

ON THE STUDY OF BOUNDARY LAYER SEDIMENT TRANSPORT PROCESSES USING NEW DEVELOPMENTAL ACOUSTIC TECHNIQUES

Peter D Thorne¹ David Hurther² Richard D. Cooke³ P. A. Barraud⁴ J.M. Barnoud⁵ I. Caceres⁶ and A. Sanchez-Arcilla⁷

Abstract

This study aims at presenting a set of novel acoustic flow and sediment measuring tools used in a complementary way for the investigation of fine-scale flow and sediment transport processes above a rippled sand bed under waves. Measurements were conducted in the 100m long wave channel at UPC-LIM with surface gravity waves generating migrating ripples on a mobile sand bed. The set of acoustic instrumentation consisted of an Acoustic 3D Ripple Profiler (3D-ARP), a novel Bedform And Suspended Sediment Imager (BASSI) and three Acoustic Concentration and Velocity Profilers (ACVP). Here we assess the ACVP's and the BASSI.

Keywords: Acoustics, instruments, transport, waves, ripples.

1. Introduction

This study aims at presenting a set of novel acoustic flow and sediment measuring tools used in a complementary way for the investigation of fine-scale flow and sediment transport processes above a rippled sand bed under waves. Measurements were conducted in the 100m long, 5m deep and 3m wide wave channel at UPC-LIM as presented in Fig. 1 with surface gravity waves generating migrating ripples on a mobile sand bed. The measurement section was located between $x=55\text{m}$ and $x=58\text{m}$ from the wave paddle with a still water depth at $x=55\text{m}$ equal to 1.65m. The mean bed slope was initially levelled to a value of 1/15. Although not represented here, the bed profile was measured at the end of the experiment with a mechanical wheel profiler to quantify the morphological variation that occurred during the experiment. The distance between the measurement section and the onshore located wave breaking region exceeded 10m in order to limit the effect of breaking induced sediment transport in the measurement section. The sand bed consists of a roughly 50cm thick mobile sand bed layer constituted of a well-sorted medium size sand of $d_{50}=243\mu\text{m}$. Twelve acoustic and resistive wave gauges are distributed along the flume to track the time evolution of the surface elevation and to extract the water level statistics and the corresponding wave properties in the different nearshore regions. Runs of regular waves were generated over 20 minute long sequences containing each 260 waves. The wave period, height and water depth at the wave paddle were set to $T=4.5\text{s}$, $H=50\text{cm}$ and $h_0=2.5\text{m}$, respectively. During the measurement campaign, runs with wave heights between 30cm and 50cm were tested in order to cover a range of ripple dimensions. In the present study, only results for the 50cm wave height are presented.

¹National Oceanography Centre, Proudman Building, Liverpool, UK. pd@noc.ac.uk

²LEGI, CNRS UMR 5519, Université de Grenoble, France

³National Oceanography Centre, Proudman Building, Liverpool, UK.

⁴LEGI, CNRS UMR 5519, Université de Grenoble, France.

⁵LEGI, CNRS UMR 5519, Université de Grenoble, France.

⁶UPC, LIM, Spain

⁷UPC, LIM, Spain

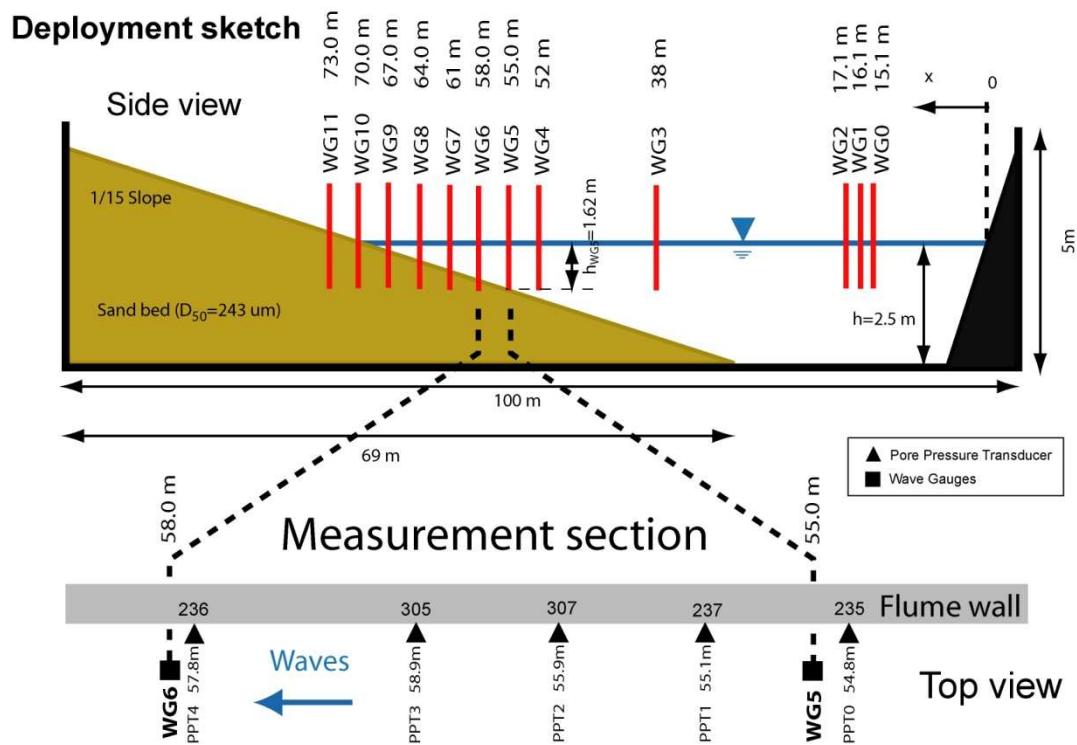


Fig 1 Deployment sketch within UPC wave channel.

The set of acoustic instrumentation consisted of an Acoustic 3D Ripple Profiler (3D-ARP, see Fig. 2a), a novel Bedform And Suspended Sediment Imager (BASSI, Fig. 2a) and three Acoustic Concentration and Velocity Profilers (ACVP). The 3D-ARP measured the time evolution of the bedforms over a bed surface area corresponding to roughly 7m^2 . This topographic survey was performed after each wave run when still water conditions are fulfilled. Therefore, no other acoustic system is working during the bedform mapping provided by the 3D-ARP. The bed area covered by the ARP can be approximated by a circular shaped surface with a roughly 1.5m radius and its was center located at the position of the ARP as seen in Fig. 2c. Fig. 2c also shows that fraction of this circular shaped area is extending beneath the BASSI in order to provide co-located bedform measurements by the 3D-ARP and the BASSI. The BASSI is a novel acoustic instrument for high rate 2D imaging of suspended sediment concentration over a 1.5m long by 1m high image. The 2D bedform evolution over this 1.5m long transect was also measured by the BASSI. In our application, the transect was oriented in the cross shore direction corresponding to the wave propagation direction.

In Fig. 2 the positions of three Acoustic Concentration and Velocity Profilers (ACVP) named ACVP1, ACVP2 and ACVP3 can be seen. These acoustic systems measured vertical profiles of one dimensional two component, 1D2C, velocity, the sediment concentration and the bed interface positions across the nearbed flow region. Both the BASSI and the ACVP observations were obtained at the intra-wave and intra-ripple temporal and spatial resolutions respectively. In the following, the measurement performance of the ACVP's and the BASSI systems are discussed.

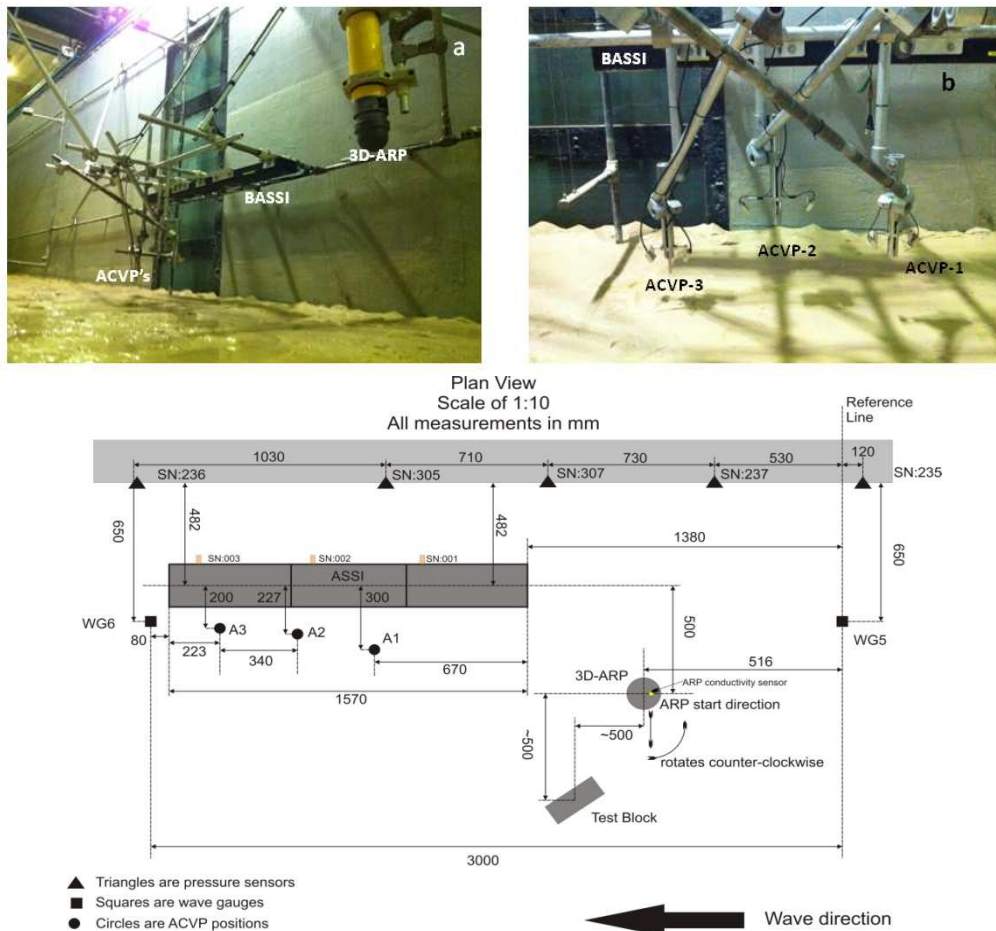


Fig 2 (a) Acoustic instrumentation setup showing the 3D-ARP, the three ACVPs and the BASSI. (b) Sideview of the nearbed ACVP-3 at 10 cm above the bed, the two standard ACVPs at more than 20cm above bed and the BASSI aligned in cross-shore direction of the Barcelona wave flume. (c) Plan view of the measurement section showing the positions of the acoustic instruments.

2. ACVP measurements

Three ACVP systems composed of one emitter and two receivers each have been deployed in the measurement section as shown in Fig. 2c. ACVP1 and ACVP2 (noted A1 and A2) were placed at a distance of 20 to 30cm (see Fig. 3) above the bed to perform velocity and sediment transport measurements across both the suspension and the bedload layers. However, due to their limitations of vertical resolution (3mm) and acoustic profiling range, the third ACVP3 has a specific geometric configuration and electronic hardware for profiling across the nearbed flow layers such as the bedload layer. As seen in Fig.3, this nearbed ACVP was located at 10cm above the sand bed. Its vertical and temporal resolution was equal to 1.5 mm and 30 ms, respectively. In order to compare measurements obtained with the BASSI system, the three ACVPs were positioned in the 1.5m long measuring volume of the BASSI as seen in Fig. 2c. Nevertheless, the ACVPs were separated laterally from the BASSI by a distance of at least 20cm to avoid acoustic interferences between the ACVP pulses and the BASSI pulses.

All three ACVP systems combine ADV and ABS technologies as previously described in Hurther et al. (2011) and Thorne et al. (2011). They provide 1D2C velocity and sediment concentration profiling at a high spatial-temporal rate allowing the resolution of intrawave scales including a range of small turbulence flow scales. In addition to these profiling abilities, the nearbed interface tracking method applied in Hurther

and Thorne (2011) is used here to evaluate the vertical position of the non moving sand bed and the overlaying suspension interface relative to the measured 2C flow field (in section 2.1).

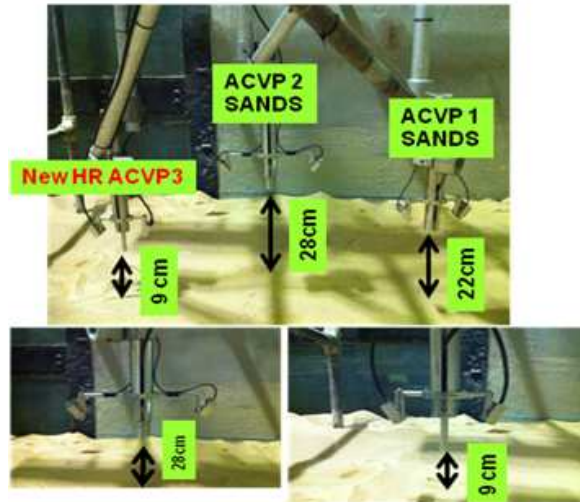


Fig 3 Settings of ACVP1, ACVP2 and ACVP3 (new High Resolution ACVP)

Fig. 4 shows the wave velocity over one period obtained after phase averaging the velocity time series measured by the ACVP2 at a distance of 20cm above the bed. This point is outside the wave boundary layer (only few centimeters high) and therefore the wave velocity in Fig. 4 represents the free-stream wave velocity. The phase averaging ensemble is composed of 144 consecutive regular waves in one of the 20 min long wave sequences. As can be seen in Fig. 4, the wave shape reveals a positively skewed velocity field due to the higher velocity amplitude during the wave crest (0.64m/s) compared to the lower one during the wave trough (0.5m/s). Furthermore, positive acceleration skewness can also be seen due to the non-symmetrical wave trough half cycle around the trough point at $t/T=0.87$.

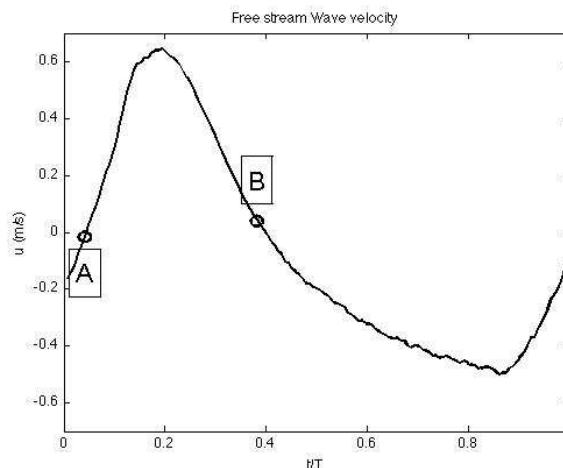


Fig.4 Phase averaged free stream velocity (144 consecutive waves) measured by ACVP2 at 20cm above the sand bed. Points A and B represent the flow reversal events at which the intrawave velocity structure is analyzed in section 2.2

2.1 Mean 2D2C flow above a migrating sand ripple

Fig. 5 represents the time averaged 2C velocity field along a ripple profile measured with the ACVP2 over a duration of 15 minutes. The x axis in Figs. 5 was obtained by assuming a constant ripple migration speed

V_r , during the passage of the bed ripple trough beneath the vertical ultrasound beam of ACVP2. Assuming a migration speed of few centimeters per minute as measured in Hurther and Thorne (2011), the migration time detected by the ACVPs can be converted into migration distance as shown in Figs. 5. Also represented in Figs. 5a and 5b, are the bed interfaces detected by ACVP2. The solid black line is the non moving sand bed and the dashed black line corresponds to the suspension interface seen by ACVP2. The 2C velocity field shown in Figs. 5 was averaged over 4 consecutive wave periods. This quantity corresponds to the 2C velocity streaming above the migrating ripple. The colour plot in Figs. 5 represents the time averaged cross shore velocity u . Outside the wave boundary layer, the mean velocity u is oriented in offshore direction all along the ripple profile and with a maximum value of about -0.12m/s above the ripple crest. In the nearbed region, the red colour region seems to indicate a mean onshore oriented streaming. In order to check this boundary layer induced effect, the high resolution measurements obtained with ACVP3 are shown in Fig. 5b. The measurements across the nearbed region clearly show the presence of an onshore oriented u streaming in the nearbed stoss region of the ripple. On the lee-side, this velocity reduced to negligibly low value compared with the value observed in the free stream region. Furthermore, the suspension interface reveals the presence of thicker bedload layer on the lee-side of the ripple compared to the stoss-side. Whether this layer is indeed associated with a zone of more intense bedload transport will be analyzed further on the basis of the sediment concentration and sediment flux measurements.

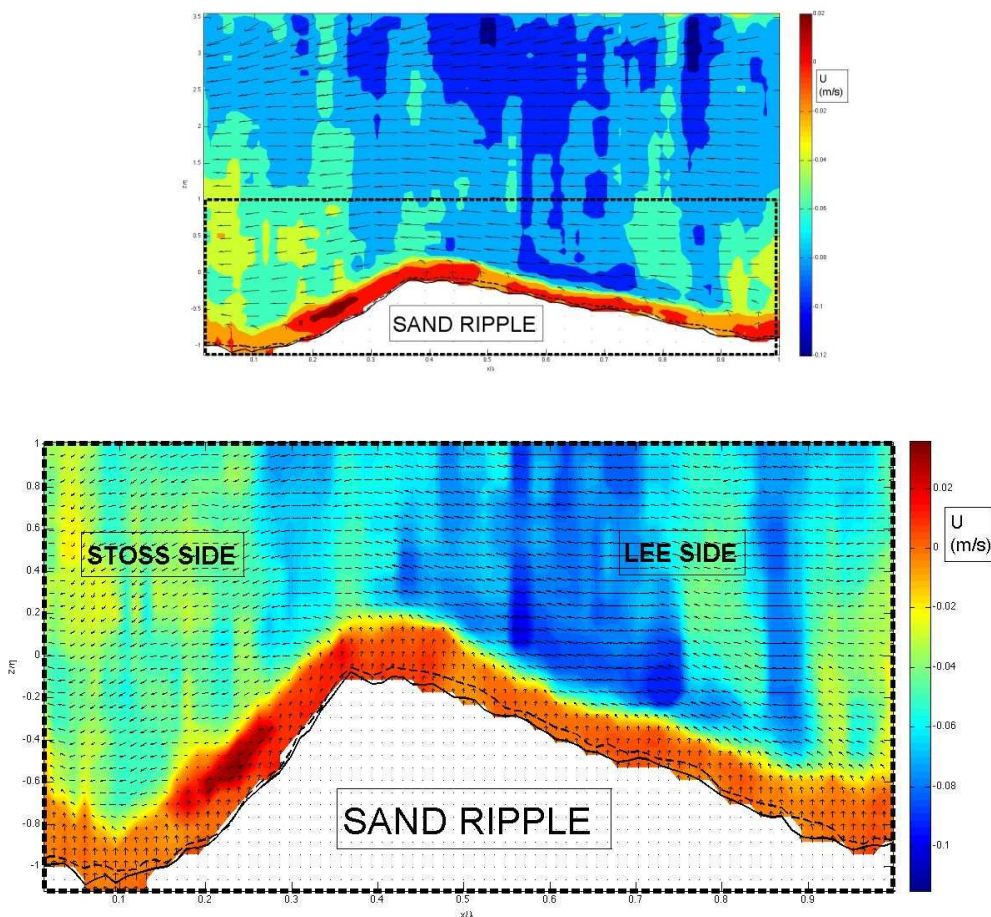


Fig. 5 (a) Time-averaged 2C velocity field along a migrating ripple profile (measured by ACVP2). The coloured background represents the colour plot of the cross shore velocity u . The solid black line represents the detected non-moving sand bed and the suspension interface, respectively. (b) High resolution 2C mean velocity measurements provided by the nearbed ACVP3.

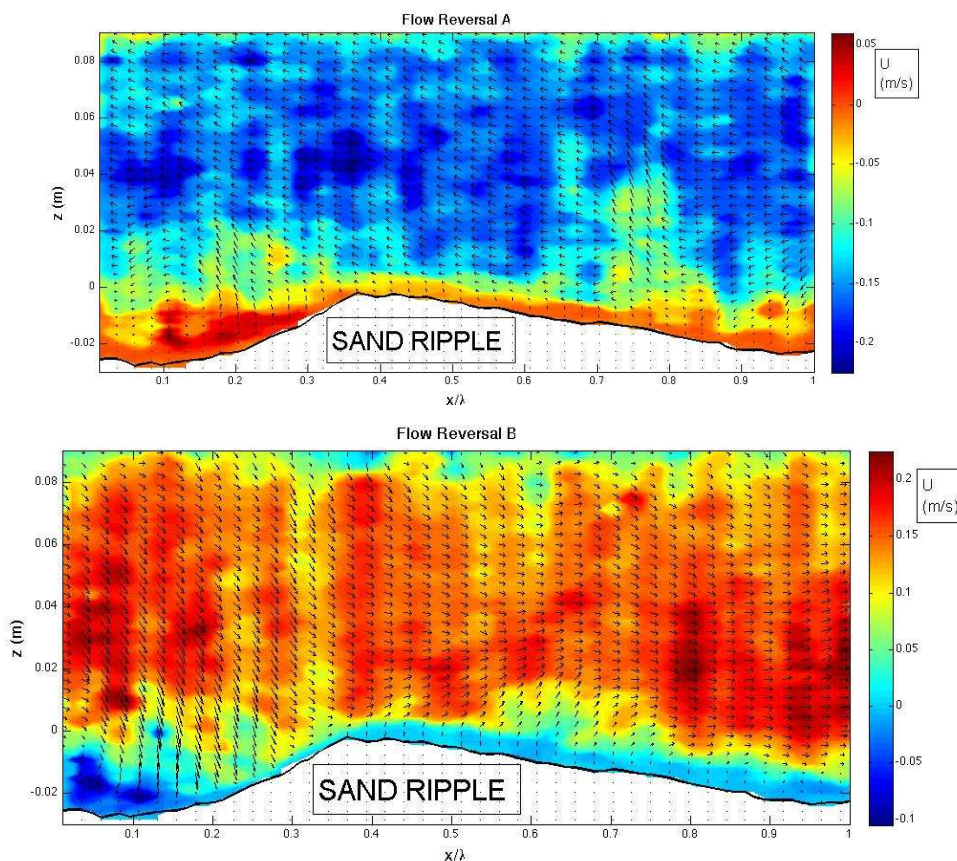


Fig. 6 (a) Instantaneous 2C velocity field along a migrating ripple profile around flow reversal A (measured by ACVP3). The coloured background represents the colour plot of the cross shore velocity u . The solid black line represents the detected non-moving sand bed. (b) Same measurements around flow reversal B. Flow reversals A and B are shown in Fig. 4

2.2 Intrawave flow behaviour around flow reversals

Figs. 5 presented the 2C velocity streaming along the ripple profile. In order to check for the presence of ripple vortices at the intrawave scale, the instantaneous 2C velocity field can be visualized around the flow reversals events noted as A and B in Fig. 4. For this purpose, the high-resolution measurements provided by ACVP3 are used. Fig. 6a shows the instantaneous velocity around flow reversal A. This event is associated with the presence of a well defined ripple vortex on the stoss side. Fig. 7b shows the same quantity around the second flow reversal event B in the wave cycle. In this case, no counter-rotating ripple vortex can be seen in the lee-side domain of the ripple. This reveals the very different contribution of the ripple vortices on either side of the ripple crest.

3. Bedform And Suspended Sediment Imager, BASSI, measurements

3.1 System overview

The BASSI consisted of three transducer line arrays, each of which was connected to a single electronic scheduling unit that controlled the sampling parameters (Moate et al 2011). A schematic of the system is presented in Figure 7, showing only a single transducer array for clarity. Each transducer array housed 15 individual narrow beam disc transducers that functioned at fixed operating frequencies, with three different frequencies interleaved across the array; these were 2.5, 1.25, and 0.75 MHz. The transducer arrays were

designed to be compact, being 0.5 m long, 0.14 m wide and 0.07 m in depth, to minimise any hydrodynamic impact of the arrays on the sediment processes being measured. In the present study the three transducer arrays were connected inline, and the complete system consisted of 45 transducers spaced regularly at 33 mm intervals over a 1.5 m range in the horizontal.

The scheduling unit included a programming interface. In the present study, the BASSI was triggered as required, over a 1 metre vertical profile, with a vertical spatial resolution of 0.5 cm. Each recorded profile was an average over 8 successive transmissions, with the recorded profile rate being 6 Hz. The scheduling unit included additional sensors for temperature and pressure, although in the present study these sensors were not used. The BASSI operated autonomously from an external 12 V battery, with a total current consumption of ~ 650 mA when active and logging data.

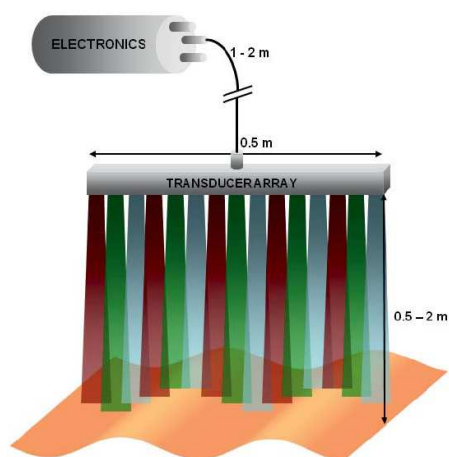


Fig 7 Schematics of a single BASSI array

3.2 Transmit/receive and logger specification

For each transducer array, all functions were controlled by an internal microprocessor, including the generation of the three operating frequencies, and the digitisation of the receiver outputs by an onboard 10 bit analogue to digital (A/D) converter. The circuitry was identical for the three operating frequencies, consisting of frequency dedicated pre-amplifiers connected to a differential bandpass filter, with the output signals then input to logarithmic amplifiers. Logarithmic amplifiers were used to provide a large dynamic range, being ~ 90 dB here. When transmitting, the system energised only one group of three frequencies at once, being three adjacent transducers in a given line array, and recorded the receiver output before advancing along that array to the next group of three frequencies. When multiple transducer arrays were connected, as was the case here, then all arrays operated in parallel. Hence, 5 transmit/receive cycles were required to sample across the whole array, and this operation mode minimised cross talk and reverb across the system. Following data capture, the data were converted to 16 bit linear numbers onboard, and an average over 8 successive transmissions calculated and then written to two 32 GB internal USB flash drives, providing sufficient storage to enable the instrument to be deployed for multiple tidal cycles. The scheduling unit allowed the transmit pulse length to be specified, and this was chosen to be 20 μ s as this matched the bandwidth of the logarithmic receivers. The scheduling unit also allowed an additional transmits delay between successive pulses to be specified, primarily to allow reverb to fully dissipate when working with the system in shallow bounded test tanks. In the present study this transmit delay was set to the minimum value possible, being 0.1 ms.

3.3 Observations and assessment of the BASSI

To examine the internal consistency of the BASSI a comparison was made of the suspended sediment time

series at each of the three frequencies for array 2. The results with height above the bed, z , are shown in figure 8. Each of the three plots show suspended sediments being entrained into the water column by the waves and as can be clearly seen the structure of the time series of the suspended sediments is comparable at each of the three frequencies. This provides confidence in the veracity of the data collected by the BASSI. Although not shown for brevity similar internal consistency was observed for array 1 and array 2.

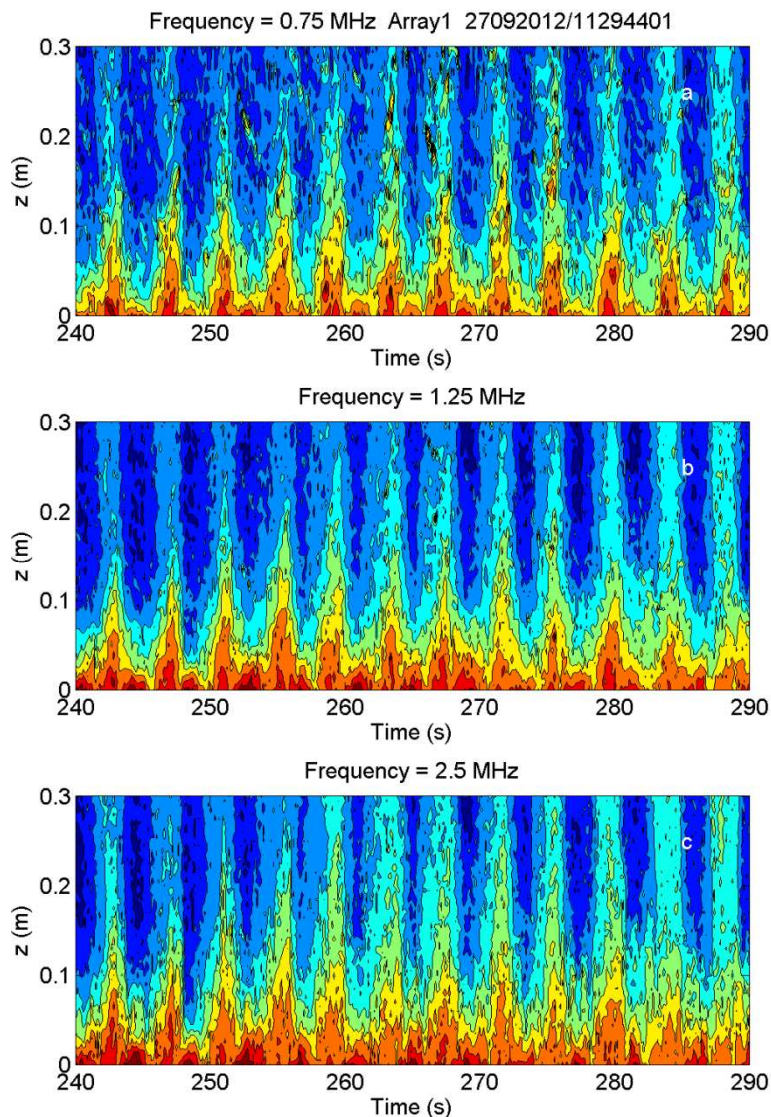


Fig 8. Temporal structure of the suspended concentration observed at the three frequencies for array2. Red high concentration and blue low concentration.

To examine the consistency of the suspended sediments between arrays, 20 minute temporal mean normalized concentration profiles at each of the three frequencies for each arrays was calculated and the results are shown in figure 9. It can be seen that to first order the concentration profiles for the different frequencies and arrays are consistent with one another, providing further evidence that the BASSI is performing as expected from the design specifications.

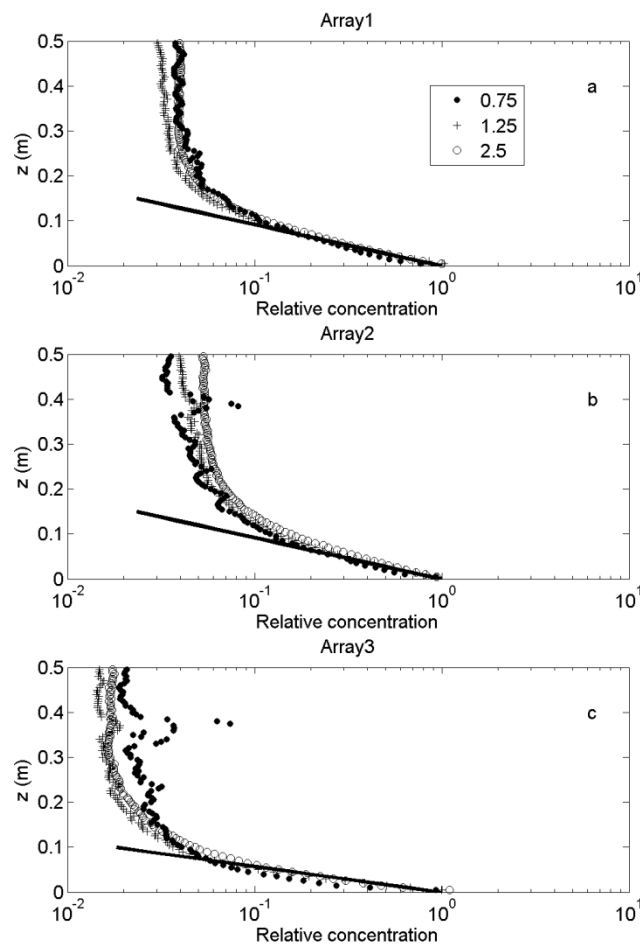


Fig 9 Comparison of 20 minute mean concentration profiles for the three arrays. At the three different frequencies

4. Conclusion

Detailed insight into the wave boundary layer structure is allowed by the use of the high resolution nearbed ACVP. The measurements show the presence of boundary layer streaming components that are non-homogeneously distributed along the ripple profile. Furthermore, the intrawave measurements around the two flow reversals in the wave cycle, have shown the existence of a well defined ripple vortex on the ripple stoss side but no equivalent vortex could be detected on the ripple lee-side around the opposite flow reversal. This reveals the highly non-symmetrical ripple vortex dynamics within the wave cycle.

Regarding the BASSI simple analysis has been conducted to assess the performance of the instrument. This focused on high temporal resolution measurements of the suspended sediment to assess the internal consistency of an array and mean profiles to assess consistency between arrays. The results were of sufficiently similarity to provide confidence in the veracity of the data collected by the BASSI.

Acknowledgements

This work was partly funded the EU HydralabIV-WISE programme. We also thank the support of CIEM technical staff in the experiments

References

- Hurther, D, Thorne, PD and Bricault M, Lemmin U and Baroud JM. 2011. A multi-frequency acoustic concentration and velocity profiler (ACVP) for boundary layer measurements of fine-scale flow and sediment transport processes. *Coastal Engineering*. 58, 294-605 doi: 10.1016/j.coastaleng.2011.01.006.
- Hurther, D., and Thorne, P. D. (2011). Suspension and near-bed load sediment transport processes above a migrating, sand-rippled bed under shoaling waves. *Journal of Geophysical Research C: Oceans*, 116, 07001.
- Moate BD, Thorne PD and Cooke RD. 2011. Acoustic Backscatter measurements in two dimensions. The acoustic suspended sediment imager. Proceedings of the 4th International conference on *Underwater Acoustic Measurement: Technologies and Results*, Kos, Greece. Edited by John S. Papadakis and Leif Bjorno. 1579-1584.
- Thorne, P. D., Hurther, D., and Moate, B. (2011). Acoustic inversions for measuring boundary layer suspended sediment processes. *Journal of the Acoustical Society of America*, 130(3), 1188–1200.