Acoustic Doppler velocity profilers: application to correlation measurements in open-channel flow

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Abstract Measurements with a monostatic and a bistatic acoustic Doppler velocity profiler in open-channel water-flow are used to calculate correlation functions. The instantaneous measurement of one or two components of the velocity vector allows to determine time-, space- and space-time-correlations with ease. It is verified that in this shear flow case the local mean velocity and the convection velocity coincide. For correlations of the vertical velocity the convection velocity is zero. Spectra characterize the flow field as isotropic. Extending the range of spectral resolution by two-gate cross-correlation is found to add at least one decade of resolution.

1 Introduction

Velocity and turbulence are important hydrodynamic parameters. Consequently, many instruments, working on a variety of principles, have been developed for their measurement. Among them, the pulse-to-pulse coherent acoustic velocity profiler (ADVP) has a unique combination of advantages:

- it can take instantaneous *velocity profiles*
  -- of all three velocity vector components simultaneously
  -- covering the total water column in open channel flow
  -- with a resolution of turbulence scales.
- it is non-intrusive.
- it works reliably in the presence of suspended particles.
- it can determine instantaneous particle *flux profiles*.

Its suitability for studies in rotating flows was first demonstrated by Takeda (1986). We have tested its feasibility for open-channel laboratory-research (Lhermitte and Lemmin 1990; Lhermitte and Lemmin 1994) based on hardware systems and signal processing algorithms which we have developed and improved since.

Much has been learned about turbulent flow in boundary layers from measurements of correlations in time and space (Favre et al. 1957; Favre et al. 1958; Tritton 1967). More recently interest in correlation functions is renewed because they can provide useful information on coherent structures (Adrian 1988). Two-point correlation measurements have suffered in the past from instrument wake effects (Comte-Bellot and Corrsin 1966) which have been corrected by using a two beam LDA (Romano 1995) The profiling capacity of the ADVP may greatly enhance the possibilities of correlation measurements since it can measure several velocity components at more than 200 points along a line simultaneously and non-intrusively.

In this paper we will briefly review ADVP configurations and demonstrate the potential of different ADVP systems in measuring various types of correlations in open channel flow.

2 ADVP configurations

Depending on the flow conditions and on the aim of the investigations, different approaches and different configurations of the ADVP can be or have to be realized. In order to optimize the ADVP system in each case, a modular arrangement of the instrument is required. We will demonstrate the flexibility of such a modular system in two different configurations: a monostatic ADVP and a bistatic ADVP.

Different signal treatment methods exist to extract the velocity information from the measured Doppler phase shift between the emitted and the backscattered signals. In the present analysis the pulse-pair algorithm (Lhermitte and Serafin 1984) is used which was found to be more reliable than the spectral analysis. In view of the good signal to noise ratio, the number of pulse-pairs was taken as $N_{PP} = 32$. Random phase coding (Lhermitte and Lemmin 1994) was used which significantly reduces the aliased echoes that may occur from multiple reflections on fixed surfaces.

2. 1
Monostatic ADVP

In a monostatic mode, one single acoustic transducer is used to emit and receive acoustic waves. ADVP velocity profiles have been taken by aligning the transducer with the direction of interest (Takeda 1995). A profile is obtained by gating the received signal to correspond to the pulse's time of flight to a certain depth. In open channel flow, vertical profiles of both the along axis and vertical velocity component are of interest. Thus a vertically pointing transducer can take a full profile of the vertical velocity in a horizontal open channel. In our study, this transducer has been placed below the channel bottom in a separate chamber separated from the channel flow by a Mylar window (Lemmin and Rolland 1996) and thus takes measurements without disturbing the flow. For the horizontal velocity component the transducer would have to be placed in the flow looking horizontally. In this case a vertical profile can only be taken by moving the transducer vertically and the multigate capability of the ADVP is of little use.

As an alternative, the transducer may be placed in the chamber below the channel bottom and tilted at an angle to the vertical. The radial velocity that this transducer measures contains contributions from the horizontal and the vertical velocity components. Under uniform flow conditions we have shown that with three consecutive measurements with three transducers mounted as shown in Fig. 1a. mean vertical profiles of the mean velocities and the variances as well as the Reynolds stresses can be obtained. Investigating stationary open channel flow over rough and smooth beds, good agreement was found for all laws for the distribution of mean velocities and turbulence parameters (Rolland 1994; Lemmin and Rolland 1996).

However, the determination of turbulence parameters with this system is limited to uniform or very gradually varying flow. It is impossible to apply it to more rapidly accelerating or decelerating flows which are often encountered in natural water flows that we are interested in.

2.2
Bistatic ADVP

Recently we have therefore extended the ADVP-technique to a system which is capable to determine instantaneous profiles of at least two velocity components simultaneously with the resolution of turbulence scales.

In this new ADVP a pulse of sound waves is emitted only from a central transducer (Fig. 1b). As in the monostatic mode this transducer can also work as a receiver of the backscattered sound waves. Additional transducers placed around the emitter will serve as receivers for the backscattered signals coming from same pulse of sound waves. For convenience and ease of signal extraction, these receivers which have to be inclined towards the central emitter are normally placed symmetrically around the emitter. In that case any sound waves which are backscattered from a certain volume in the central beam will have the same time of flight to all the surrounding receivers. One pair of opposingly inclined receivers is sufficient for the determination of two instantaneous velocity components. An additional pair in a plane perpendicular to the first one will allow to determine all three velocity components instantaneously.

For convenience this system is aligned here with the direction of the mean flow (the along axis flow in the open channel). In this case the two velocity components under consideration are the horizontal velocity u and the vertical velocity v. The emitted sound beam from which the velocity profile is determined is vertical with respect to the channel bottom. This is an advantage over the monostatic system where the profile has to be taken along an inclined sound beam. Details of the signal processing and the determination of the instantaneous velocities are given in Rolland (1994). Profile measurements made with the bistatic ADVP in an open channel with smooth bed are reported in Rolland and Lemmin (1996).

3
Correlation measurements

To evaluate the ADVP in turbulent open channel flow, the present experiments were conducted under uniform flow conditions in a recirculating glass-wall channel with a smooth steel floor. It is L = 43 m long, b = 2 m wide and 0.16% tilted. The measurements were made at 16 m from the channels entrance where the turbulent flow generated by wall friction is well-established and in equilibrium. Experiments conducted with the ADVP system were concerned with clear water (better than 98 percent transmissivity) which was permanently filtered. No seeding was done. Details of the installation and of the basic pulse-to-pulse coherent ADVP equipment operating at 1 MHz are given in

Lhermitte and Lemmin (1994); Lemmin and Rolland (1996) and Rolland and Lemmin (1996). Measurements reported here were made in uniform turbulent flow (Re = $U_1 h/v$ = 3.5 to 3.6×10^5; Fr = 0.79 to 0.87; bottom friction velocity u_* = 3.79 to 3.94 cms^{-1}). The water depth h in the present experiments was between 10 and 11 cm, the mean along axis velocity U_1 = 87 to 82 cms^{-1} and the aspect ratio b/h = 19.8 to 18.2. The vertical profile of the horizontal velocity component follows the logarithmic law for z/h < 0.2 and Coles' law of the wake in the outer layer (Lemmin and Rolland 1996).

3.1
Taylor's hypothesis

Taylor (1938) assumed that the velocity field is 'frozen' and convected downstream. In homogeneous turbulence the convection velocity is the same for all eddies and equal to the mean velocity U_i. This implies that a partial time derivative $\frac{\partial(..)}{\partial t}$ and a partial space derivative $\frac{\partial(..)}{\partial x_i}$ are related by

$$\frac{\partial(..)}{\partial t} = U_i \frac{\partial(..)}{\partial x_i} \qquad (1)$$

and that a fluctuating velocity $u(x,t)$ can be expressed as:

$$u(x,t) = u(x + U\tau, t + \tau) \qquad (2)$$

for not too large values of time lag τ (Townsend 1976). Taylor's hypothesis has been found valid for large Reynolds numbers and small turbulence intensities $(\overline{u_i^2})^{1/2} << U_i$. Within the above restrictions the use of the frozen flow assumption applies to all flows. However, when the gradient of the mean velocity is large such as in boundary layers, the local convection velocity may deviate from the mean velocity.

A correlation in space ($\tau = 0$) may then be related to a correlation in time ($r = 0$; r determines the distance between two points of measurement) as

$$R_{11}^{N}(0,0,0;\tau) = R_{11}^{N}(U_1\tau,0,0;0) \quad (3)$$

In this equation the superscript N indicates normalized correlations and the subscript 11 indicates that the correlations are measured in a direction r which is parallel to the direction of the mean flow. In the open channel this is a direction parallel to the channel bottom.

For the present correlation measurements the acoustic transducer of the monostatic system was placed horizontally in the axis of the channel looking into the flow in mid-depth ($z/h = 0.5$). The influence of the transducer on the measurements was minimized by setting the first gate of the profile at 12 cm ahead of the transducer face (diameter 3 cm). The gate spacing was 6 mm and simultaneous measurements were taken at up to 100 equally spaced gates.

Fig. 2 shows the comparison of the two correlation functions in eq.(3). The reference velocity in this case was not the mean velocity U_1 but the local mean velocity $\bar{u}$ at the depth of measurement. We find agreement between them for $r_1/h > 2$. The deviation for higher values of separation distance r_1 observed by Cenedese and Romano (1991) does not occur in our case because the flow is uniform and well established. For the same reason we do not observe the difference between the positive and the negative displacements either. The existence of uniformity and thus homogeneous turbulence can be made evident by comparing autocorrelation functions for different gates along the channel axis. If the condition of homogeneity is satisfied all autocorrelation function have to be identical. This is demonstrated in Fig. 3 for three gates separated each time by 60 mm which have been acquired simultaneously. We have also compared autocorrelation functions of the horizontal velocity component with those of the vertical component. We find (Rolland 1994) that in the correlations of the vertical component the initial fall-off is at least twice as rapid as that of the horizontal component indicating that the integral scales of the vertical turbulence are smaller than those of the horizontal one. This agrees with the observations of Nezu and Nakagawa (1993) who have pointed out that in the outer region of the flow where our measurements were taken, turbulence intensity in the longitudinal direction is 1.45 to 1.8 times greater than in the vertical direction.

3.2
Spatial correlation

The vertically pointing transducer allows to establish the relationship between the vertical component of the velocity measured at a reference level (gate) and at other depths in the flow. The ADVP is well suited for this measurement because it is placed outside the flow field (Fig. 1a) and it does not require to invoke Taylor's hypothesis nor the use of a second sensor within the water column. Fig. 4 presents several examples of the spatial correlation functions. All data have been acquired in a single measurement. A systematic variation in the structure of the correlation function can be seen which depends on the reference level chosen. One may consider that the surface below the curve is representative for a correlation length related to a turbulence scale. The examples in Fig. 4 show that the scales of vertical turbulence are larger in the central part of the water column. They fall off as expected when the free surface or the channel bottom is approached.

3.3

Space-time correlation with time delay

As in the preceding measurements a horizontally pointing transducer at mid-depth and a vertically pointing transducer both working in the monostatic mode are used. The correlation functions are each time calculated from data obtained in a single multigate acquisition.

The results for the horizontal correlation function are shown in Fig. 5. For each separation distance, the correlation function passes through a maximum. The delay of this maximum τ_m is directly proportional to the separation ζ_m between the two gates in question. From these two parameters the convection velocity $u_c = \zeta_m / \tau_m$ can be calculated. In our case the convection velocity is always equal to the local mean velocity $\bar{u}$ at that depth. This observation confirms again that Taylor's hypothesis is valid in a shear flow if the local mean velocity $\bar{u}$ is used to transform a time signal into a space signal. Favre et al. (1957,1958) had already shown that in air shear flow Taylor's hypothesis is valid. However, in their case the convection velocity was generally equal to 0.8 $\bar{u}$. Romano (1995) has shown that in duct flow (using water) $u_c/\bar{u} = 1$ is approached for high Reynolds numbers. The amplitude of the maximum of the correlation functions decreases with increasing separation in contradiction to Taylor's hypothesis while the radius of curvature become larger at the same time. This was predicted and explained by Townsend (1976) and observed in all studies cited above. However, we note that after the initial fall-off the further decrease in our case is much less that seen before indicating that in uniform open channel flow the loss of correlation and thus of identity of the turbulence is less significant.

The same analysis can be carried out for the vertical velocity component obtained from the vertically pointing transducer. Results are given in Fig. 6. This figure shows clearly that the convection velocity in the vertical direction is zero: the maxima of all curves fall onto the line $\tau = 0$. One may note a certain tendency that gates with the same distance from the reference level have a slightly higher correlation in the upward direction than in the downward direction. This can be interpreted to indicate that turbulence patterns move from the channel bottom towards the surface.

3.4
Iso-correlation patterns

The bistatic ADVP as indicated above can measure instantaneous vertical profiles of two velocity components over the whole water column. Assuming that Taylor's hypothesis is valid over the whole water column, time correlation functions determined over the whole water column can be interpreted as spatial correlation functions. Curves of iso-correlation can then be established for any given reference level. In the present study we will again take the reference level at mid-depth z/h = 0.5. The hydraulic conditions remained unchanged from the above monostatic measurements. Each of the cases discussed below results from one simultaneous recording of profiles of the two velocity components at 22 gates in the vertical.

In the first case, iso-correlation curves have been determined for the longitudinal velocity component. Results are shown in Fig. 7. It can be seen the iso-correlation curves are ellipses which are inclined by about 20° in the direction of the mean flow. The direction of inclination which is the line connecting for each gate those points that have the highest correlation is an indication of the direction of movement of the turbulence structures. This result agrees well with the observations made by Blackwelder and Kovaznay (1972) and the calculations by Townsend (1976) for the theory of rapid distortion of isotropic turbulence.

In the second case, the same calculations as above have been carried out for the correlations for the vertical velocity component. The resultant iso-correlation curves are shown in Fig. 8. In this case the curves are again ellipses but their main axes all coincide with the vertical. Furthermore, a very rapid de-correlation is observed in the mean flow direction. As was already seen above, this indicates that vertical turbulence in the outer region is organized on smaller scales than the horizontal component. In the vertical, correlation above the level of reference extends to longer distances of separation than in the downward direction.

In the third case use is made of the simultaneous recording of profiles of two orthogonal velocity components. Normalized cross-correlations are determined between the horizontal velocity at the reference level and the vertical velocities measured at all other gate levels. Results are presented in Fig. 9 where a certain asymmetry with respect to the vertical line at the origin is observed. Correlations are stronger in the direction of the mean flow than in the opposite direction. This behaviour was already outlined by Townsend (1976) and is indicated by the cross-correlation curves given by Tritton (1967). It may also be noted that the cross-correlation is stronger towards the channel bottom than towards the free surface. This is reflected in the distribution of the Reynolds stresses which have their maximum on the channel bed.

4

Spectral analysis

Spectral analysis provides a statistical means to determine the distribution of turbulent energy between different frequencies which may in turn provide information on the distribution of spatial and temporal turbulence scales. Here we will calculate one-dimensional spectra on timeseries of the horizontal and the vertical component of the flow field invoking Taylor's hypothesis. The spectra have been obtained using standard FFT technique on partially overlapping subsets.

For the monostatic ADVP, the data obtained with the inclined transducers (Fig. 1a) have been analyzed. For stationary uniform flow the spectrum of the horizontal component can be extracted after some signal procession (Rolland 1994). The result is shown in Fig. 10 where the ADVP data have been compared with results from hot-film anemometer measurements which were taken afterwards at the same location. Good agreement is found between the two techniques. Energy containing scales are observed for frequencies $f < 0.1$ Hz. The inertial subrange starts between $0.1 < f > 1$ Hz and is well established for $f > 1$ Hz. The present ADVP spectra are limited to $f < 20$Hz while the inertial subrange extends to at least $f = 100$Hz as seen from the hot film measurements. This limit is due to the choice of $N_{pp} = 32$. The good agreement between the results from the two measuring techniques shows that the choice of N_{pp} was correct for eliminating parasitic signals from the ADVP velocity determination.

Spectra have also been obtained from the measurements with the bistatic ADVP. In this case, spectra for both velocity components were calculated for several depths (Fig. 11). No difference in the spectra with depth is observed. For the longitudinal components the peak in the energy containing scales agrees with the monostatic measurements. The inertial subrange is established over nearly two decades starting at $f = 0.1$ Hz. For the vertical component the range of the energy containing eddies is much broader and extends to 1 Hz. For the next decade the inertial subranges of the two velocity components agree well. It is evident, as was seen already in the correlation analysis above, that the vertical velocity component is organized on smaller length scales than the horizontal component.

5
Correction for Doppler ambiguities

A spectral resolution to higher frequencies may at times be desirable. Two processes interfere with the resolution at higher frequencies and both occur also with laser and Radar systems. However, their consequences are more accentuated in acoustic systems because of the greater wavelength. The first process is attenuation caused by spatial averaging inside the measuring volume, biased by the coefficient of directivity of the emission. Little can be done about this effect. The second process is the Doppler ambiguity and generally this one is much more important than attenuation. Doppler ambiguity results in spectral broadening (Lhermitte and Lemmin 1994). This occurs because of the random transit of the scatterers across the measuring volume of finite dimensions from one sound pulse to the next.

Garbini et al. (1982) have suggested that the measured Doppler phase may be decomposed into a phase spatially averaged across the acoustic beam and an instantaneously fluctuating phase. Both contribute to the spectrum and the latter one mainly to the high frequency end. The pulse-pair algorithm is capable of extracting the velocity correctly from the ambiguity noise because it is a real time autocovariance algorithm. Thus, for a sufficiently large number of pulse pairs (Zrnic 1979) an estimate of the mean velocity inside the measuring volume can be correctly made and spectra without Doppler ambiguity effects can be obtained as seen above.

The higher temporal resolution requires a reduction in N_{PP} which will in turn introduce the effect of the Doppler ambiguity. For measurements with transducers inclined to the direction of flow, Garbini et al. (1982) have shown that the Doppler ambiguity can be eliminated while the desired velocity information is maintained when signal timeseries from two gates measured in the same acoustic beam and at the same time are correlated. If the two gates are sufficiently close to each other (but not too close to avoid overlapping or shading) the cross-correlation is a good approximation of the autocorrelation function. We have shown (Rolland 1994) that for our measurement conditions two consecutive gates should be cross-correlated.

The results of the application of this procedure are shown in Fig. 12. In order to obtain the same temporal resolution (f = 100 Hz) as the hot film anemometer, the number of pulse pairs has to be lowered to $N_{PP} = 4$. The spectrum which results directly for $N_{PP} = 4$ is progressively affected by the Doppler ambiguity for frequencies $f > 10$ Hz. This can be eliminated when cross-correlating the signals between two consecutive gates instead. Some aliasing effects become visible in the resultant spectrum near f = 100 Hz. These can be eliminated by other means. Thus the range of spectral resolution of the ADVP can be expanded by applying the proper signal treatment methods. In order to show that the pulse pair algorithm automatically eliminates the Doppler ambiguity effects when N_{PP} is high enough, the spectrum for $N_{PP} = 32$ and the spectrum obtained by cross-correlation of two consecutive gates are compared in Fig. 13. The good agreement between the two spectral curves is evident.

6

Concluding remarks

The Acoustic Doppler Velocity Profiler has been evaluated for its use in boundary layer flow conditions in open channel flows. From the analysis it is evident that the ADVP hardware and the software algorithms applied to the extraction of the velocity vector are well suited for the analysis of turbulent flow characteristics without the need for a calibration procedure. Measurements can be taken rapidly with a degree of accuracy better than that of many conventional in situ sensors which at the same time stand to significantly modify the local flow conditions by intruding into the flow. The ADVP is easier to operate than laser velocimeters and essentially provides instantaneous velocity profiles instead of point measurements. This opens new research possibilities in the study of coherent structures (Shen and Lemmin 1996a).

Compared to existing instrumentation, the ADVP profile measurements take only a small fraction of the time for the same resolution. Furthermore, since ADVP profile measurements are taken simultaneously under the same flow conditions, the resultant profiles are found to be smoother than those taken in sequence by existing instruments. Still higher spatial and temporal resolution can be achieved by using a higher acoustic frequency.

We have also tested the same ADVP in rivers and lakes (Lemmin et al. 1995; Lemmin and Jiang 1996). In these environments, typical values of the sampling frequency needed for correctly studying turbulence are about 10 Hz. The ADVP systems of the type discussed here seem to be the most appropriate instrument. The presence of particles in low to medium concentration in the flow does not influence the acoustic system at all, a great advantage over the LDA. Therefore the pulse-to-pulse coherent technique presented here appears to be a rather promising tool in field studies. In the laboratory the presence of particles, their concentration and the variance may be investigated by exploiting the profiles of backscattering intensity information provided by the ADVP at the same time (Shen and Lemmin 1996b). This information, combined with the instantaneous velocity profile can be used for detailed studies of sediment transport fluxes (Shen and Lemmin 1996c).

In conclusion, the investigations carried out so far have already shown the potential of the high frequency ADVP as a valuable tool for hydraulic research under a large variety of conditions. More sophisticated techniques for beam focalization (Hurther and Lemmin 1996), data acquisition and signal processing or beam scanning techniques may have to be further investigated before the optimal configuration and the range of application of a high frequency ADVP designed for hydraulic research can be fully determined. It can be expected that these developments will extend the capabilities of the acoustic systems to advance the understanding of the turbulent water flows.

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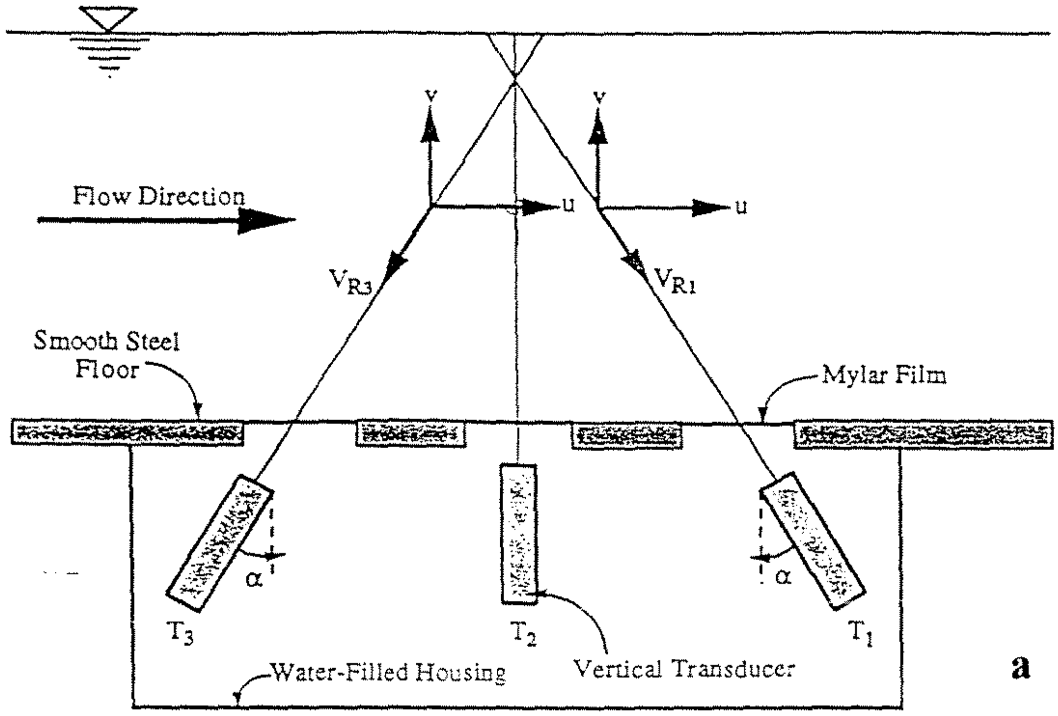

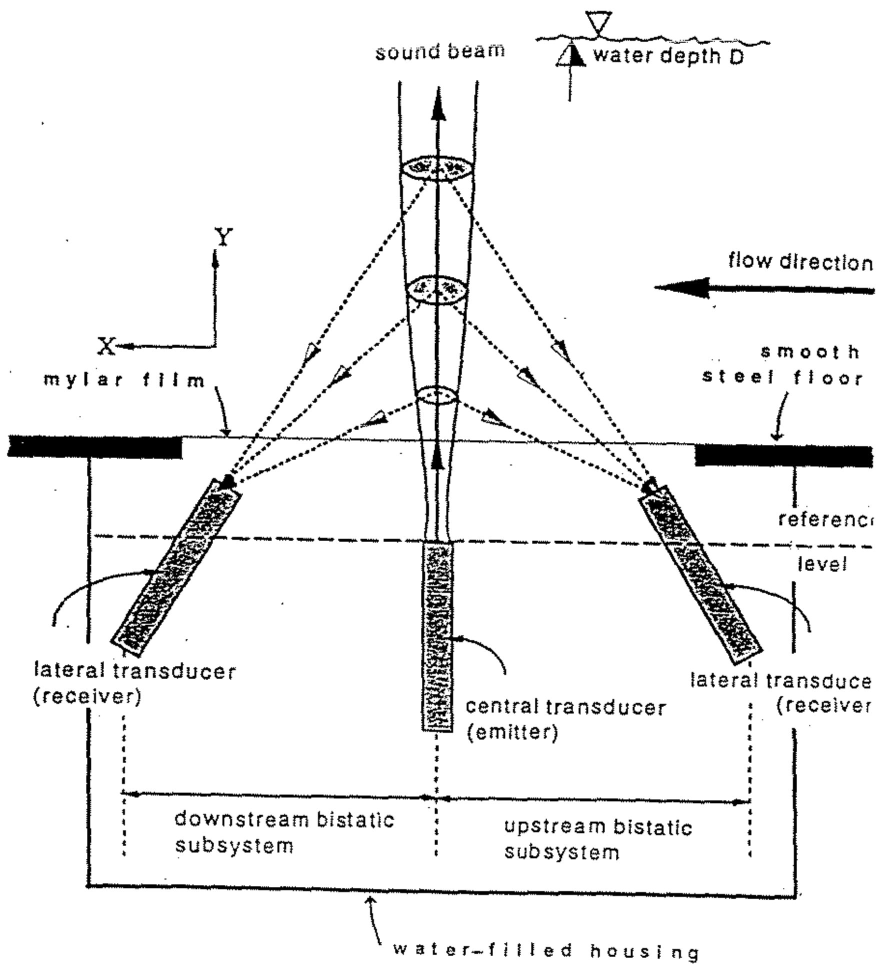

Fig. 1a,b. Acoustic Doppler velocity profiler layouts: **a**: Monostatic ADVP; **b**: Bistatic ADVP.

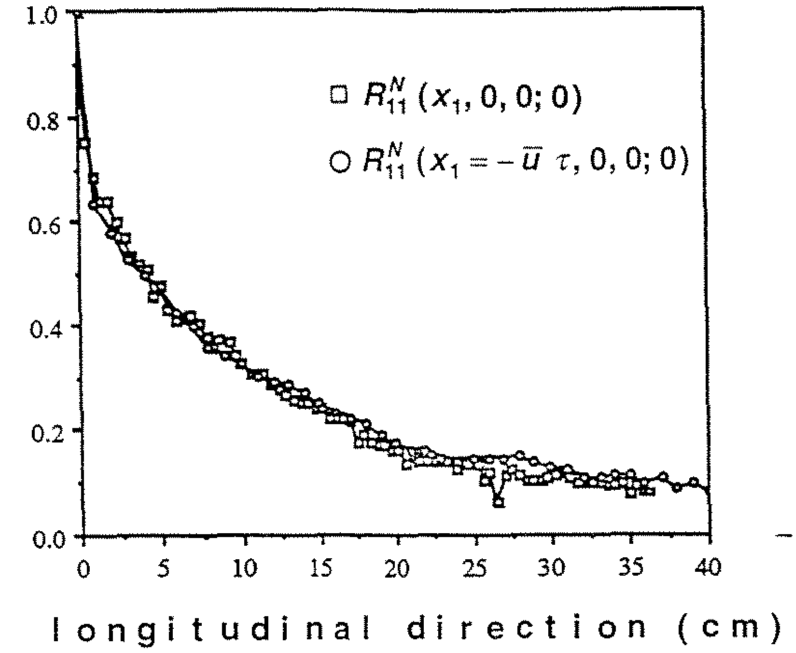

Fig. 2. Spatial correlation functions of the horizontal velocity component at z/h = 0.5 measured with the monostatic ADVP.

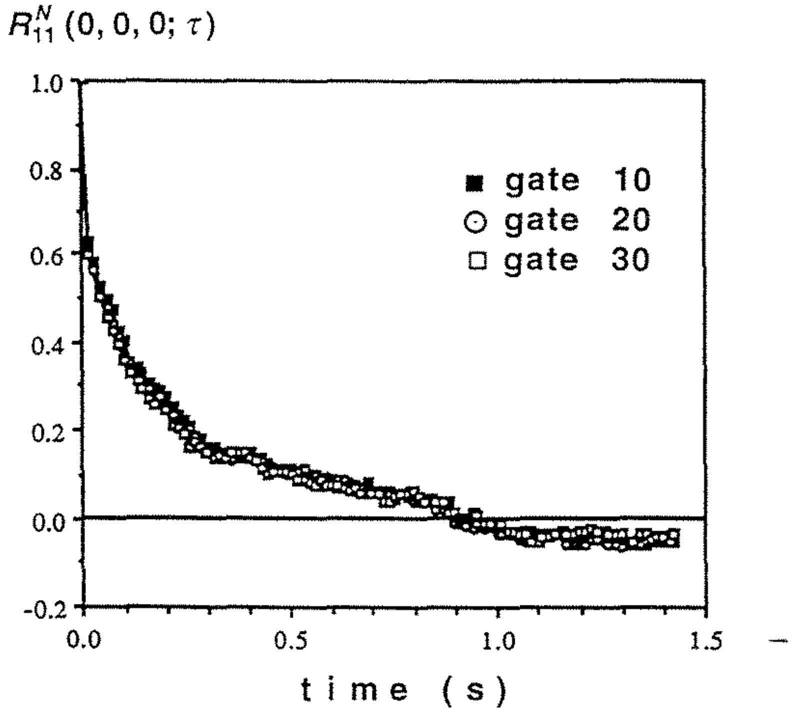

Fig. 3. Auto-correlation functions of the horizontal velocity component at z/h = 0.5 for different gates measured with the horizontal monostatic ADVP.

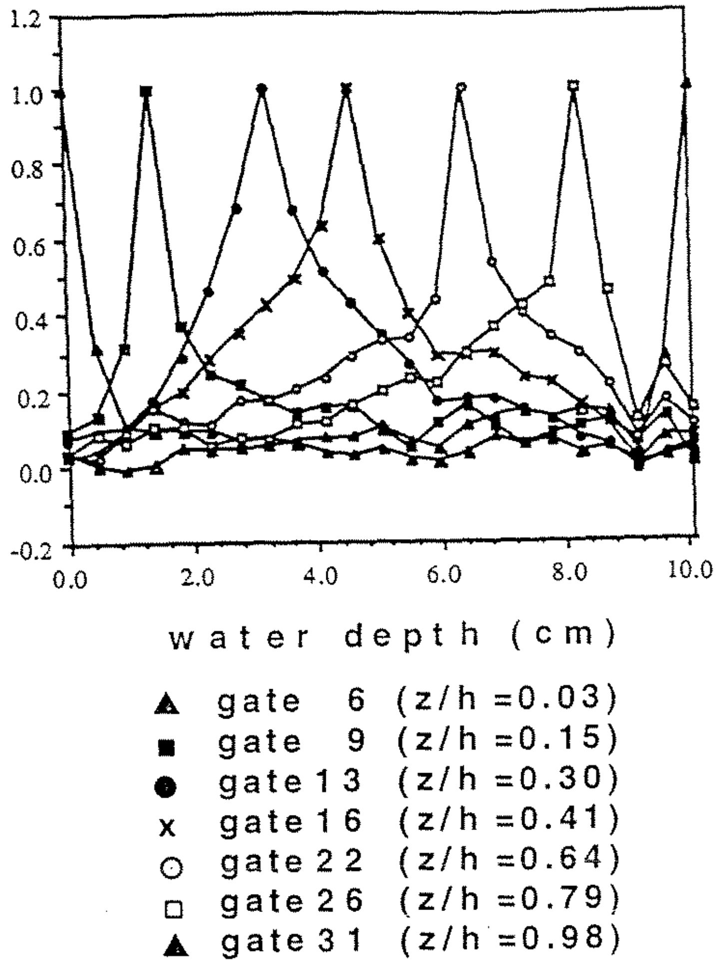

Fig. 4. Spatial correlation functions of the vertical velocity component for different reference gates measured with the vertical monostatic ADVP.

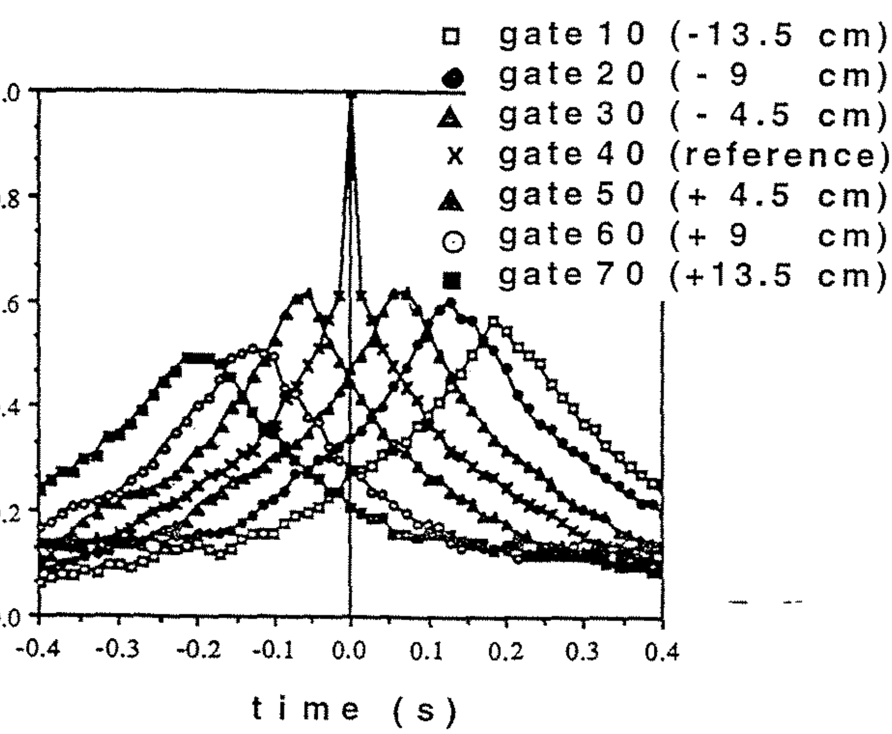

Fig. 5. Space-time correlation functions of the horizontal velocity component at z/h = 0.5 measured with the horizontal monostatic ADVP.

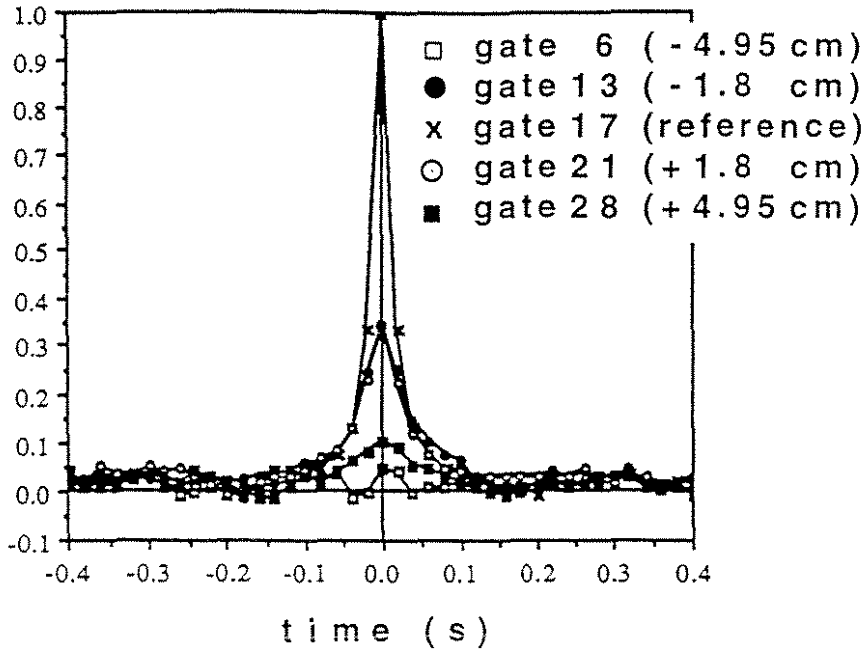

Fig. 6. Space-time correlation functions of the vertical velocity component measured with the vertical monostatic ADVP.

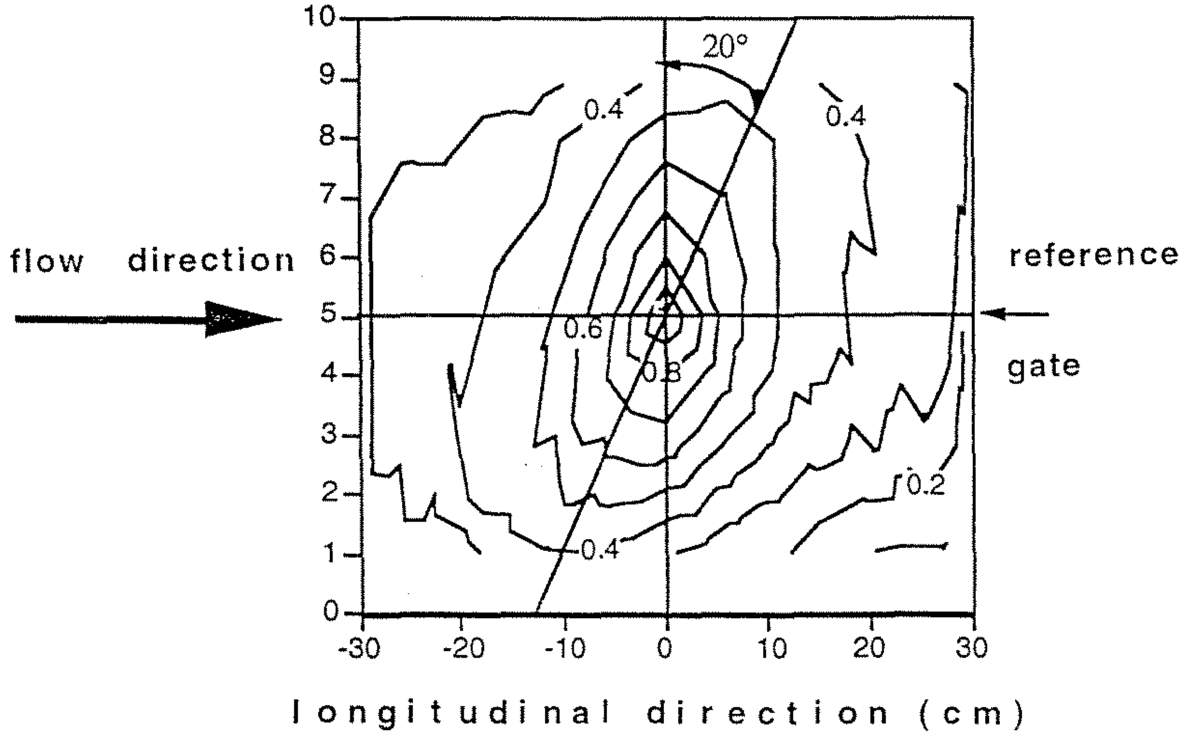

Fig. 7. Iso-correlation pattern of the horizontal velocity component for the full water depth measured with the bistatic ADVP.

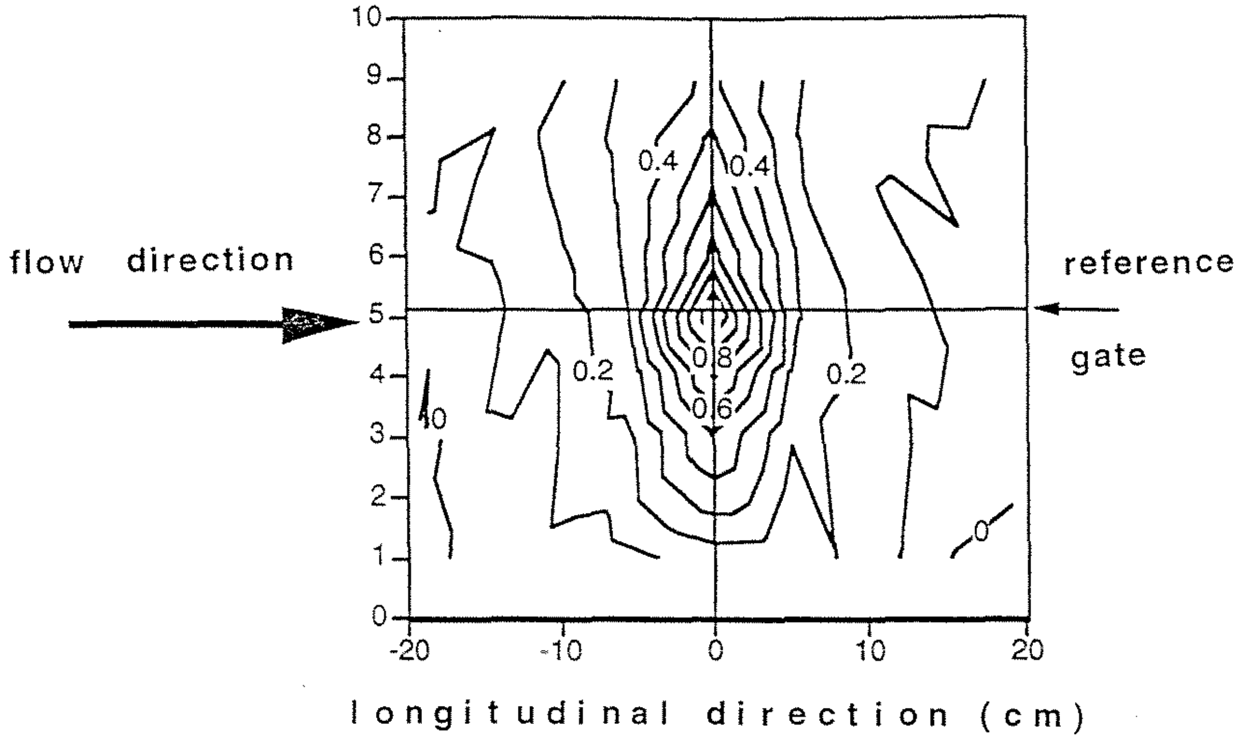

Fig. 8. Iso-correlation pattern of the vertical velocity component for the full water depth measured with the bistatic ADVP.

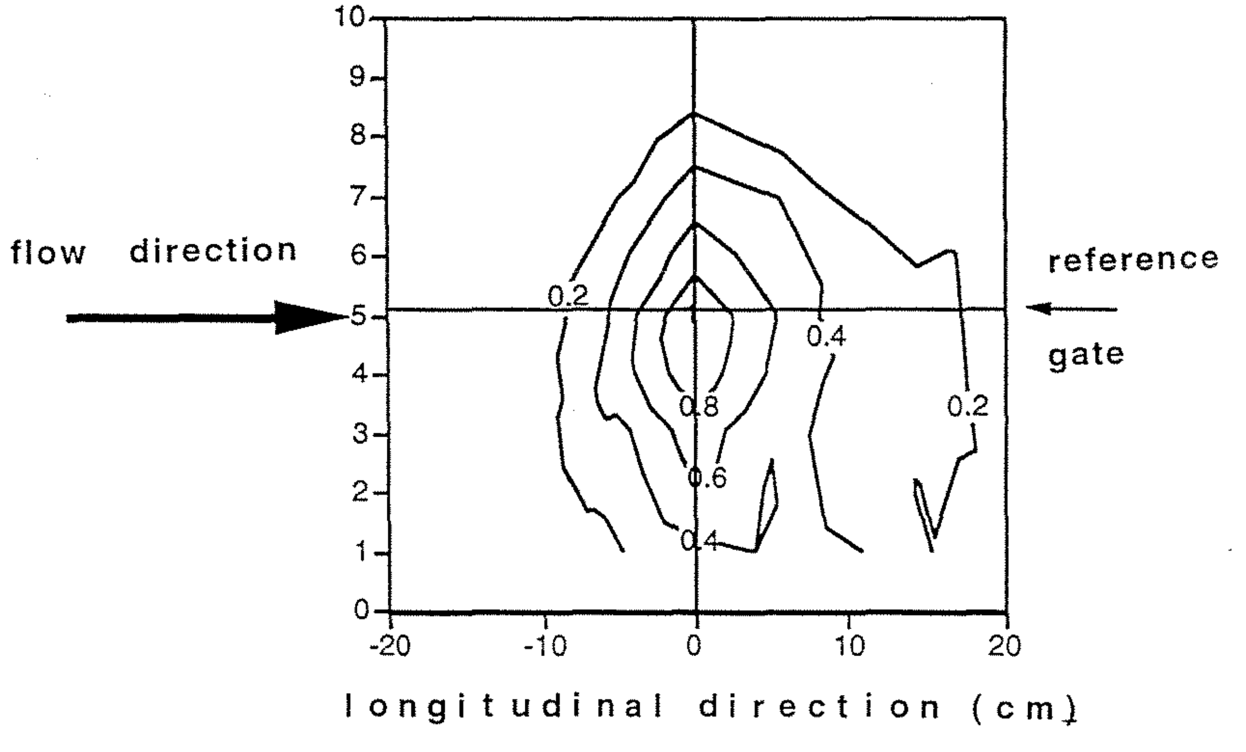

Fig. 9. Iso-cross-correlation pattern between the horizontal velocity component measured at $z/h = 0.5$ and the vertical velocity component for the full water depth; measured with the bistatic ADVP.

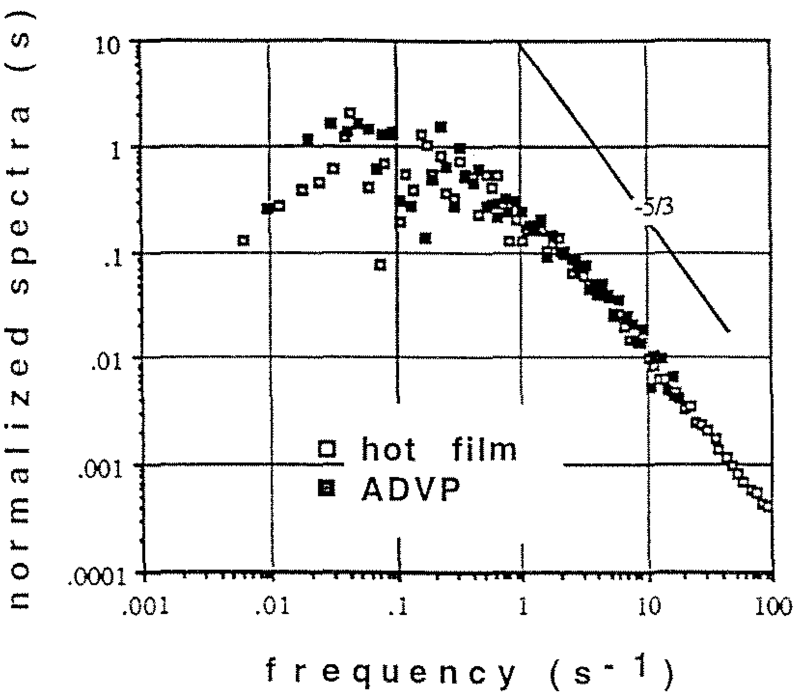

Fig. 10. Spectrum of the horizontal velocity component measured with the inclined monostatic ADVP and with the hot film anemometer.

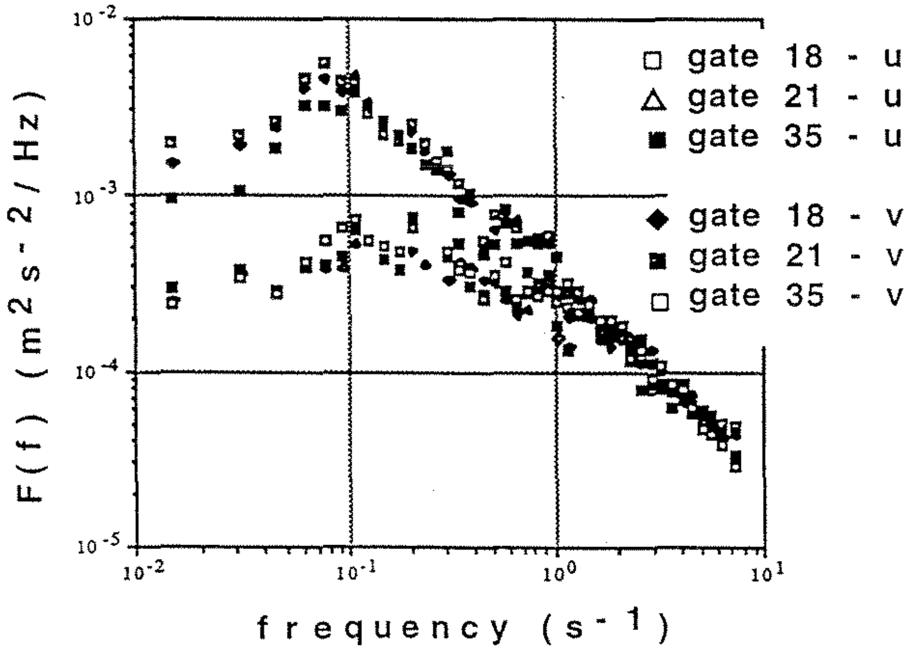

Fig. 11. Spectra of the horizontal and the vertical velocity components at different depths measured with the bistatic ADVP.

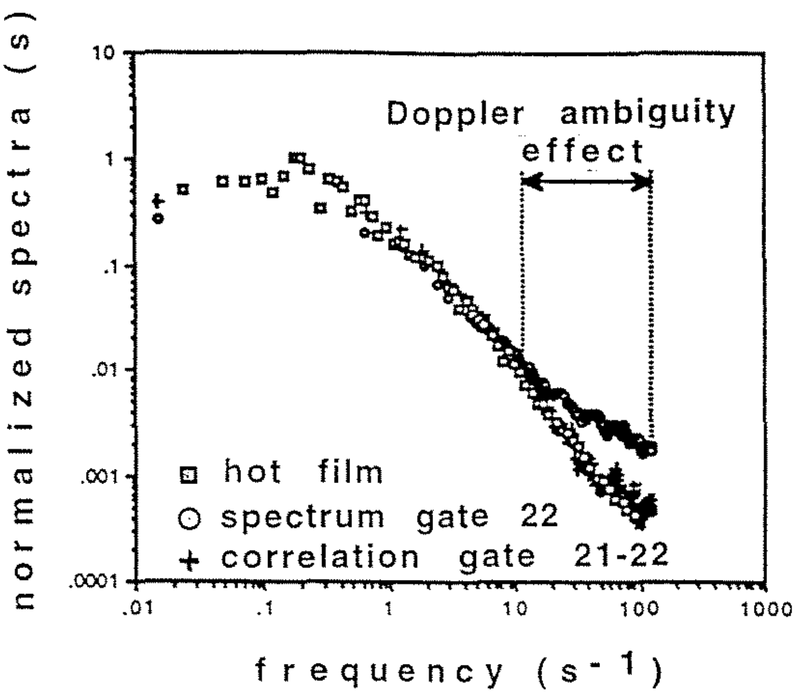

Fig. 12. The Doppler ambiguity effect and its elimination. Spectra of the horizontal velocity component measured with the inclined monostatic ADVP and with the hot film anemometer.

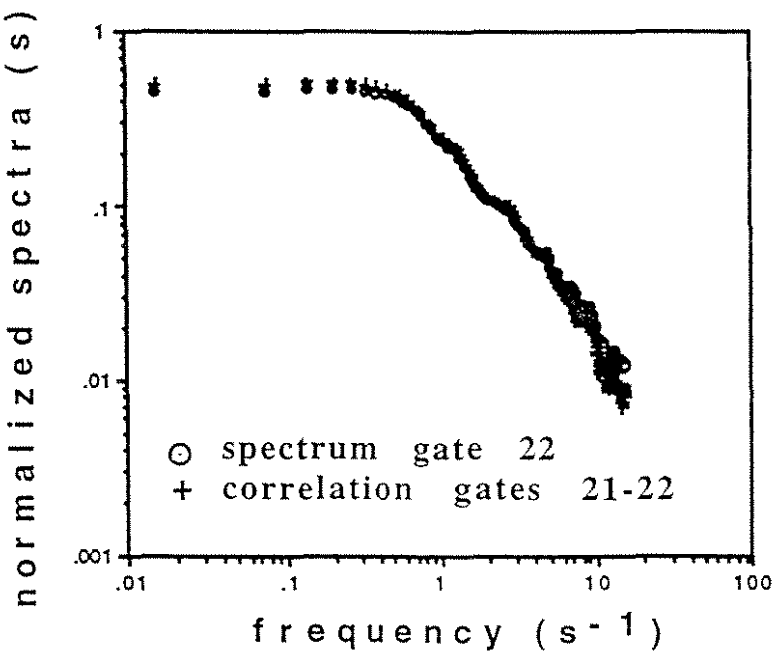

Fig. 13. The Doppler ambiguity effect and its elimination. Spectrum of the horizontal velocity component measured with the inclined monostatic ADVP and N_{pp} = 32 compared to the spectrum obtained by the two gate cross-correlation procedure.