t) \quad (5)$$

where P_1 and P_2 are the rectangular M x N windows of two successive pings. 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, R. The process is then repeated across a grid of different areas in the first ping to produce a two-dimensional matrix of velocity estimates. A refinement has been made by including a gradient-ascent algorithm to find the peak correlation and thus save processing time. This was possible as the correlation peaks were found to be smooth over a large area, which is probably caused by the spatial averaging performed on the magnitude data. Cubic interpolation is performed on the samples around the peak to refine the vector estimate on a sub-pixel level. Temporal averaging is then performed with a simple moving-average for each vector component.

3 Tank Testing

Controlled testing of the 7125 MBES took place in September 2007 at the New and Renewable Energy Centre (NaREC) at Blyth on the Northumberland coast, UK. The tank is a former dry-dock and is approximately 100m x 19m x 6m, with a capacity of around 10^4 cubic metres of water, pumped in on the flood tide of the adjacent estuary. To enable the sonar transducers to remain in a fixed position during the test, a stage lighting-truss was assembled and lifted by crane to a position spanning the 19 metre width of the tank. Figure 2 shows the empty tank with the truss in situ. The mounting pole for the transducers can be seen at the centre of the span.

Fig.2 NaREC tank facility, Blyth, prior to flooding, The MBES mounting pole is at the centre of the span.

The transducers were mounted such that the MBES swath was aligned across the tank. This orientation was chosen to enable a controlled density current to flow through the swath from an outlet box placed on the floor at the centre of the tank. However, the mixing and pumping system introduced large quantities of cavitation bubbles, prohibiting accurate backscatter measurements of the suspended material. An alternative method of introducing suspending sediment into the water column was devised. The method simply consisted of releasing known quantities of wet sediment down a vertical pipe attached to the truss. The end of the pipe fed directly into the MBES swath and the back-scatter from the descending plumes was recorded.

Three sediment types were used during the testing, kaolin clay (D_{50} = 7.4µm) and Ballotini (sand-sized man-made beads), with two different size distributions (D_{50} = 41µm, 270µm). Background recordings were taken every day before sediment was introduced into the dock for different settings of power, gain, pulse length, time-varying gain and for both frequencies of operation. Fig. 3 shows typical data obtained during the tests. The scale is reverberation level, Sv, converted to a normalised, linear scale. This was calculated with Eq(1) using raw magnitude data averaged with a median filter over circular areas with a radius of 12.8cm and over 5 successive pings (repetition rate was 10Hz to allow sufficient time for dissipation). The scale on Fig. 3 will be proportional to mass concentration for a constant grain-size distribution.

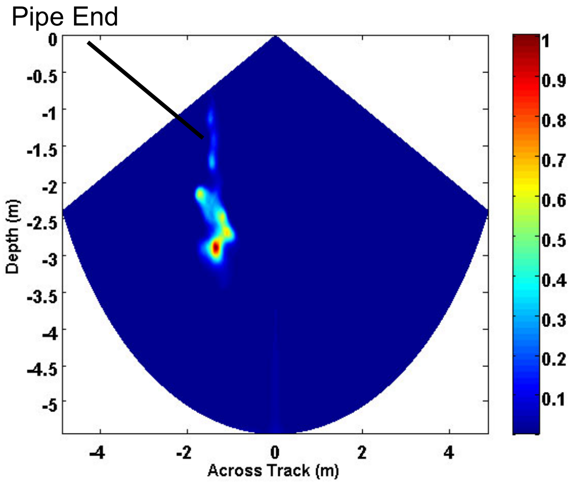

Fig. 3 Gravity plume of 1kg of coarse ballotini released from the end of a pipe.

Various quantities of sediment, ranging from 7g to 1kg were released during the tests, *all* of which were observable in the back-scatter data. Fig. 4 shows one of the later tests with a plume of 400g of the coarser Ballotini beads, around 12s after being released into the pipe. In the background the remnants of a suspension of the fine-grained kaolin clay is visible, released into suspension some minutes earlier. The tests with kaolin were conducted towards the end of the last day of testing owing to the time taken for the suspension to settle. Fig. 4 shows that the MBES successfully resolves the contrast between the Ballotini and the clay suspension.

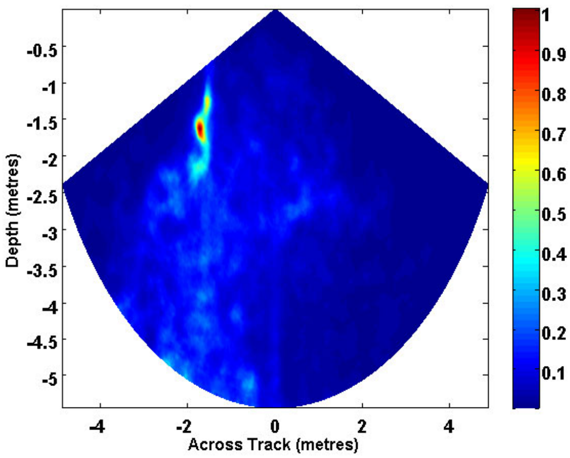

Fig. 4 Descending plume of 400g of coarse Ballotini contrasting with a diffuse background suspension of kaolin clay.

Direct samples were obtained using a Rutner sample bottle lowered into the water column after the sediment had been released. Further samples were also taken using a peristaltic pump system attached to a tube inserted into the end of the release pipe. Work is in progress to calibrate the back-scatter to the sample grain-size distributions and concentrations. The background measurements are also currently being analysed to enable the subtraction of noise across the swath by creating a model of expected noise values for the different sonar settings. Analysis of the effects of the time-varying gain settings on the back-scatter magnitudes is also being undertaken.

The tests undertaken at Blyth show promising results, and with further analysis of the acoustic data and the samples it is hoped to develop more fully the relationship between back-scatter strength and mass concentration.

4 Field Results

Field data was obtained around the confluence site of the Mississippi and Missouri rivers north of St Louis in October 2007. Fig. 1 shows the raw magnitude data of a single ping obtained on the 400kHz setting with 256 beams. The data was collected with the survey vessel moored at a point, positioned over the lee-side of a sand-dune in the Mississippi with the transducers orientated parallel to the flow. The solid line is the bathymetry data from the bottom-finding algorithm. A lee-side slope, with smaller superimposed bedforms, is clearly visible at an angle of around 7-8^o. Within the area above the specular side-lobe arc a typical suspended sediment structure can be advecting with the flow from left to right.

The cross-correlation method described in section 2.2 was applied to this dataset. The magnitude data was averaged using the method of section 2.1 with an averaging radius of 6.4cm, to give mean reverberation levels (arbitrary reference). The data was then interpolated onto a Cartesian grid with 0.025m spacing. Windows of 160 x 160 samples (4m x 4m) were then cross-correlated using Eq. (5). The resultant vectors were then averaged using a moving-average window of 9 pings (Ping repetition rate was 10Hz). The results were obtained over a 3m x 5m grid, with 0.5m spacing. Fig. 5 shows the mean vectors (and their positions relative to the swath) over a period of 70s. The mean horizontal (downstream) component across the grid is 1.35ms^{-1} and the mean vertical component is -0.18ms^{-1} (towards the bed). An Acoustic Doppler Current Profiler (ADCP) was used at the same site and obtained average readings of 1.36ms^{-1} downstream and -0.058ms^{-1} in the vertical, for a depth corresponding to the centre of the grid shown in Fig. 5. The discrepancy between the two vertical values might be explained if the MBES mounting was slightly inclined to the vertical.

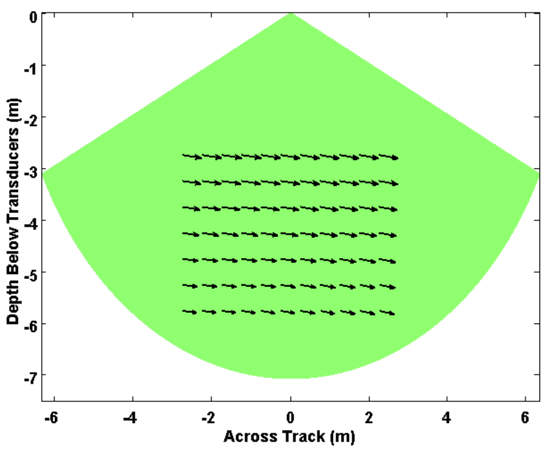

Fig. 5 Mean flow structure velocity vectors over a period of 70s for a grid of vectors with a vertical depth range of –2.75m to –5.75m (below the transducers) and a horizontal range of –2.75m to 2.75m (across track).

Fig. 6 shows the velocity vectors at a single frame in the sequence. The colour scale here depicts the normalised reverberation level of a single ping after averaging. The velocity vectors were averaged for 9 successive pings, centred on the ping shown. The vertical components of flow have had their mean value subtracted and are exaggerated in scale by a factor of 5 to demonstrate their relationship to the advecting suspended sediment flow structure. The area of high concentration and increase in the upward component of velocity are clearly related. Fig. 7 shows the same sequence 2 seconds later. Here in the wake of the structure, the vertical component of velocity is now downward in comparison to the mean values.

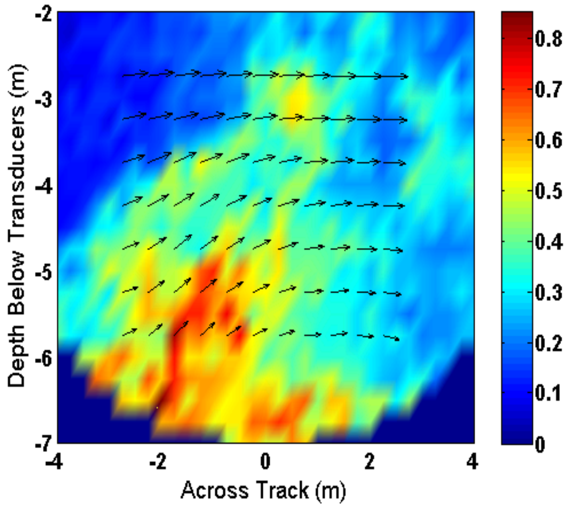

Fig. 6 Velocity vectors estimated for the grid shown in Fig. 5. The background scale is normalised to the maximum reverberation level in the data-set. The vertical components of velocity have had their mean value subtracted and are exaggerated in scale by a factor of 5.

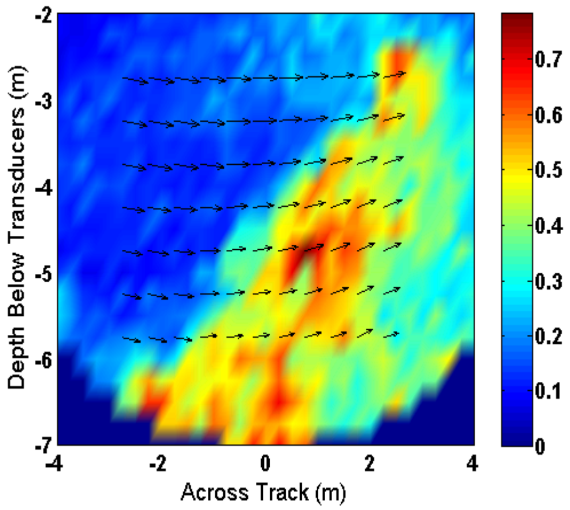

Fig. 7 As for Fig.6, but two seconds later in the data sequence.

Figs 8 and 9 respectively show the two components of velocity for the vertical column of seven vectors on the left-side of the grid over the full 70s time period. The downstream components show a decrease in the velocity gradient towards the bed throughout the sequence, although the size of the gradient and the magnitudes vary significantly in time. The data shown in Fig. 6 corresponds to 8s after the start of the sequences whilst Fig. 7 corresponds to 10s after the start. As the flow structure is passing through the MBES swath at 8s, the horizontal velocity gradient increases and the magnitudes become slower towards the bed. At 10s, the velocity magnitudes have increased and peak in the wake of the structure and then converge to near uniformity around 15s.

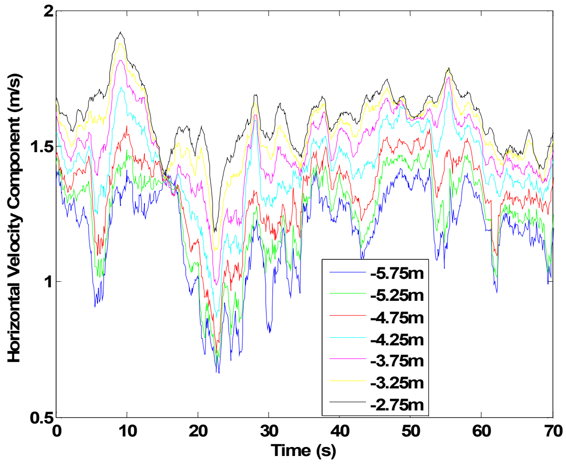

Fig. 8 Variation of the horizontal velocity component for the leftmost column of seven vectors shown in Figs 5, 6, 7. Each is separated vertically by 0.5m over a depth from –2.75m (black) to –5.75m (blue, nearest the bed) below the transducers.

The vertical components shown in Fig. 9 show a peak upward movement at 8s and then move downwards rapidly in the wake to a trough at around 10s.

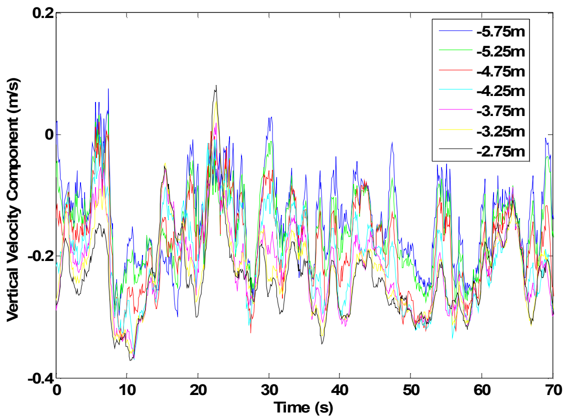

Fig. 9 Variation of the vertical component of velocity for the same vertical column of vector positions as shown in Fig. 8.

5 Conclusions

This paper has demonstrated the potential of MBES systems to concurrently estimate suspended sediment concentration and flow dynamics in two dimensions. Such systems are also capable of high-resolution bathymetric profiling and hence provide a holistic tool for examining the nature of such flows and their relation to the bed topography. Further developments and refinements in this approach hold the key to gaining a better understanding of the interactions of turbulent flow and sediment suspension over bedforms and will enable improved monitoring, modelling and management of environmental systems.

Acknowledgments

Many thanks to RESON Inc., Goleta, CA, for their cooperation with the partnership grant and to Pawel Pocwiardowski, and Eric Maillard for their technical assistance. Thanks to the staff of NaREC, Blyth for their support during the tank testing and to the USGS for their assistance during the field season at St Louis.

References

[1] D.R. Parsons, J.L. Best, R.J. Hardy, R. Kostaschuk, S.N. Lane and O. Orfeo, "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 (2005)

[2] P.D. Thorne, P.J. Hardcastle, R.L. Soulsby, "Analysis of acoustic measurements of suspended sediments", *J. Geophys. Res.* 98(C1), 899-910 (1993)

[3] P.D.Thorne, D.M. Hanes, "A review of acoustic measurement of small scale sediment processes", Continental Shelf Research 22, 603-632 (2002)

[4] C.E. Willert, M. Ghrabi, "Digital particle image velocimetry", *Exp Fluids* 10, 181–193 (1991)