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Heft 69, (2005), Sonderheft Promorph, Artikel 1, Seiten 442, E 34 450 Lit.

A Proposed Approach for the Determination of the Accuracy of Acoustic Profilers for Field Conditions

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Summary

In this paper an innovative approach to estimate the accuracy of measuring devices for field measurements is proposed. The approach uses simultaneous measurements taken with identical devices close to each other. This method was successfully applied in the evaluation of the accuracy of a 1200kHz ADCP for cross-sectional measurements of current velocities in tidal channels. Measurements were carried out from measuring devices mounted on vessels moving close to each other on parallel tracks. Measurement campaigns covered tidal ranges of about 3.5 m and depth-averaged current velocities ranging from 0.30 to 1.05 m/s. Point estimates were defined by fitting a logarithmic velocity profile to the measured values. The variability of point measurements is estimated from the simultaneous measurements. The accuracy of the depth-averaged velocity values is obtained by computing several probability intervals on the basis of re-sampling techniques. The standard deviation for point measurements were found to be constant at 0.06 m/s and 0.14 m/s for distances above and below 1 m from the sea bottom, respectively. Results are in reasonable agreement with those reported by VAN RIJN et al. (2002a), despite the different instruments and experimental and environmental settings. The accuracy of an ADCP measuring the depth-averaged velocity values was approximately constant at ±0.015 m/s. Resulting accuracy values have been used in the calibration and validation of depth-averaged two-dimensional and three-dimensional flow models.

Zusammenfassung

In dieser Arbeit wird eine innovative Methode zur Abschätzung der Messgenauigkeit von Messgeräten unter Naturbedingungen vorgestellt. Der Ansatz impliziert zeitgleiche und eng benachbarte Messungen mit technisch identischen Geräten. Dieses Verfahren wurde erfolgreich zur Evaluation der Genauigkeit des 1200 kHz ADCP bei Querprofilmessungen der Strömungsgeschwindigkeit in Gezeitenrinnen angewendet. Die Messungen erfolgten mit Messgeräten, die auf Schiffen installiert waren. Diese fuhren denselben Kurs in unmittelbarer Nähe zueinander. Die Messkampagnen beziehen sich auf einen Tidehub von etwa 3,5 m und tiefenintegrierten Strömungsgeschwindigkeiten von 0,30 bis 1,05 m/s. Punktuelle Abschätzungen wurden durch Anpassung eines logarithmischen Geschwindigkeitsprofils an die Messwerte definiert. Die Variabilität der Punktmessungen wird aus den zeitgleichen Messungen geschätzt. Die Genauigkeit der tiefenintegrierten Geschwindigkeitswerte aus der Berechnung mehrerer Wahrscheinlichkeitsintervalle auf Grundlage von „Resampling“ Techniken erhalten. Die Standardabweichungen für Punktmessungen lagen konstant bei 0,06 m/s für Entfernungen von mehr als 1 m bzw. bei 0,14 m/s für Entfernungen von weniger als 1 m Bodenanstand. Trotz der Verwendung unterschiedlicher Geräte, Experiment- und Umwelt-Maßzahlen stimmten die Ergebnisse recht gut überein mit denen von VAN RIJN (2002a). Die Genauigkeit einer ADCP-Messung für tiefenintegrierte Geschwindigkeitsmessungen lag nahezu konstant bei ±0.015 m/s. Die ermittelten Messgenauigkeiten wurden bei der Kalibrierung und Validierung tiefenintegrierter zwei- und dreidimensionaler Strömungsmodelle eingesetzt.

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Keywords

ADCP, Accuracy of Measuring Devices, Current Velocity, Bootstrap Method …

Contents

1. Introduction

In the framework of the German government funded research project entitled "Predictions of Medium Scale Morphodynamics- PROMORPH" selective measurements of current velocities using acoustic profiler were carried out at several tidal channels of a tidally-dominated area of the German Wadden Sea. The measurements aimed at calibrating and validating flow models for the area of investigation. A set of statistical parameters was used to assess the quality of the flow model results in relation to current velocities (PALACIO et al., in this volume). As measurements always include errors, a suggested approach to account for the influence of observational errors is to subtract these from the absolute error, thereby yielding an adjusted relative mean absolute error (WALSTRA et al., 2001; VAN RIJN et al., 2002b). While information on the accuracy of these devices is usually provided for laboratory conditions, very little is known about their performance in the field, particularly for depth-averaged velocity values.

In this paper an approach to estimate the accuracy of measuring devices for field conditions is proposed. The approach uses simultaneous measurements taken with identical devices mounted on vessels moving close to each other on parallel tracks. The proposed method was applied for field measurements of current velocities along cross-sections of tidal channels at the German North Sea coast. Results of the application of the approach to estimate the accuracy of a 1200 kHz Acoustic Doppler Current Profiler (ADCP) in the field are presented. The performance of the devices for point and depth-averaged velocity values is determined.

2. Acoustic Doppler Current Profilers (GORDON, 1996)

ADCPs use a principle that relies on the presence of particles (scatterers) in the water column to reflect back a transmitted acoustic signal. An acoustic short pulse of high frequency is transmitted to the water column with a fixed and known frequency through the transducer. Since the scattering particles move either closer or away from the device, the returned echoes experience a Doppler shift. Based on the measured shift, the speed of the scat-

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tering particle relative to the device can be determined and converted into current velocities. The principle of operation of ADCP relies on a number of assumptions, the most important of which in terms of data quality are homogeneity of the measurement layer, constant speed of sound over the measurement range and the average independent movement of scatterers to be zero.

Fig. 1 shows a typical output plot of a cross-section surveyed by an acoustic profiler, i.e. a path followed by a vessel during the measurements. Cross-sections are comprised of ensembles, i.e. columns of data along the vessel path. Ensembles are in turn divided into bins, i.e. measuring units with a thickness varying from about 10 cm to 1 m.

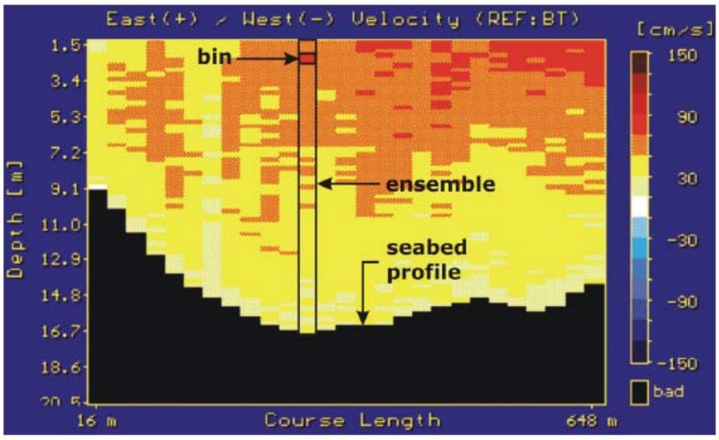

Fig. 1: Main elements of a transect obtained from a ship-mounted ADCP

The accuracy of ADCPs for point measurements under laboratory conditions is quite high in the order of a few mm/s. In the field, devices have been used mainly as bottom-mounted or as ship-mounted. Their performance is often strongly dependent on the environmental conditions. Moreover, the experimental settings, the characteristics and amount of suspended sediment matter and air bubbles in the water column, among others, can also affect their performance. VAN RIJN et al. (2002a) reported values of the accuracy of a 1500 kHz ADCP for field conditions. The accuracy of the bottom-mounted stand-alone device for point measurements is 1 % of the measured value and ± 0.5 cm/s at the maximum output rate. The downward looking ship-mounted ADCP shows an accuracy of ± 5.3 cm/s for 10 seconds averaging (1.0 m cells) and ± 5.1 cm/s for 30 seconds averaging (1.0 m cells).

3. Experimental Set-Up and Measured Data

The present investigation focuses on a tidal channel of the Central Dithmarschen Bight on the German North Sea coast (see Fig. 2). The study area is located about 100 km north of Hamburg between the Eider and Elbe estuaries. The morphodynamics of the study area is dominated by tidal flats and a tidal system composed of three channels: the Norderpiep in the northwest, the Suederpiep in the southwest, and the Piep tidal channels, which is formed at the intersection of the Norderpiep and Suederpiep. The flow conditions in the area are dominated by a combination of tidal, wave-induced and wind driven currents. Under normal conditions the tidal effect prevails. The area is characterized by a mean tidal range of 3.2 m.

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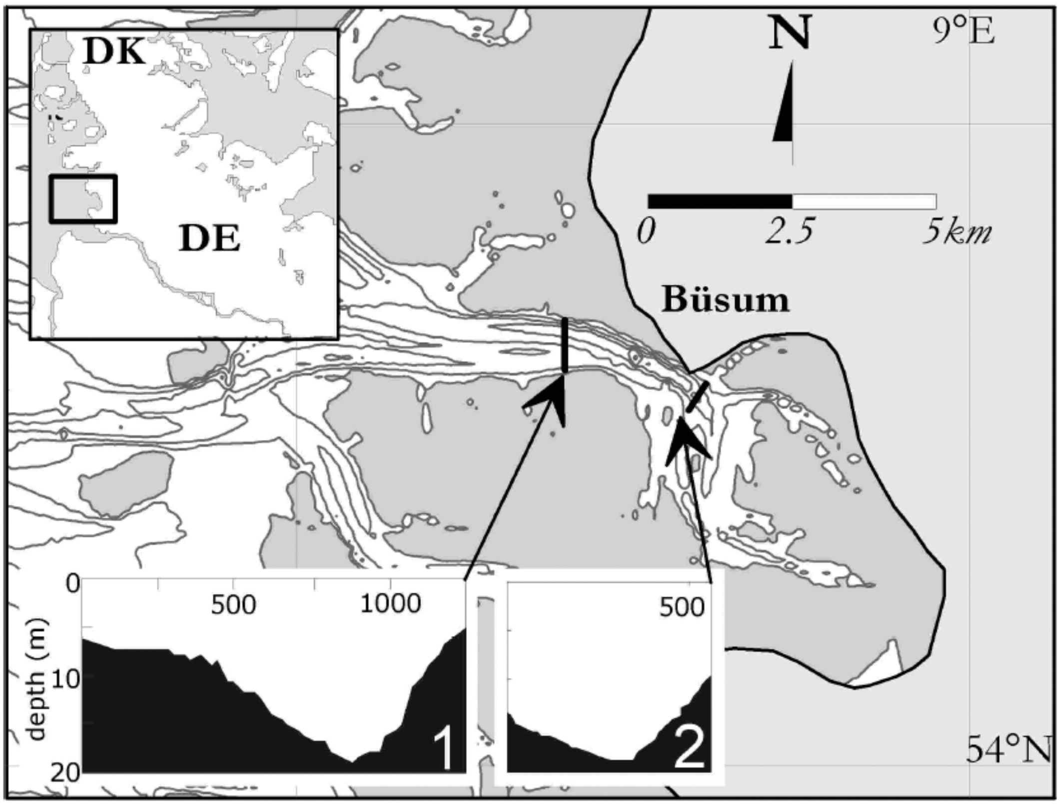

Fig. 2: Area of investigation

The water depths in the channels are up to about 20 m. The temporal and spatial variations of the current velocities are strongly influenced by the complex bathymetry. The current velocities in the tidal channels attain maximum values of about 2.8 m/s (TORO et al., in this volume).

The investigations were carried out at two cross-sections of the Piep tidal channel as indicated in Fig. 2. The mean water depth at the cross-sections varies from about 5–8 m to 18–20 m. The mean transect length is approximately 1000 m and 570 m at cross-sections 1 and 2, respectively. The cross-sections are about 3 km apart. Measurement campaigns in these two cross-sections were carried out on October 9, 2000 and February 1, 2001 at a tidal range of 3.5 m. The weather conditions during the measurements were essentially calm. Fig. 4 shows the time series of water levels during the measurement campaign indicating the times at which the cross-sectional measurements were taken. Measurements covered the ebb and flood phase during the 1st and 2nd measuring campaign, respectively. Details of the experimental settings are summarised in Table 1.

The data required for estimating the accuracy of an ADCP used for field measurements were obtained from identical instruments deployed on two vessels moving close to each other on a parallel course (Fig. 3). The two ADCPs, i.e. a 1200 kHz Workhorse Sentinel and a Direct Reading Broad Band, had been manufactured by RD Instruments. Their accuracy for point measurements under laboratory conditions is given as ± 0.25 % of the measured value ± 0.0025 m/s by the manufacturer. The instruments were mounted at the bow of the vessels pointing downward. Measurements covered the water column from about 1.6 m below the free surface (transducer draught and blanking distance) down to the seabed. The bin sizes during the measurements were set to 0.5 m.

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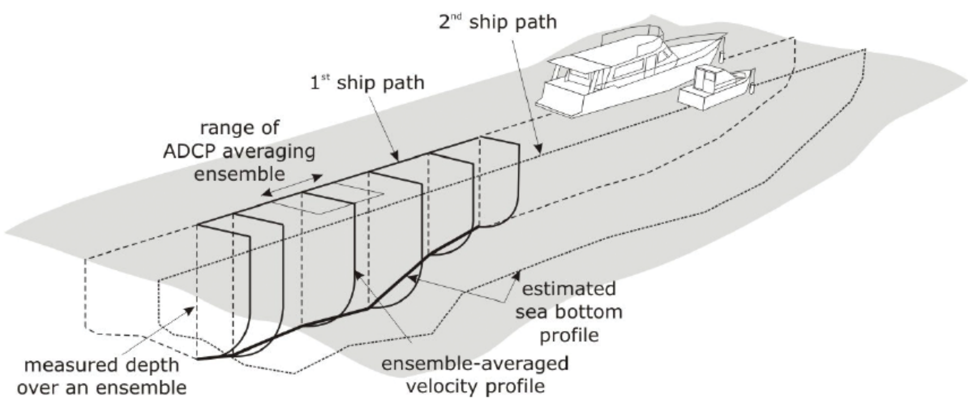
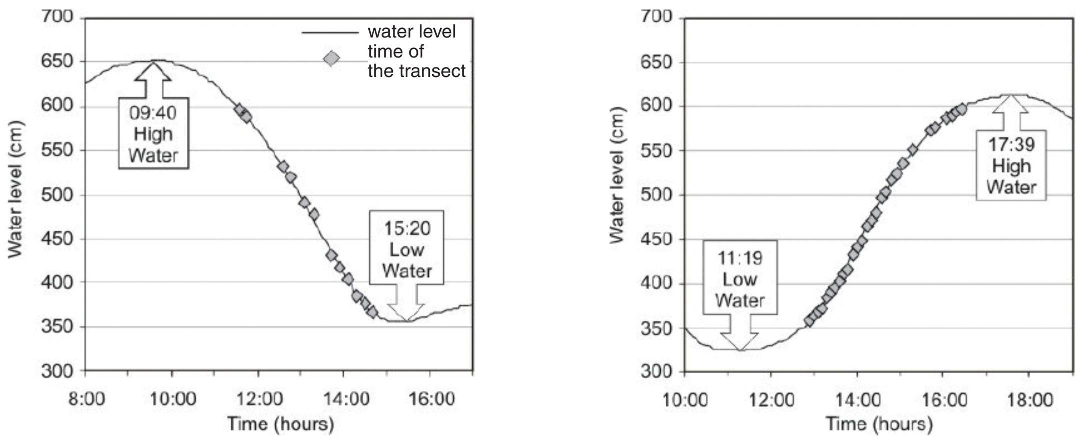


Fig. 3: Main elements of transect from ship-mounted ADCP

Several measurement runs within the tidal cycle were carried out. Altogether 21 runs, i.e. 5 from the 1st and 16 from the 2nd measuring campaign were considered for analysis. From these, a total of 686 current velocity profiles (207 from the 1st and 429 from the 2nd measuring campaign) were derived. To assure that the variation of the velocity over the depth follows a logarithmic distribution, the analysis focused on velocity profiles with a maximum point velocity exceeding 0.3 m/s. The depth-averaged velocity values used in the analysis range from 0.28 to 1.06 m/s.



(a) 1st measurement campaign
Cross-Section 1

(b) 2nd measurement campaign
Cross-Section 2

Fig. 4: Time series of water levels and cross-sectional measurements

Table 1: Details of the measurement campaigns

	1st measurement campaign	2nd measurement campaign
Cross-Section	1	2
Date	October 9, 2000	February 1, 2001
Start and termination	11:34 till 14:40 hrs.	12:55 till 16:26 hrs.
Tidal cycle analysed	Ebb	Flood
Tidal range	3.5 m	3.5 m
Range of depth-averaged velocities	0.30–1.05 m/s	0.28–1.06 m/s
Number of parallel transects	5	16
Mean transect length	1000 m	570 m
Distance between vessels (mean)	2 to 24 m (6.5 m)	4 to 48 m (15 m)

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4. Data Analysis and Discussions

4.1 Model for the Velocity Distribution Over the Vertical

The distribution of the velocity profile over the water column in steady uniform flows is known to follow a logarithmic distribution that can be mathematically expressed as follows:

$$\frac{u_z}{u} = \frac{1}{} \cdot \ln\left(\frac{z}{z_0}\right) \tag{1}$$

with u_z = velocity magnitude in m/s at a distance z in m from the bottom
u = shear velocity in m/s
= von Karman coefficient assumed equal to 0.4
z_0 = zero-velocity crossing in m, which in case of rough regimes is a function of the roughness size only.

Flow in tidal channels is unsteady and non-uniform. Therefore, although the velocity profiles follow approximately a logarithmic distribution, the shear velocity and zero-crossing values are bound to vary in time. In this study the proposed model for describing the velocity distribution over the water column is written as:

$$u_z = a + b \ln(z) \tag{2}$$

Equation 2 is linear in the form $u_z = a + bx(z)$. The values of the coefficients a and b that best adjust to the measured velocity values over the water column can be obtained by simple regression techniques. Measured sets of current velocity profiles in the water column, i.e. ADCP ensembles $\{(z_i, u_i), i = 1, \ldots, k\}$ were considered. z_i denotes the distance to the seabed; u_i is the velocity magnitude and k the number of bins, i.e. measured units (point measurements) over the vertical. Point estimators for the depth-averaged velocities at each vertical profile were obtained by analytical integration of the fitted profiles divided by the corresponding water depth.

4.2 Variability of Point Measurements

The simultaneous measurements carried out side-by-side from the two vessels lead to two vertical velocity distributions at approximately the same location. Although good agreement between the profiles is expected, this was not always the case. Fig. 5 shows typical measured vertical profiles; one showing good agreement (Fig. 5a) and the other one with discrepancies (Fig. 5b).

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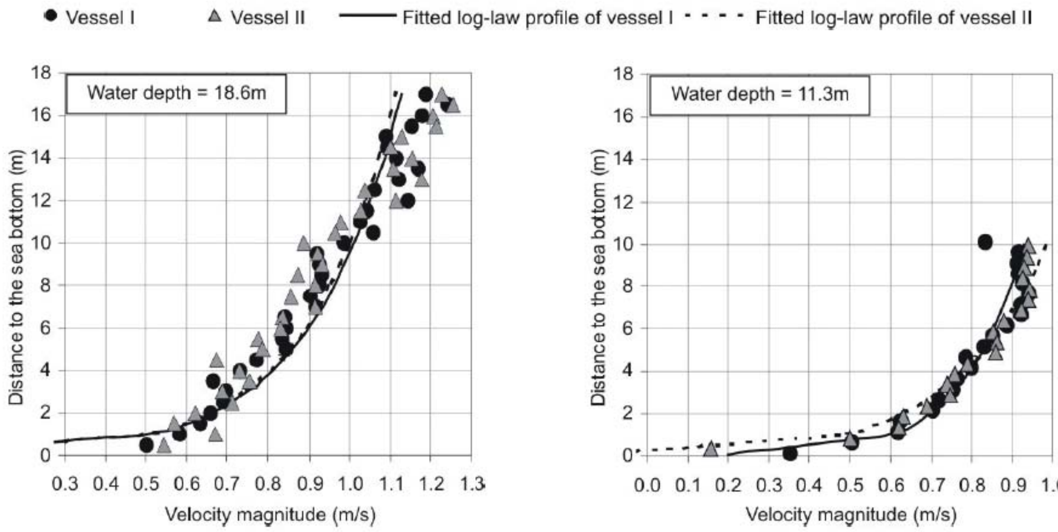

(a) Good agreement (b) Non-satisfactory agreement

Fig. 5: Comparison between simultaneous data sets

To check the agreement between the simultaneous data sets at the same location a multiple linear regression analysis was carried out. Several significance tests based on the t-distribution for the multiple regression coefficients were performed. A significance level of 5 % was considered to differentiate between a good and non-satisfactory agreement. In 43 % of the cases bad agreement resulted. Since the field data were collected using identical devices deployed simultaneously and very close to each other, the resulting discrepancies could be considered to correspond to the variability of point measurements in the field. In order to evaluate this variability, the differences between point velocity magnitudes belonging to simultaneous data sets were computed.

The accuracy of ADCP is known to decrease closer to the seabed due to decreasing intensity and side lobe interference. To account for this decrease, the variability was analysed with respect to the location of the point measurements within the water column. Weighting the percentage of acceptable values obtained by the ADCP was considered. Several F-tests were performed to figure out the optimal division of layers within the water column, so that the variability within each layer would remain approximately constant with significance levels of 10 %, 5 % and 1 %. The Kolmogorov-Smirnov goodness of fit test was applied to check the hypothesis of normality of the groups. Satisfactory results were obtained in all cases as summarised in Table 2. Two layers within the water column with approximately constant variabilities could be identified: a) bottom layer up to about 1m above the seabed and b) remaining water column up to about 1.6 m below the free surface. The standard deviation of the group sample in the lower layer turned out to be more than twice the value of the upper one. Considering the differences in instrumentation and environmental conditions, it should be noted that the results obtained in the upper layer are in good agreement with the ones reported by VAN RIJN et al. (2002a).

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Table 2. Variability of point measurements over the vertical

Layer distribution	Standard deviation of the group sample (variability) in m/s
Bottom layer : up to 1m from seabed	0.143
Upper layer : from 1 m above the seabed up to 1.6 m below free surface	0.065

4.3 Variability of Depth-Averaged Velocity Values

The variability of the depth-averaged velocity values was obtained by applying re-sampling techniques. In this study the *bootstrap* method by EFRON and TIBSHIRANI (1993) was used. A brief description follows.

For each measured vertical current velocity profile, i.e. each ADCP ensemble, a data set $\{(z_i, u_i, g_i), i = 1, \ldots, k\}$ was considered. z_i denotes the distance to the seabed, u_i is the velocity magnitude, g_i the percentage of acceptable values given by the ADCP and k the number of points measured over the vertical (bins).

For each set of data, 10^4 *bootstrap samples* were computed. *Bootstrap samples* are random samples drawn with replacement from the original population. They consist of members of the original data set, some being absent, others appearing one or more times. For each *bootstrap sample* the coefficients a^* and b^* in Equation 2 were estimated by fitting the log-law distribution. The log-law profile defined by the simulated coefficients (a^* and b^*) represents an ideal state that never occurs in real measurements. Two sources of errors were accounted for: a) the variability of point measurements listed in Table 2 and b) the regression residuals defined by the differences between the measured values and the values predicted by the log-law fit.

The approach adopted to account for the probability intervals of the depth-averaged velocity is illustrated in Fig. 6. First, each of the fitted log-law profiles was discretised over the vertical with a 1 cm resolution. Then, for each discretised point a value corresponding to the residual values was simulated and added, following a normal distribution with zero mean and variance equal to the sum of the variance of the regression residuals and the one introduced by the variability of point measurements over the vertical. Finally, for each of the 10^4 *bootstrap samples*, the depth-averaged velocity values were computed. This was done by dividing the numerical integration of the discretised point velocity values by the corresponding water depth. The resulting sets of simulated values of the depth-averaged velocity in a vertical distribution over the water column allow the computation of percentiles which in turn enables the estimation of probability intervals. In the figure, the original field data and a bootstrap sample are shown in conjunction with their corresponding log-law fits. The points obtained by adding the simulated normally distributed residuals to the discretisation of the logarithmic profile fitted to the bootstrap sample are also indicated.

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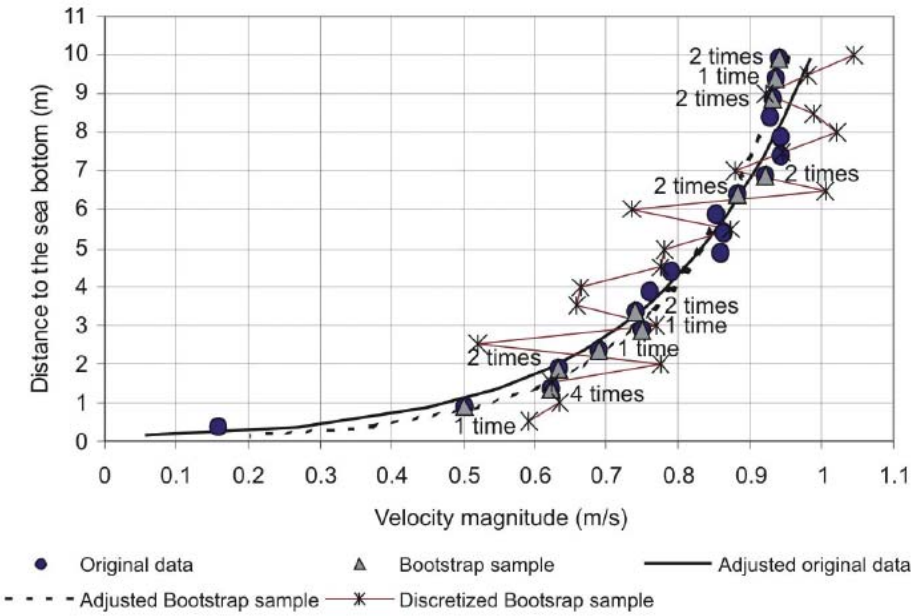

Fig. 6: Bootstrap procedure for a given vertical profile

4.4 Probability Intervals of Depth-Averaged Velocity Values

The accuracy of an ADCP in measuring depth-averaged velocity values for field conditions was estimated by computing six probability intervals corresponding to confidence levels of 98 %, 90 %, 80 %, 70 %, 60 % and 50 % on the basis of simulated depth-averaged velocity values.

Comparisons between the point estimators obtained by analytical integration of the measured values that were fitted to the original set of data divided by the corresponding water depth, and the mean and median values corresponding to the *bootstrap samples* led to a quite satisfactory agreement. The simulated data obtained by re-sampling techniques were homogeneously distributed without important asymmetries. Fig. 7 shows the distribution of the depth-averaged velocity values corresponding to the *bootstrap samples* for the two vertical profiles shown in Fig. 5. It can be seen that the point estimator of the values depth-averaged is well centered.

To create a better comparison, cross-sectional averages of the interval lengths of the depth-averaged velocity were calculated. These values were obtained by averaging the entire set of interval lengths corresponding to each ensemble. The cross-sectional averages of the probability interval lengths and their variances behave in a quite constant and regular way. Therefore, in general, they are found to be independent of the water level or the depth-averaged velocity.

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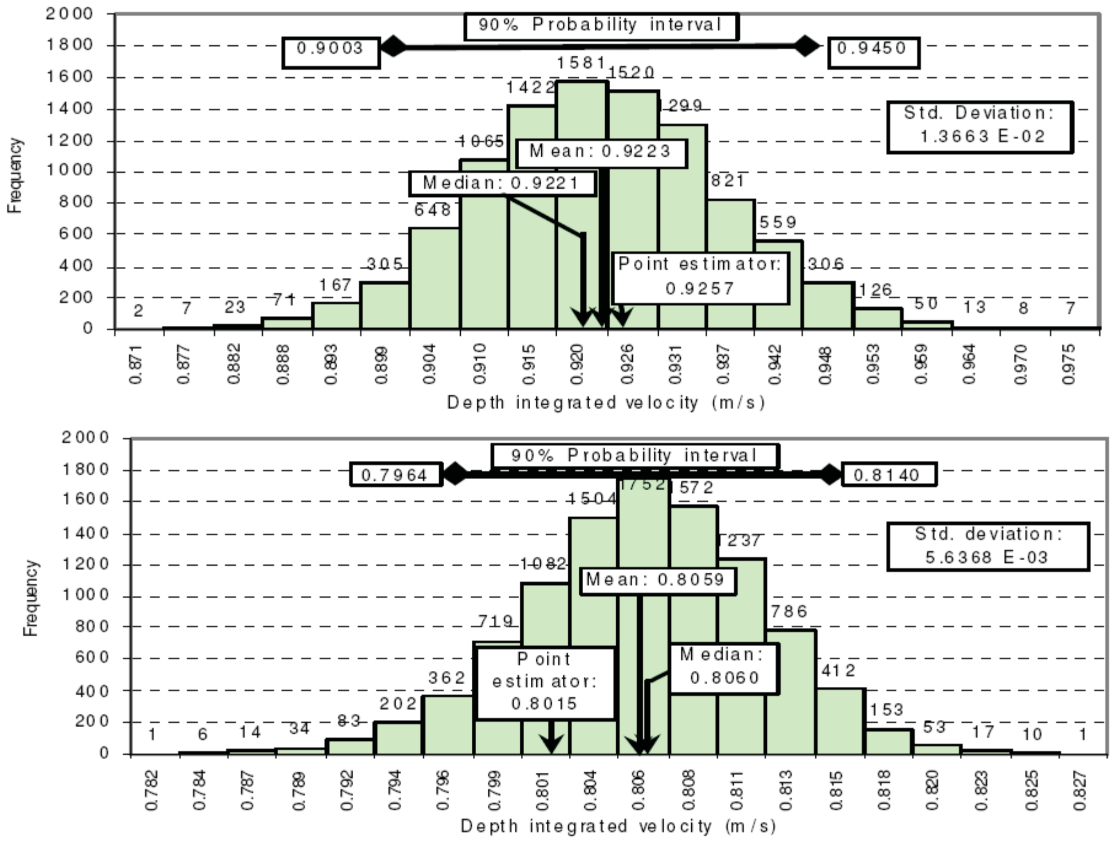

Fig. 7: Distribution of the bootstrap results for two given velocity profiles

Table 3 summarises the mean values of the resulting cross-sectionally averaged velocities for the various significance levels obtained by analysing the measured data from both measurement campaigns. The accuracy values were defined by assuming homogeneity and symmetry of the simulated sets of data obtained using *bootstrap techniques*. Moreover, it was assumed that the point estimator of the depth-averaged velocity is well centred in the *bootstrap sample*.

Table 3. Interval lengths and accuracy values of the depth-averaged velocity values

Confidence level	1st Measurement Campaign			2nd Measurement Campaign		
	Length[1] (m/s)	Accuracy (m/s)	Accuracy[2] (%)	Length[1] (m/s)	Accuracy (m/s)	Accuracy[2] (%)
98 %	0.037	± 0.018	2.07–2.85	0.048	± 0.024	2.73–3.75
90 %	0.026	± 0.013	1.45–1.99	0.034	± 0.017	1.90–2.62
80 %	0.020	± 0.010	1.14–1.56	0.026	± 0.013	1.48–2.03
70 %	0.016	± 0.008	0.91–1.25	0.021	± 0.012	1.19–1.64
60 %	0.013	± 0.007	0.74–1.02	0.017	± 0.009	0.97–1.33
50 %	0.011	± 0.006	0.60–0.82	0.014	± 0.007	0.80–1.09

[1] Length of the probability interval.
[2] Accuracy value given as percentage of the cross-sectional depth-averaged velocities.

It can be seen that the length of the confidence intervals is slightly larger for the 2nd measuring campaign. This can be attributed to the spatial dependence, different tidal phases, i.e. ebb and flood phase respectively during the 1st and 2nd measuring campaign and variation

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in distances between the vessel tracks. The fact that the two campaigns were carried out in the same tidal channel along two cross-sections not faraway makes the consideration of the spatial dependence doubtful. Bearing in mind that the length of the probability intervals was independent of water level and current velocity values, further rejects the hypothesis that the differences may be caused due to the different tidal phases. Therefore, the main reason of slightly larger values during the 2nd measuring campaign was attributed to the larger distances between the vessel tracks.

Taking into account the symmetry and homogeneity of the resulting sets of simulated data, a constant accuracy value of ± 0.015 m/s, based on the 90 % confidence levels from the two measuring campaigns, resulted for the depth-averaged velocity values.

5. Conclusions

In this paper an approach for estimating the variability and accuracy of measuring devices for field conditions is proposed. The method was applied successfully to the estimation of the accuracy of a 1200 kHz ADCP for field measurements of current velocities along cross-sections of tidal channels. The analysis focused on velocity profiles with maximum point velocity values exceeding 0.3 m/s giving depth-averaged velocity values from 0.28 to 1.06 m/s. The results indicate that the standard deviation of an ADCP for point measurements in the tidal channels of the central Dithmarschen Bight is constant at 0.14 and 0.06 m/s for vertical distances below and above 1m from the seabed, respectively. Results are in reasonable agreement with those reported by VAN RIJN et al. (2002a), despite the different instruments and experimental and environmental settings. The length of the probability intervals for the depth-averaged velocity is approximately constant and independent of water levels and the magnitude of depth-averaged velocities. A constant accuracy of about ± 0.015 m/s (at a 90 % confidence level) was obtained.

The approach offers an alternative and innovative way of estimating accuracies of measurement devices for field conditions. It attempts to account for the main factors that affect the variability of field measurements. Despite the fact that the experimental settings on the two parallel tracks are quite similar, other factors not directly taken into consideration, such as the variations of the suspended sediment during the measurements, insufficient suspended matter in the water column leading to insufficient signal detection as well as a complex and mobile bathymetry may also influence the accuracy.

6. Acknowledgements

The results presented here form a contribution to the research project “Predictions of Medium-Scale Morphodynamics – PROMORPH” funded by the German Ministry of Education and Research (BMBF) from year 2000 to 2002. The authors gratefully acknowledge the German Ministry of Education and Research for funding the project. We also wish to thank the staff of the Research and Technology Centre Westcoast of the University of Kiel for the planning and execution of the field measuring campaigns and for supporting in the interpretation of the results. Dr. Ian Westwood is greatly acknowledged for his English corrections and proofreading. The authors furthermore thank Dr.-Ing. V. Barthel as well an anonymous reviewer for their constructive remarks.

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