Underwater acoustic scattering and its application to sediment transport physics in coastal and river flows

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Environmental fluid Mechanics and hydraulics are facing important scientific and technological challenges imposed by the impacts of global climate change on the coastal, estuarine and river environments. Coastal and river sediment transport during climatic energetic and extreme events such as storms, hurricanes or cyclones are known to control the coastline and the morphological evolutions of the coastal nearshore zone and the continental watersheds. Under such extreme forcing conditions, the flow and the sediment transport regimes are particularly intense and our knowledge of the underlying key interaction processes between the water flow, the mobilized sediments and the flow bed morphology, remains very limited today. The concept of the Sediment Transport Triad originally proposed by [1] illustrates the complexity of the dynamical interactions between these three components of aquatic environments. Different examples will be discussed as well as the physics involved in the sediment transport processes within the bottom boundary layer. In particular, the difficulties to measure high-resolution flow and sediment transport data across the active nearbed sediment layers known as the suspension and the bedload layers, will be described. Why and how underwater acoustic scattering is currently used as a powerful measurement technique in this field of research will be presented and discussed in the keynote lecture.

Keywords: Acoustic flow instrumentation, sediment transport, Pulse coherent Doppler systems, Acoustic Backscattering Systems, turbulence, Doppler noise, de-alaising techniques

1 THE HIGH-RESOLUTION ACOUSTIC CONCENTRATION AND VELOCITY PROFILER (HR-ACVP) TECHNOLOGY

The HR-ACVP technology (see Fig. 1) developed within the european projects Hydralab 3 & 4 will be presented. This technology provides co-located high-rate profiling of the multi-component velocity field and the sediment concentration as proposed in [2] It combines multi-frequency incoherent scattering techniques used in Acoustic Backscattering Systems (ABS, [3]) with multi-bistatic pulse-to-pulse coherent Doppler velocity techniques used in Acoustic Doppler Velocity Profilers (ADVP, [4], [11], [12]). The measurement principles, performances and limitations will be presented. The following hardware and signal processing methods developed to overcome certain of these limitations will be described:

(a) the Doppler noise reduction methods used to improve the measurement accuracy of the turbulent flow quantities. These cross-correlation techniques are based on the simultaneous measurement of a redundant but statistically independent velocity component in the same acoustic sample volume. The Doppler noise variance is directly estimated for the redundant velocity component and evaluated theoretically for the other measured components using the geometrical transformation matrix as proposed by [5]. The velocity redundancy can be obtained from an additional receiver as originally proposed by [5] or from an interlaced dual-frequency transmitting mode as proposed in [6].

(b) the de-aliasing technique used to overcome the velocity-depth ambiguity range imposed by the pulsed operation mode of coherent Doppler systems. The method proposed in [2] allows to increase the resolved Doppler velocity range by 100% to 200% depending on the selected de-aliasing mode. Compared to other well-known de-aliasing techniques such as the dual-PRF method or the Doppler phase-tracking method, this method does not require any specific hardware modifications. It relies on a specific post-processing method of the Doppler frequencies as will be shown in the presentation. It is particularly well adapted to oscillatory flows such as propagating surface gravity waves in the coastal region.

(c) the dual-frequency inversion method used to improve the sediment concentration profiling across the dense nearbed sediment layer known as the bedload layer. In this flow region, the acoustic intensity is subject to strong attenuation induced by sediment scattering effects. Consequently, the inversion equation becomes implicit and is subject to severe inversion instabilities when the standard iterative implicit inversion method is used. The dual-frequency inversion method proposed in [2] and [7] eliminates these inversion instabilities by the use of two acoustic frequencies in the Rayleigh scattering regime.

(d) the Acoustic Bed Interface Tracking (ABIT) method used to determine the vertical position of the non-moving flow bed. This currently developed technique separates the bed echoe affected acoustic intensity from the one scattered by the moving sediments. As a consequence the vertical position of the flow bed can be tracked as a function of time under flow conditions subject to bed erosion or accretion. How this powerful technique is used in sediment transport process studies is shown in the second part of this keynote lecture.

2 APPLICATION TO BOUNDARY LAYER SEDIMENT TRANSPORT PHYSICS IN COASTAL AND RIVER FLOWS

Two studies in which the HR-ACVP technology is used as the principal investigation tool will be presented. The first concerns the ripple vortex regime occurring under coastal waves above a sand bed constituted of orbital ripples ([8]). The second study focuses on the migration mechanisms of sand dunes in rivers subject to strong forcing conditions during floods ([9]).

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2.1 The ripple vortex regime under coastal shoaling waves

Nearly full-scale ripple vortex experiments over a mobile sand bed have been carried out in the large-scale wave channel at the Catalonia University of Technology, Spain. An instrument rig holding a set of acoustic flow measuring instruments (**A**coustic **B**ackscattering **S**ystem, **A**coustic **R**ipple **S**canner, **A**coustic **C**oncentration and **V**elocity **P**rofiler) has been deployed in the wave shoaling region of a barred beach profile (Figs.2a-b).

The time-averaged sediment flux along a ripple profile (Fig.2a) reveals the presence of an offshore oriented sand transport (blue color) in the suspension layer which emanates from the mean lee-side flow circulation rotating in clock-wise direction (pink circle on the lee-side of the ripple crest in Fig. 2a). This mean rotational flow pattern is the residual velocity of the lee-side ripple vortex. In the nearbed region, onshore oriented (red colour) net sand transport is observed over more than 70% of the ripple length. The corresponding spatial averaged sediment flux (along the ripple profile) shown in Fig.2b, confirms the presence of a net sand transport in opposite directions between the upper suspension and the lower bedload layer. In order to understand the underlying physical process, intrawave flow and sediment transport processes are then discussed based on the quasi-instantaneous measurements shown in Fig.3.

Similar to the water tunnel experiments of [10], it is shown here for real gravity surface waves, that the difference in strengths of the ripple vortices on either side of the crest (Fig.3 sequences A and D) are due to the positive wave velocity skewness under shoaling waves. Sediment entrained by the lee-side ripple vortex is consequently more important than the stoss-side ripple vortex entrainment. Because of this lee-side vortex dominated sand entrainment, around the flow reversal between wave crest and trough (i.e. phase lagged relative to the wave crest), the subsequent sediment advection in the offshore direction dominates the mean suspension transport. The total net sediment transport (integrated vertically) is discussed in relation to the experimental and numerical studies of sediment transport above migrating sand ripple under skewed oscillatory flows ([10]).

2.2 Mechanisms of sand Dune migration in steady uniform river flows

During floods, bedforms develop on the river bed. Dunes are the most common bedforms in lowland river channels consisting of sand and gravel. They have heights of 10-30% of the water depth and lengths around 10 times their height. River bedforms influence water levels significantly, because they impose roughness on the flow. Knowledge about bedform evolution and associated roughness remains limited today. In this context, two intensive campaigns of river dune experiments have been conducted in 2011 and 2012 at the Leichtweiss Water Institute of the Tech. University of Braunschweig, Germany. The results obtained in [9] will be summarized here. Fig. 4 (upper panel) shows the type of sand dunes generated under steady uniform open-channel flow conditions. The HR-ACVP in its 1D2C version has been used as the principal flow and sediment transport investigation tool. The middle panel in Fig. 4 shows the mean streamwise velocity profiles measured along one dune wavelength. The typical flow recirculation zone on the lee-side of the dune can be clearly observed. The lower panel in Fig. 4, represents the mean horizontal sediment flux extracted from the simultaneous and co-located measurement of the velocity and sediment concentration profiles. Using the ABIT method decribed in section 1, the capacity to estimate the total transport in the bedload and the suspension layers will be discussed. How these different loads contribute to the bed morphodynamics as steamwise migrating sand dunes will be developed.

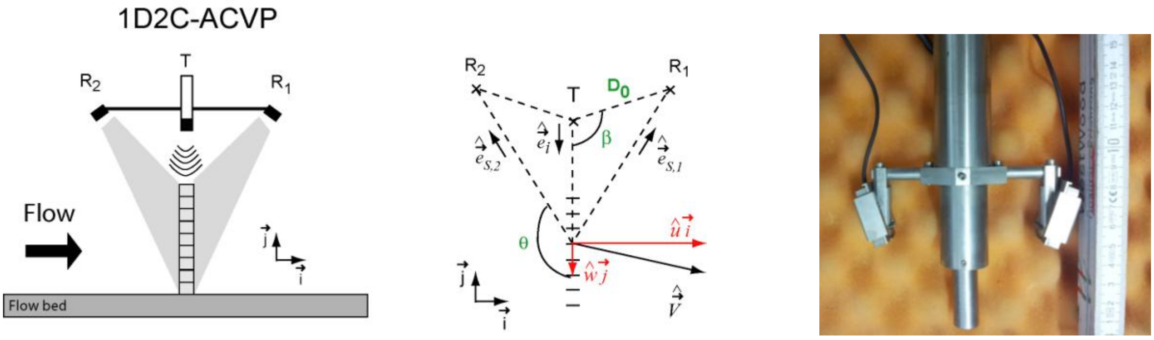

Fig. 1 On the L.H.S., Sensor setup of an HR-ACVP configured as a 1D2C system. In the middle, the corresponding local velocity decomposition. On the R.H.S., a photograph of the sensor head developed by LEGI.

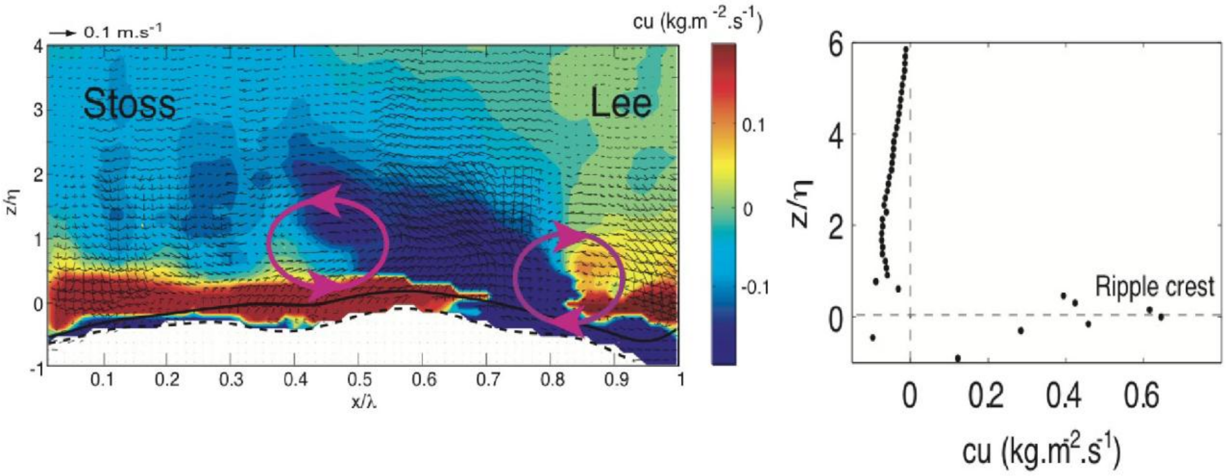

Fig. 2 (a) ACVP measurements along a ripple profile of the time averaged vector velocity field and cross-shore sediment flux. The dashed and solid lines respectively represent the undisturbed sand bed and the suspension interface. (b) Spatial averaged sediment flux (along ripple profile)

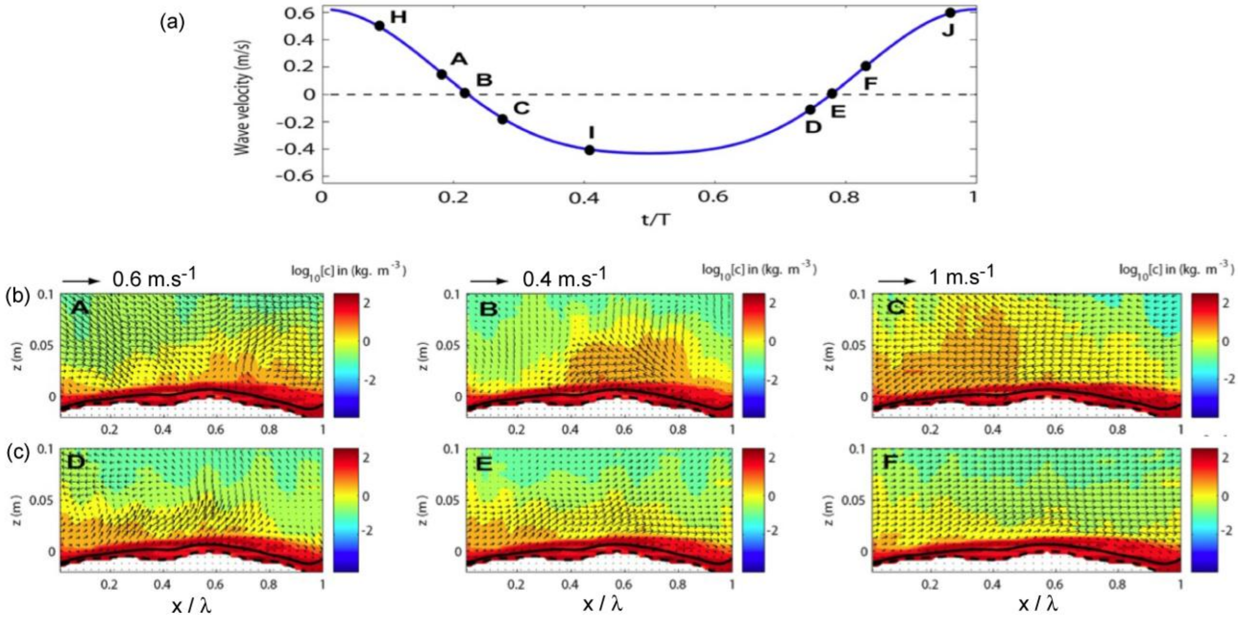

Fig. 3 (a) Wave velocity over one cycle. (b) Selected sequences in the wave cycle of the velocity field ***V***(*u*,*w*) overlaid onto a colour plot of $\log_{10}(c)$ the suspended concentration

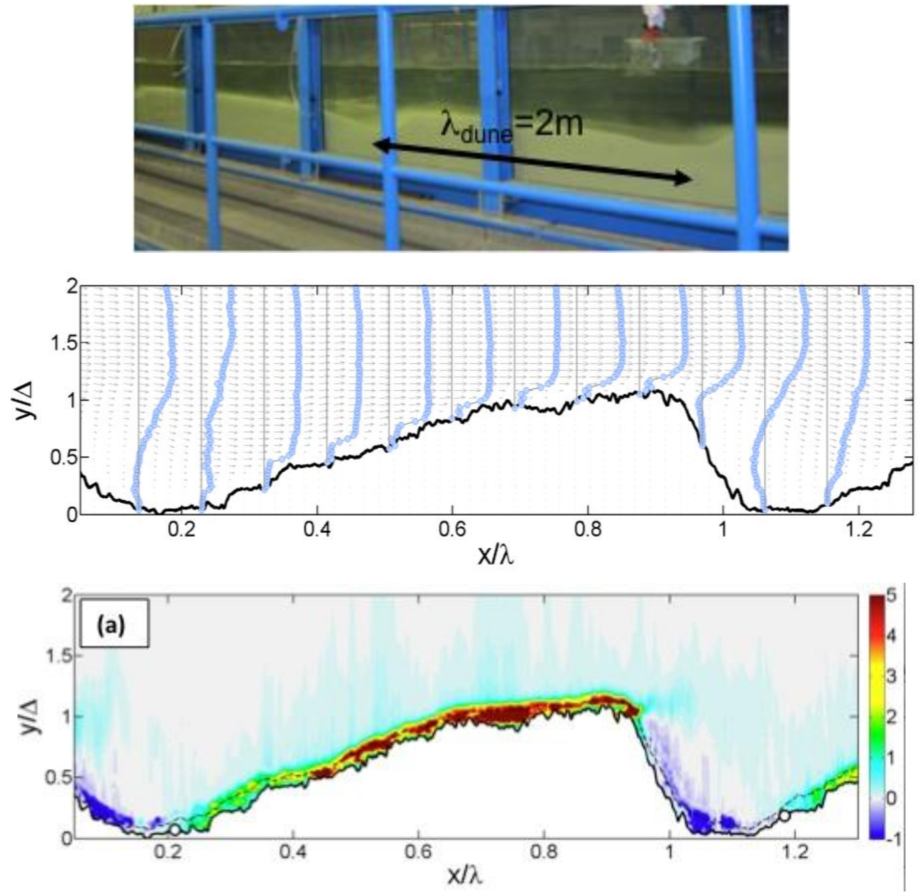

Fig. 4 (Upper panel) Photograph of the dune experiment conducted at the LWI Institute at TU Braunschweig, Germany. (Middle panel) Mean 2C velocity measurements provided by the HR-ACVP. (Lower panel) Mean horizontal sediment flux colourplot obtained measure with the HR-ACVP.

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