© 2006, Proceedings of the First International Conference on the
Application of Physical Modelling to Port and Coastal Protection. ISBN 90-78046-04-X

PERFORMANCES OF ULTRASOUNDS TECHNIQUE IN PHYSICAL MODELLING OF COASTAL PROCESSES

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Abstract

A summary is given on the use of UltraSound techniques in application to physical modeling of coastal flows. Specific attention is paid to the instrumentation based on the use of Acoustic Doppler Velocimetry and advantages/disadvantages with respect to other available techniques are discussed. A few examples are proposed of applications to the measurement of mean flows induced by wind waves propagating, with breaking, over a beach.

1. Introduction

Boundary layer-type environments are not rare for application to physical modelling for coastal hydro-morpho-dynamics purposes. Due to the increasing attention and importance of the use of acoustic techniques to measure velocity and turbulence in such environments, we find it useful, for those who plan laboratory or field measurements in strongly aerated flows with wave breaking and in very shallow water, a discussion on the capabilities and limits of UltraSounds (hereinafter US) in conditions for which other instruments are not suitable.

In the last few decades many techniques have been developed to measure flow fields and turbulence, which are based on a variety of principles. Measuring fluid velocity under gravity waves and bores with Laser Doppler Velocimetry (LDV), Hot Wire and Hot Film anemometry (HV), Particle Image Velocimetry (PIV) gives excellent results but has several limitations essentially due to air bubbles. The Doppler Ultrasonic technique, which is a good candidate for measurement of complex two-phase flows, has been used to measure water flows for wide engineering applications and it is now a widely recognized tool to study the physics of fluid flow (Takeda, 1999). The technique was initially applied to measure flow velocities within a single volume (Acoustic Doppler Velocimetry, ADV) and then applied to obtain velocity measurements at several points along a given axis (Acoustic Doppler Velocity Profiler, ADVP or Acoustic Doppler Current-meter Profiler, ADCP for field applications).

The ADV (Kraus *et al.*, 1994) is now a commonly used instruments for velocity measurements over a wide range of applications in the laboratory (Voulgaris and Trowbridge, 1998; Doering and Baryla, 2002; Sancho *et al.*, 2001, and many others) and in the field, in the surf zone (Crawford and Hay, 2003; Smyth *et al.*, 2002; Elgar *et al.*, 2001 and many others) and in the swash zone (Raubenheimer, 2002; Raubenheimer *et al.*, 2004). More sophisticated, the ADVP is able to measure velocities along a beam axis. Experiences of Acoustics instruments aimed of measuring currents in nearshore waters are presented in Lane *et al.* (1999), where the advantages of this technology with respect to others often used in the field are discussed.

In view of the increasing attention and importance of the use of acoustic techniques to measure velocity, velocity profiles and turbulence, the present paper focuses on the performances of US for measurements in laboratory breaking waves and shallow-water bores (Longo *et al.*, 2001; Archetti and Brocchini, 2002; O'Donoghue and Hondebrink, 2006) where non-intrusive instruments are needed and high temporal and spatial resolutions are requested.

Beyond giving a broad overview of US flow measurements, specific attention is paid to the applications of instrumentation based on the use of Acoustic Doppler Velocimetry and to describe advantages/disadvantages with respect to other available laboratory techniques. A few examples are illustrated of specific applications to the measurement of mean flow induced by wind waves propagating over a beach.

2. Description of US measurements: operation, performances, advantages and possible problems.

2.1 The operation

The principle of operation of acoustic velocity instruments is based on the Doppler effect. The working principle, described in detail in Takeda (1995) and in Lemmin and Rolland (1997), is the following: acoustic waves, with a given frequency in the US range and speed, are emitted by a transducer and travel through the space filled with targets which move with velocity *(U, V)*, whose component in the direction of the ultrasonic beam is u (also known as radial or axial velocity). The waves are reflected by the targets (represented by omnipresent density interfaces such as solid particles, seeding, air bubbles, plankton, density differences created locally by dissolved salts) and the echo has a different frequency respect to the incident signal. For a stationary receiver and emitter located at the same position (monostatic configuration) the difference between the frequencies of the emitted and received signals, called the Doppler frequency, is proportional to the radial (or axial) velocity u.

Most acoustic velocimeters are based on a pulse-to-pulse coherent configuration (Lhermitte and Serafin, 1984; Zedel *et al.*, 1996): the "pulse" is a short train (burst) of typically four to eight sinusoidal waves with frequency f_0 which is emitted from the transducers into the water and is repeated at a lower frequency, called the pulse repetition frequency f_{PRF}. By gating the received signal to correspond to the pulse's time of flight to a certain depth, a small sampling volume, usually called "gate", can be interrogated. In this way a complete velocity distribution can be obtained on a sequence of gates, which can be considered to be interrogated simultaneously. Physical relationships among the maximum measurable depth, the f_{PRF} and the maximum unaliased velocity, u_{max} and f_0 can be easily recovered to link u_{max} with h_{max}.

For example, in water with a 1 MHz emitting frequency the maximum radial velocity is u_{max} ~5.6 m/s for $h_{max} = 5$ cm, while $u_{max} \sim 0.18$ m/s for $h_{max} = 1.5$ m. The instruments can measure over a large number of gates. This feature, combined with different emitting frequencies and numerous pulse repetition frequencies, allows for application of the ultrasonic Doppler velocimetry to a wide range of applications.

Several configurations of measurements were developed for a monostatic ADVP, able to measure the velocity component in the direction of the beam of a piezo-electric transducer axis, and more recently for bi-static ADVP (e.g., Rolland and Lemmin, 1997) which can measure profiles of two (or three) components of the instantaneous velocity vector.

Unlike the coherent Doppler approach, measurements based on a more recent technique, called Cross Correlation Velocity**,** employ a pair of horizontally-separated transducers directed vertically downward and the cross-correlation of the backscattered signals from the transducers pair is used to obtained flow velocity. The technique and some laboratory measurements are described in Thorne and Hanes (2002).

2.2 The performances

A significant advantage of US with respect to other fluid velocity measurement techniques is that they can be used in optically-opaque, relatively highly concentrated fluids (Ouriev, 2000) like mud (Besque *et al.*, 2000), and in high-temperature fluids like liquid sodium (Eckert and Gerbet, 2002). ADVPs can be non-intrusive with the probes installed directly in the flow field or encapsulated in supports outside. In the latter case refraction occurs of the beam, as it propagates through the support mean to the water. An example is described in Archetti and Sancho (2001): the probes were fixed in PVC supports, located in a longitudinal trench at the bottom. Horizontal velocity profiles were measured in shallow waters (several mm) of the swash zone, with a high spatial resolution (< 1 mm).

The spatial resolution between measured volumes depends on the emission frequency, on the fluid in use and on the number of cycles per burst. The lateral size of the sampling volume (which is the volume from which particles contribute to the measurement of a single velocity value) is determined by the shape of the ultrasonic field. Typical values are from few mm to few cm and dramatically increase far from the transducer, especially for low frequency carriers. The axial dimension of the sampling volume is fixed by the duration of the emitted burst and by the bandwidth of the receiver. Typical values are in the order of one to few mm. The minimum distance between two adjacent gates is determined by the sampling rate of the incoming echoes and has a minimum value of tenth of millimetres. It can be much smaller than the axial size of the volume of measurements, with two adjacent volumes overlapping. In addition, the position of the first measurable gate (blank layer) depends on the emitting frequency, the burst length and the size of the active element that generates the ultrasonic waves. In general the higher the carrier frequency, the smaller is the active diameter. For instance, at 8 MHz the probe can be as small as 3 mm in diameter, the first measuring gate can be placed at around 3 mm from the surface of the transducer, which value should be considered as the minimum distance. For field-type current meters the blank layer can reach several decimetres. The velocity resolution depends on the length of a word in Analog/Digital data conversion. The time resolution depends on the instrument set-up and is intrinsically limited by the US celerity. Typical set-ups can give velocity profiles with 200 gates at less than 100 Hz (100 profiles per second). The choice of the frequency of the carrier depends also on the absorption of the medium. Energy dissipation is due to viscosity and to thermal conductivity and is proportional to the square of the frequency. Higher frequency means higher resolution but also higher absorption. A lower frequency guarantees a much reduced dissipation but cavitation can appear if the emitting power is too high.

Acoustic instruments often provide also the backscatter energy, which is a relative uncalibrated measure of solids concentration. It follows that it is possible to gain information on sediment concentration (White, 1998) under the assumption of a linear relationship between the acoustic backscattering coefficient and the particle concentration. Measurements of sediment concentrations through an extension of an ADVP are described by Shen and Lemmin

(1999) while a recent review of acoustic measurements of small scale sediment processes is given by Thorne and Hanes (2002). Fugate and Friedrichs (2002) estimated the fall velocity and the concentration using an ADV (2002), and Hoitink and Hoekstra (2005) estimated the suspended sediment concentration with a 1.2 MHz ADCP.

2.3 The error and the limits

The main sources of errors in acoustics measurements are due to the physical parameter involved in the measurements and to the Doppler noise and the presence of bubbles. The error varies with the chosen configuration of the instruments and can be reduced to less than 5% of the velocity with and overall axial position error better than 1 %. Detailed analyses of resolution and accuracy of velocity measurements were performed by Rolland (1994) and by Lemmin and Rolland (1997). They studied the accuracy of ADVP velocity measurements in comparison with more traditional hot film sensor velocity measurements and they found similar values for both instruments. Results are listed and discussed in Rolland (1994): for typical set up conditions it was found that the tilt angle error is by far the most important so they concluded that the global error of the technique is strictly related to the precision of the set up and to the precision in evaluating flow parameters like the US celerity.

Based on several studies and experiments Thorne and Hanes (2002) compared velocity and turbulence measurements in gravity waves made with Doppler profilers and LDAs: they found that the measured velocities are very comparable with a regression coefficient of about 0.99. ADV, ADVP and ECM measured velocity time series and spectra under breaking waves were compared giving good results, with correlation coefficients up to 0.9 (Tomasicchio and Sancho, 2002; Archetti and Sancho 2001).

In general the determination of turbulence parameters is limited to uniform or slowly-varying flows. For example, in rivers and lakes, where typical values of sampling frequencies needed to correctly resolve turbulence are of about 10 Hz, the monostatic ADVP is an appropriate instrument (Nezu and Nakagawa, 1993) to use. Measurements of macro-turbulence were successfully performed with acoustic profilers both in the laboratory and in the field with a sampling rate of 30Hz and a spatial resolution of a centimetre by Smyth *et al.* (2002) and with a similar set of parameters by Longo and Petti (2004) and by Sancho *et al.* (2001). Trowbridge and Elgar (2001) made measurements of macro-turbulence in the surf zone with ADVs by sampling at 7– 8 Hz. The relatively low frequency rate is the main limit for ADVP micro-turbulence measurements. Amongst the ADV, Vectrino (www.nortek.com) can reach the highest acquisition frequency of 200 Hz.

A more recent signal analysis tool based on a cross correlation technique, to estimate a time difference between the echo signals of a pair of emissions of US pulses, was developed by Ozaki *et al.* (2002). They showed how, for a performed experiment, the time resolution could be improved up to 500 μs, and how a velocity profile obtained with the present technique is in good agreement with that of LDVs.

Multiple particles or micro eddies present in the volume of measurement scatter echoes broadening the spectral peak. Some tests conducted by Nikora and Goring (1998), indicate that Doppler noise is essentially a Gaussian white noise; Doppler noise depends on the seeding particles, and is higher in the presence of bubbles. In many cases flows due to gravity waves are characterized by a two-phase nature due to the entrapment or release of air, the most evident condition refers to velocity measurements of breaking waves. In these conditions LDV measurements of fluid velocities are rather difficult, due to frequent unlocking especially at high void concentration. On the other hand, PIV can be used with good results but with several limitations, such as the need of a transparent medium.

Acoustic measurements are good candidates for velocity measurements in bubbly flows. The air influence on velocity measurements with ADVs was investigated by Nielsen *et al.* (1999). They observed that air bubbles in the signal path significantly enhance the variability of the instantaneous velocities around the mean velocity, hence, increasing the turbulence intensities. As bubble concentration increases the ADV is mainly measuring the velocity of the air bubbles. More recently Longo (2006) conducted a series of experiments in order to provide an exhaustive analysis of the influence of bubbles on ADVP and ADV velocity measurements in different fluids and flows conditions. Theoretical and experimental analyses led him to conclude that measurements of velocity with US Doppler-based instruments in two phase flow fields (bubbles and water) give substantially the velocity of air bubbles, independently of the void bubble volume fraction. In most practical situations (bubble volume fraction < 0.1) the US celerity is unaffected by bubble presence and the celerity in pure water can be used with negligible error. All the above mentioned results are valid in the range 1-10 MHz of the US carrier. Due to the intrinsic nature of bubbly flows, the STD of the measured velocity is relatively high and is not a good indicator of the turbulence energy. In general more power is necessary in the presence of bubbles at high concentration, due to the increased dissipation also enhanced by multiple reflections and refractions at the bubbles interface.

Apparently the commercially-available US based measuring systems do not include validation criteria in the data elaboration, except for a data rejection with a zero velocity value as output if the energy of the echo is below a given level. The absence of data validation can generate errors due to aliasing: if the Doppler frequency is out of the bandwidth, the spectrum is aliasized and the estimated velocity is not correct. This limit is important especially in high turbulence flows. Some recent papers give wrong conclusions on the reliability of the ADVP in different flow conditions, but clearly these conclusions are based on wrong set up of the instrument. Some suggestions are available for eliminating velocity aliasing in acoustic Doppler velocity profiler data (Franca and Lemming, 2006) but they all suffer of limitations. Also the suggestion to enlarge the velocity range is of limited use: larger range of velocity means lower velocity resolution and, hence, limited value of the data for post processing.

A comparison amongst the most used techniques to measure laboratory flow fields and turbulence, ADVP, LDA and PIV, are presented, a summary is given in Table 1. In Lemmin and Rolland (1997) it is shown that the main disadvantage of the ADVP with respect to other mentioned techniques is the limited sampling rate necessary for micro-turbulence measurements and the limit due to radial velocity measurements. The latter limit has been overcome with a bi-static probe configuration. With this configuration also a flow field visualisation (similar to those given by PIV) is possible. The relatively low frequency rate, which varies with the configuration parameters in standard conditions, is usually less than 100Hz. In comparison with other measurements techniques the acquisition rate is of the same order of magnitude of commercial PIV (top-level experimental PIV can reach 1 MHz in frequency) but much lower than typical values of LDA. The ADVP can also provide a velocity profile while LDA profiling can only be done point-by-point. The further limit of acoustic measurement techniques is the relatively large size of the sampling volume: for example the DOP2000 (www.signalprocessing.com) smallest sampling volume is a cylinder of diameter equal to 1mm and thickness equal to 0.64 mm, but the radius increases far from the probe. The limit due to a large volume of measurement can be eliminated using some focused probes and choosing a proper frequency of the carrier.

Table 1 – Comparison of ADVP performances with standard velocity measuring instruments commonly used in hydraulic laboratories.

	Acoustic (ADVP)	Laser (LDA)	PIV
Profile determination	Possible in just one acquisition	Point by point	Possible in just 1 acquisition
Measurement Volume	Depends on frequency > 1 mm^3	< 1 mm^3	Depends on optics
Max Acquisition Rate	Low Frequency (100 Hz)	Very High Frequency (MHz)	Low Frequency (30 Hz) in commercial models. Up to 1 MHz in prototypes
Possibility of measurement in high concentrated fluid	YES	NO	NO
Measure of concentration of sediment	Possible only after calibration	NO	NO
Possibility of measurement in strongly aerated fluid	YES	NO	NO
Flow visualization	YES	NO	YES

The sample volume for LDA measure is usually less than 1 mm^3 and for the PIV depends on the optics, and can be reduced to µm-scale. A comparison between measurements technique is given in Table 1.

3. Example of application: measurements of bottom stresses and velocities under gravity waves

Experiments aimed at characterizing bottom stresses in the inner surf zone were carried out in the small flume in the laboratory of the Ocean and Coastal Research Group at the Universidad de Cantabria in Santander, Spain. The flume is 24 m long, 0.58 m wide and 0.8 m deep and has glass sidewalls and bottom (Figure 1). A false PMMA (polymethyl methacrylate, Plexiglas) bottom was installed in the wave tank, creating a uniform slope of 1:20 starting 8.0 m from the paddle. A detailed description of the set-up is given in Longo *et al.* (2001).

An ADVP was used for velocity measurements only in section A and in section B, respectively with still water level of 11 cm and 5 cm. In each section, three Ultrasonic transducers, with a carrier frequency of 1 MHz, were affixed below the false bottom, the middle being perpendicular to it and the other two at ± 20° with respect to the vertical. With such set-up, the frequency of acquisition was of ~ 30 profiles/s per-probe. A total of 5000 profiles for each test and in each section were recorded for later analyses.

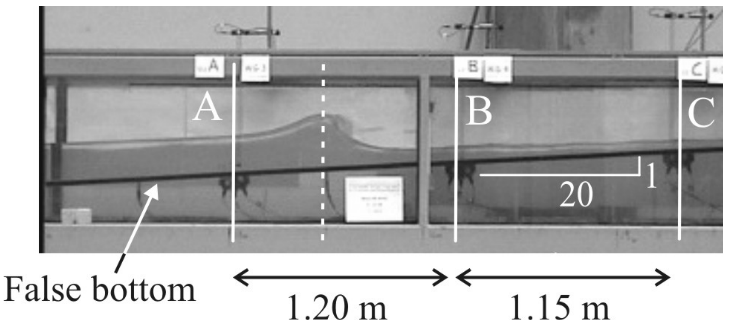

Figure 1. Layout of the Santander flume. The US probes are at sections A and B.

When locating the volume of measurements, it is necessary to consider that the Ultrasonic beam passing through the

Plexiglas modifies its path, due to refraction in the medium having different acoustic impedance. The first useful point of measurement is near the false bottom and measurements extend for 126 spatial positions (gates) along the US probe axis. The measuring volume of a single gate is a disk having a thickness of 1.5 mm and a radius progressively increasing starting from 7 mm. The tests under analysis refer to a 5th order regular wave (T = 2.0 s; 2.5 s; 3.0 s and H = 10 cm), breaking as a spilling breaker in section A. In section B and C an aerated bore is periodically present.

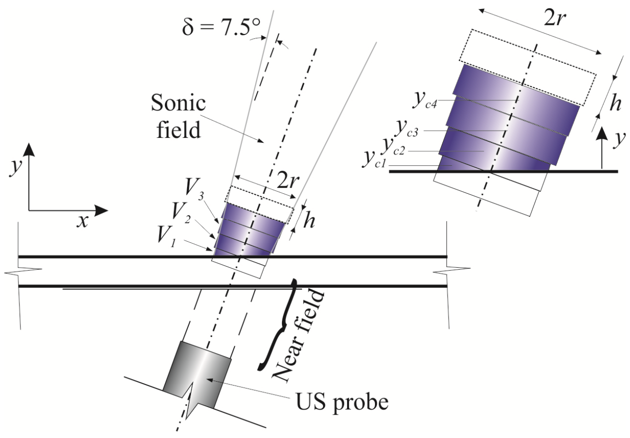

Figure 2. Characteristics of the measurement volume near the bottom.

If the volume of measurement intersects the wall, only the portion of the volume in the flow field is active. As a consequence while the gates far from the bottom are equally spaced at a relative distance h (in the US axis direction), the first gates (y_{c1} and y_{c2} in Figure 2) are unequally spaced and very close to the bottom. It is a major advantage because it represents an increment of spatial resolution in the zone where we need it in order to evaluate the bottom stress.

To check the reliability of the measurements, the mass balance within a period was verified. It is well known that on a long straight coast with uniform longshore condition, or in a flume, the cross-shore mass flux must be zero, even though a circulation is associated due to shoreward mass flux over the crest region, especially in presence of breaking. The offshore current below the mean water level, the undertow, compensates for the mass flux of the waves. In all tests the error in the mass balance was less than 3% of the mass transferred shoreward (or seaward) during the half-cycle. Part of this mass flux is due to the presence of bubbles (which are recorded as water mass by the instrument), part is due to the unavoidable 3-D effects and to errors in the measurement technique. For the present flow the traditional ADV could not be used because it needs at least 5cm from the emitter- receiver to measure (and here the minimum depth was of 4 cm). The comparison with other measurements is clearly impossible and the mass balance is the simplest way to verify the accuracy of measurements.

There have been many previous studies on the vertical flow structure under waves, but quit few on flows under bores after breaking.

Examples of results are reported in Figure 3, where the average Velocity Uav, the friction and the bottom stress in section A are presented; details of the analysis are given in Longo and Petti (2004). The error bars represent the error estimate on predictions and the missing points refer to a correlation coefficient < 0.5. The low value of the correlation coefficient was chosen because the presence of external disturbances on the viscous sub-layer induces frequent modifications of the linear velocity profile. Many missing points appear at flow inversion, due to measured velocities nearly equal to the measurement resolution and also with a possible separation or boundary layer elimination.

The friction factor shows two peaks on a smoothly varying background, due to zero values of the friction velocity.

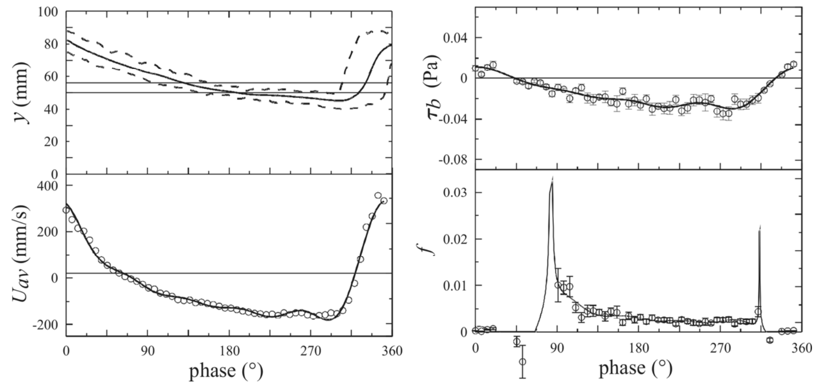

Figure 3. Depth-averaged horizontal velocity, friction and bottom stress. T = 2.0 s.

Similar results were obtained for swash zone flows, in a aerated region over a rough bottom where velocity profiles were measured with an ADVP: the logarithmic velocity profile, typical of steady flows, was seen to adequately represent the near-bottom velocity (Archetti and Brocchini, 2002).

4. Comments and conclusions

US techniques have many advantages with respect to other fluid velocity measurements methods: they can measure with data rates virtually independent on seeding concentrations and can also be used in aerated fluids. The ADVP has the further advantage to give information on spatio-temporal velocity. The error is strictly related to the accuracy of the set-up, and can be reduced to 5 % with a major contribution due to the lack of precision. Accuracy is usually high.

The commercially-available systems apparently have the disadvantage of no data validation. The absence of data validation can generate errors due to aliasing: if the Doppler frequency is out of the bandwidth, the spectrum is aliasized and the estimated velocity is not correct. This limit is important especially in highly turbulent flows.

The volume of measurements is usually large, although this limit can be eliminated using some focussed probes and choosing a proper frequency of the carrier. The highest spatial resolution, or smallest sample volume for ADVP is today a disk of around 1mm in diameter and a thickness of 1 mm.

The relatively low data rate is a limit of the US technique. This limit is intrinsic in the carrier celerity, of around 1500 m/s in water. The highest acquisition rates reach 200 Hz for one point measurement (Vectrino) and can be around 100 Hz for ADVPs, which allows, at most, for macro-turbulence measurements. Recent studies have shown that innovative signal processing (cross correlation analysis) can overcome this limit reaching a much higher temporal resolution. US profilers will certainly not replace PIV and LDA, but ADVP gives much more quickly some ″mean information″ over a wide area. Mean information because ADVP has a relatively large volume of measurements, and wide area because velocity is measured quasi-simultaneously in several points of the flow field.

The technique is presently the only one that has the potentiality to measure simultaneously flow velocity and sediment concentration, which is one of the main topics in coastal engineering research. In the flows analysed in the present experimental activities, the instrument has shown good performances especially in situations where LDV measurements cannot be used like in post-breaking bores. The presence of bubbles is relatively unimportant as long as the void fraction is less than 0.1 and the bubbles follow with a negligible lag the fluid. The presence of bubbles increases the variance of the signal in a way that is difficult to account for. As a consequence US measurements should not be used for turbulence measurements in bubbly flows but only for mean velocity measurements.

In the reported analysis it was found that also the mass balance is affected by bubbles, which are not recognised as voids by the instrument.

With a suitable choice of transducers, velocity measurements very near to the bottom are possible using US and the instrument is especially suited for measurements in the boundary layer. Velocity profiles have been also measured in a region where the velocity profile is linear at least at moderate friction velocity. In this region the effects due to the measurement volume size are important. The measurements in the viscous sub-layer permit the estimation of the bottom stress even under periodic flows as well as under waves and subsequent bores.

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