Velocity and Turbulence Measurements at the Ems Barrage

Oliver Lojek, Knut Krämer, Anna Zorndt, Nils Goseberg and Torsten Schlurmann

Summary

From July 14th-16th, 2012 a joint measurement campaign was conducted at the Ems barrage in Gandersum, Germany, by The Lower Saxon State Department for Water, Coastal and Nature Conservation (NLWKN), the Water and Shipping Authority (WSA) Emden and the Franzius-Institute for Hydraulic, Waterways and Coastal Engineering (FI). Both, moored and mobile measurements were carried out.

Measurement results of mobile 3D-current velocities by Acoustic Doppler Current Profiler (ADCP), complemented by a conductivity, temperature and depth (CTD) sensor for vertical profiling are presented here. Results support the calibration and development of a hydro numerical model by the NLWKN.

Keywords

Ems, barrage, ADCP, CTD, Reynolds stresses, TKE, gradient Richardson number

Zusammenfassung

Vom 14. bis 16. Juli 2012 wurde am Emssperrwerk in Gandersum, Deutschland, von dem Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN) zusammen mit der Wasser und Schifffahrtsverwaltung des Bundes (WSA/WSV) sowie dem Franzius-Institut für Wasserbau, Ästuar- und Küsteningenieurwesen (FI) eine gemeinsame Feldmesskampagne durchgeführt. Es wurden Messungen von vertäuten sowie mobilen Plattformen aus durchgeführt.

Messergebnisse von 3D-Strömungsgeschwindigkeiten gemessen mittels Ultraschall-Doppler-Profil-Strömungsmesser (engl.: Acoustic Doppler Current Profiler, ADCP), sowie ergänzende Leitfähigkeits-, Temperatur- und Tiefenmessungen im Profil mit einer gefierten CTD-Sonde werden hier vorgestellt. Die Ergebnisse eignen sich für die weitere Entwicklung und Kalibrierung eines hydro-numerischen Models der Ems durch das NLWKN.

Schlagwörter

Ems, Sperrwerk, ADCP, CTD, Reynolds-Spannungen, TKE, Gradient Richardson Zahl

Contents

1 Introduction

The Lower Saxon State Department for Water, Coastal and Nature Conservation (NLWKN) is evaluating the use of an existing storm surge barrage in the lower river Ems in order to influence the estuaries sediment transport behaviour (see Fig. 1 OBERRECHT and WURPTS 2014). From July 14th-16th, 2012, a tidal control experiment was conducted at the Ems barrage in Gandersum, Germany. The aim of the series of experiments is the investigation of a possible manipulation of tidal- and sediment dynamics in the Ems estuary. Supplementing in-situ measurements, a numerical model of the estuary is developed by NLWKN. The model is capable of simulating the operation of the Ems barrage as well as the Ems-specific fluid-mud dynamics. Prerequisite for a successful calibration and operation of the model is the knowledge of the local current- and turbulence characteristics in the vicinity of the barrage. By means of a specific time-variable operation of the barrage gates, the tidal flow during the flood phase was slightly delayed in order to reduce tidal asymmetry.

The reduced water level gradient in combination with narrowing of the flow cross section was expected to minimize the flood momentum and therewith the sediment transport capacity. The tidal control experiment was complemented by a comprehensive measuring campaign.

2 Methods

A number of research vessels took various measurements of different characteristics in the area of the barrage. Measurement stations located both seaward and inland of the barrage were operated by the Water and Shipping Authority (WSA) Emden, moored NLWKN R/V Burchana performed stationary turbulence measurements employing Acoustic Doppler Current Profiler (ADCP)-Turbulence and – for reference – Acoustic Doppler Velocimetry (ADV). The NLWKN survey vessel Nynorder Oog, performed bathymetric soundings both. Furthermore, the research boat of the Franzius-Institute (FI) conducted current- and turbulence measurements in direct vicinity of the barrage by means of an ADCP complemented by a conductivity, temperature and depth (CTD) sensor. Over a period of five tidal cycles, the secondary barrage gates (Nebenöffnungen) were closed approximately 30 min before ebb slack water, and were kept shut during the flood period until the following high water. Measurements in 2009 already revealed that the narrowing of the flow cross section results in significantly increased current velocities within the proximity of the remaining two open weir gates. By means of ADCP measurements conducted by FI, the effect of the tide control experiment on current velocities and current fields were monitored.

2.1 Measuring equipment

Measurements evaluated here were conducted with the research boat of the Franzius-Institute. Vectorial 3D-current velocities were measured by means of an ADCP Work Horse Rio Grande by Teledyne TD Instruments with a working frequency of 600 kHz. The orientation of the ADPC is determined by internal sensors registering pitch and roll magnitudes. Absolute positioning of the vessel is obtained by its geodetic differential GPS-receiver by Trimble which features its own reference station allowing for real time kinematic (RTK) correction of the vessels position. This allows an absolute positioning within decimetre precision. The orientation of the vessel as well as the ADCP in the measuring plane is obtained by means of a GPS-compass rendering the method immune to ferromagnetic distortions such as could be present near the barrage gates or pile moorings at the Ems barrage. In case of failure of the GPS-compass yaw line-of-sight (LOS) rates were also recorded using the vessels gyroscopic system for a fail-safe determination of bearing information via dead reckoning. Vertical profiles of salinity, turbidity and temperature in the water column were measured utilizing a CTD-probe. The most important parameters of the operated instruments are summed up in Tab. 1 below.

Table 1: Overview of measurement instruments operated on the FI-vessel.

Instrument	Type	Manufacturer	Test frequency	Resolution
ADCP	WH Rio Grande	Teledyne RDI	2,5 Hz	0,25 m
dGPS	Trimble 5700	Trimble	1 Hz	0,1 m
Rotation rate sensor	Gyro Plus 2	Raymarine	10 Hz	0,1°
GPS-compass	LV 100	Hemisphere	10 Hz	0,1°
Conductivity, temperature and depth sensor (CTD)	ECO IV	Grisard	1 Hz	-

2.2 Measuring schedule

The tidal control experiment stretched over four tidal cycles ranging from July 14th to 16th, 2010. In order to evaluate the influence of the experimental tidal control run onto local current conditions supplemental unimpeded “zero-tides” have been measured before and aft. The measurement campaign was especially focused onto varying flood-current-velocities. Measurement times/periods were tied to the tidal control experiment from ebb slack tide to mean tide. Measurements were conducted in so called measurement cycles (mc) which are made up of profile groups featuring distinct procedures of ADCP-profiles and CTD-measurements. Measurement positions are depicted in Fig. 1.

One regular measurement cycle entails one longitudinal (P0) and five cross-sectional profiles (P1-5) landward and one profile seaward of the barrage. Additional CTD-measurements were conducted at the intersections of the cross-sectional profiles P1, P4 and P5 with the longitudinal profile as well as at the position of the NLWKN research vessel Burchana between the first and second rows of pile moorings at level with the southern pier of the main barrage opening (HSÖ) (V1-V4). In total 130 ADCP-profiles and 78 vertical CDT-profiles were measured, whereof 17 pairs rendered suitable for an advanced scientific investigation regarding possible turbulence parameters.

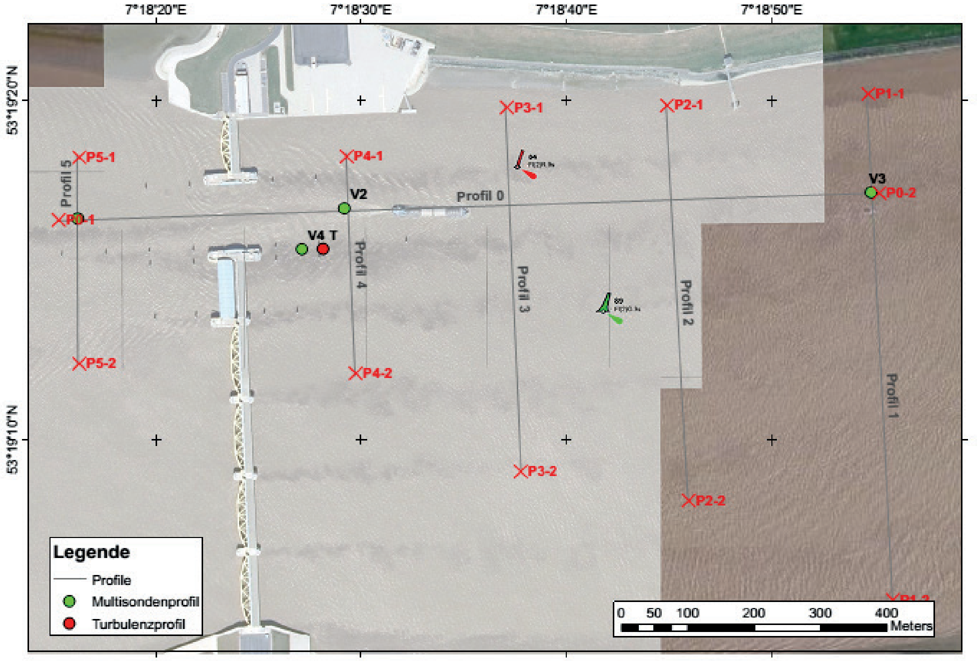

Figure 1: Overview of the measurement profiles (—) for the FI-boat with CTD-measurement positions (•) and turbulence measurement positions (•).

2.3 Blending of ADCP- and CTD-data

Standalone ADCP- and CTD-measurements form the basis upon which local current characteristics before and after the barrage under changing gate operation are evaluated. Furthermore a conjoint deployment of the ADCP and the CTD probe allow for a subsequent blending of the data for a specific location using the instrument timestamps. By interpolating the CTD data linearly onto the ADCP data (cf. Fig. 2) one value is obtained for salinity, temperature and pressure for every ADCP depth cell at a point in time.

This approach allows for turbulence parameters such as the turbulent kinetic energy (TKE) or gradient Richardson numbers (Ri) to be determined for specific positions.

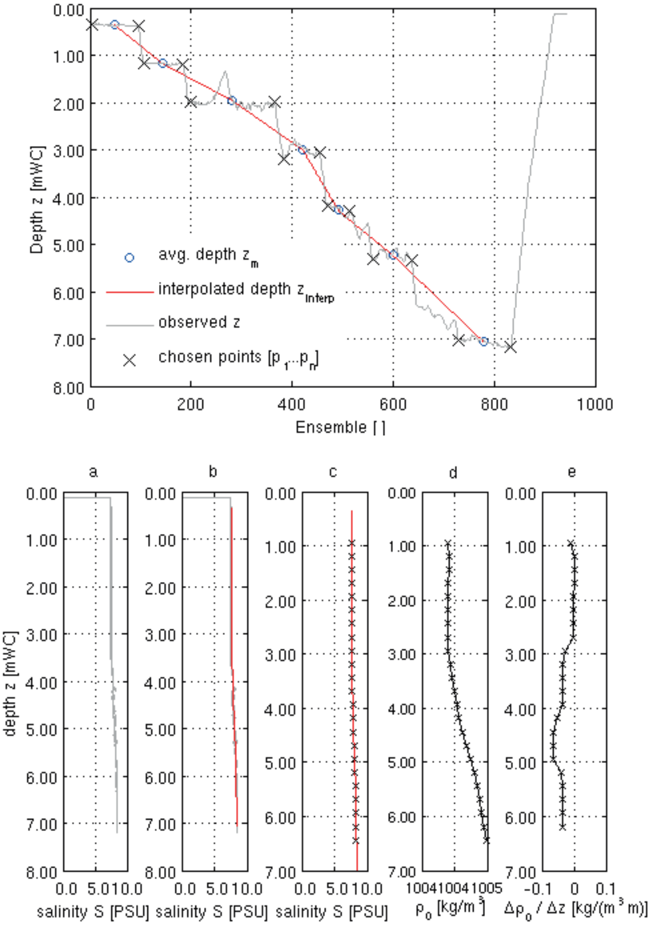

Figure 2: First panel: Linear interpolation of CTD-measurements for further blending with ACDP-measurements. Second panel: Stepwise generation of input data for determining turbulence parameters. Exemplary salinity data. a) CTD-measurements of salinity over the water column. b) PSU-function based upon averaged depth-values. c) interpolated PSU-cell-centre-values (x). d) Potential density in kg/m³ determined based upon the interpolated values (x). e) Change of the pot. density over the depth in kg/m³ (x).

3 Results

In-situ measurements of pressure, temperature and conductivity by CTD illustrate the evolution of the said parameters over the tidal cycle. In addition, blending the ADCP velocity measurement data with the CTD profile data obtained at the same locations allows for calculating turbulence parameters. Therefore, the CTD data was linearly interpolated onto the vertical positions of the ADCP bins, resulting in one value per variable (salinity, pressure, temperature) per ADCP depth cell. Reynolds stresses ($R_{i,j}$) have been determined using the variance technique described by Lohrmann et al. (1990).

Turbulent kinetic energy (TKE) was calculated following the approach described in Lohrmann et al. (1990), as well as Stacey et al. (1999a, 1999b). Finally, profiles of gradient Richardson numbers (Ri) were calculated, which serve as an indicator for stability of a stratification in the water column. The theoretical framework of Lohrmann et al. (1990) has been used, which relates the stratification to the velocity shear. The investigations revealed a distinct influence of the tidal control experiment on the local turbulence regime. These observation-based results support the calibration of the numerical model of the river Ems and the barrage developed and operated by the NLWKN.

3.1 ADCP-measurements

3D-current velocity measurements were carried out with an ADCP which was operated on the FI-boat. Thus, current measurements have successfully been conducted over a wider area. Fig. 3 depicts the temporal distribution of conducted measurement cycles (mz02-19) with the underlying tide.

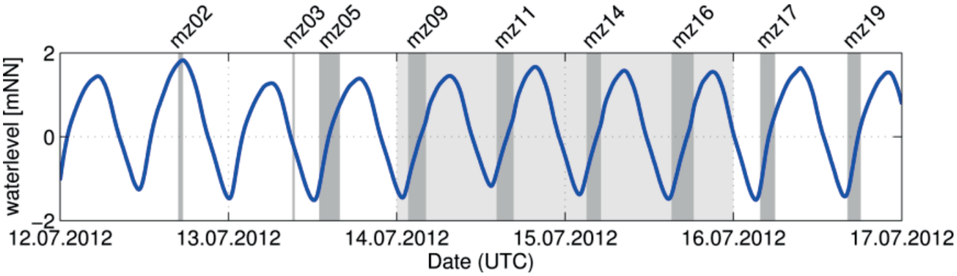

Figure 3: Overview of ADCP-measurements conducted with the FI-boat during the measurement campaign July 14th–16th, 2012. Turbulence measurement cycles (■), Tidal control experiment (🟦), Water level at the gauge Ems barrage (—).

3.1.1 Baseline measurement

The tidal control run was preceded by measurement cycle mc05 during which current velocities were recorded. For the baseline measurement all gates of the barrage were kept open. Three measurement cycles were conducted (mc05a - mc05c). Fig. 4 shows results for mc05c.

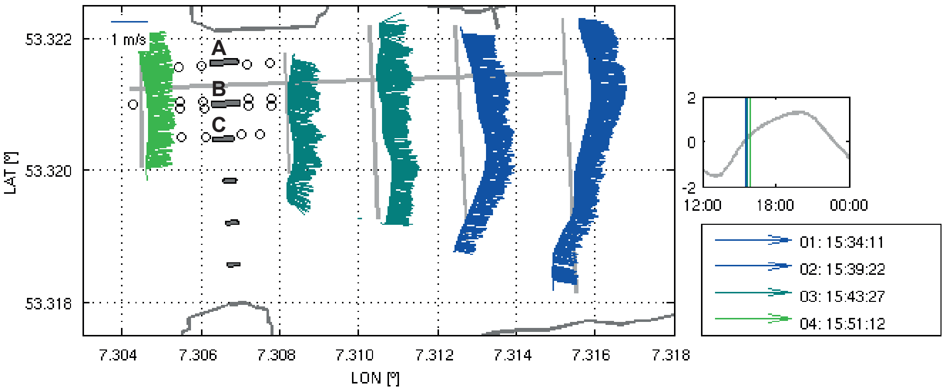

Figure 4: ADCP-velocity measurements during a "zero tide". mc05c, six profiles within the time period 15:34:11−15:53:59 UTC|13.07.2012. The Ems flows unimpeded and develops an approximately constant current field A) NÖ1, B) HSÖ, C) BSÖ.

The first mc05a, recorded on the 13.07.2012 from 12:57 to 13:34 UTC, captures the current velocity distribution near the barrage shortly after the flood stream flow began. Depth averaged flow velocities reach 0,3 - 0,6 m/s. Due to the larger flow cross section within the area of NÖ1 (A), HSÖ (B) and BSÖ (C) a reduction of the current velocities from the northern shore towards the southern shore can be observed. Mc05b was measured at fully developed flood stream between 14:25 and 15:00 UTC. Velocities range from 0,8 m/s to 1,2 m/s. The formerly mentioned reduction of the velocities from northern to southern shore is less distinctive. mc05c was captured during mean tide and features velocities ranging from 0,6 to 0,8 m/s (cf. Fig. 4).

3.1.2 Tidal control run

For visual assessment of the current velocity field influenced by the tidal control experiment during mc09, recorded the 14th of July 2012 with four full profile groups from 01:28 - 04:10 UTC, is presented here. Fig. 5 shows ADCP-measurement results for mc09b.

mc09a was recorded between 01:38 and 02:06 UTC, shortly after low tide. Current velocities within the area of the navigational sluices reach 0,7 m/s at the beginning and continuously rise during the mc and reach 1,5 m/s. Due to a reduction of the cross-section to the navigation openings a backflow develops downstream the closed gates. It reaches velocities of up to 0,6 m/s in the southern half of the river. In the course of the flood the current velocities rise up to 2,0 m/s in the main navigational openings during mc09b. Furthermore, the backflow intensifies and reaches up to 1,0 m/s.

During mc09d, velocities within the navigational channel still reach 2,0 m/s, whereas the backflow slightly diminishes to 0,6 m/s.

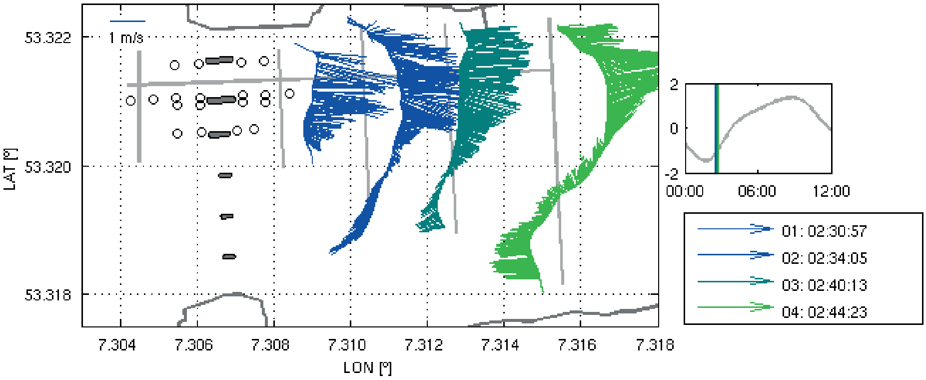

Figure 5: ADCP-velocity measurements during the tidal control run. mc09b, four profiles within the time period 02:30:57–02:44:23 UTC|14.07.2012. Landwards of the barrage towards the southern shore a distinct eddy and backflow develop.

3.1.3 Comparison

The baseline measurement preceding the tidal control experiment (mc02, mc03 and mc05), depicts a uniform current field with a tendency for slightly higher velocities in the navigational channel near the northern shore of the Ems. Compared to the baseline measurement the tidal control run clearly constricts the flood stream to the main and inland navigational gates, inducing an intense velocity shear between the northern and southern part of the river as well as the development of an eddy in the southern part of the river. Depth averaged maximum flood velocities reach 2,5 m/s in the navigational channel during the tidal control experiment with peak values above 3,0 m/s. Follow-up baseline measurements (mc17 and mc18) document that the previously measured uniform current field is re-establishes. Depth averaged velocity values are not altered by the foregone control run e.g. due to the retention of backwater.

3.2 CTD-measurements

Salinity and temperature have been measured by means of a CTD probe at various locations and intervals (cf. Fig. 1). The development of the variables over the tidal cycle, as anticipated, depicts a slight variability in time.

However, no stratification can be detected in the measurement data. Nevertheless, the salinity data reveals the development of a vertical salt gradient (cf. Fig. 6).

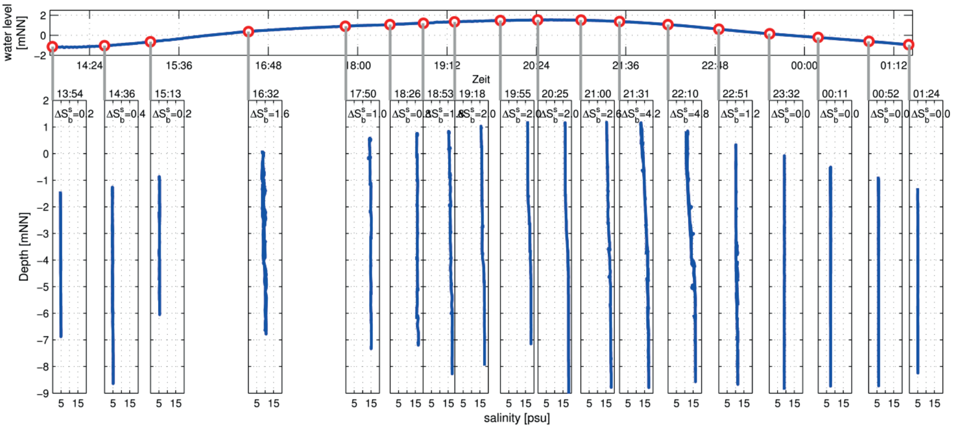

Figure 6: CTD measurements of salinity in PSU in the water column over the tide. mc11-13, 19 profiles within the time period from 13:51:59 14.07.2012–15.07.2012 13:27:03 UTC.

3.2.1 Salinity

The CTD-salinity-data shows four distinct phases. At low water the measured salinity reaches 5 PSU and the water column is completely mixed. Difference between top and bottom layer are 0,2 PSU. During flood stream the salinity values rise continuously until they reach 10 PSU at mean tide water. The difference reaches up to 1,2 PSU here. From mean tide to high water a slight layering of the salinity values within the water column can be seen. Values reach 15 PSU near the surface and 17 PSU near the bottom. With the initial ebb stream values decrease again due to the increasing influence of the headwater discharge, resulting in surface values of 10 PSU, maximising the internal gradient. From mean tide onwards the ebb stream shows a completely mixed water column again. Salinity values drop continuously from 10 to 5 PSU at low water.

3.2.2 Turbidity

The turbidity is measured by means of an optical attenuation sensor and describes the ratio of the emitted to absorbed and scattered light. A turbidity of 0 % is reached when 100 % of the emitted light is detected at the end of the measuring distance. A turbidity of 100 % results when 100 % of the emitted light is scattered and/or absorbed. The measurement values of the turbidity sensor have been evaluated by means of onsite collected water samples. These were stepwise diluted with fresh water afterwards in order to obtain a suitable calibration for the sensor. Accounting for the high turbidity in the Ems river, a customized measuring distance of 15 mm has been used instead of the 135 mm long standard distance.

The CTD turbidity data shows four distinct phases. From low tide to mean tide, high turbidity values around 95 % with a completely mixed water column were observed. From tide mean water to the subsequent high tide a reduction of the turbidity to 70 % was measured in the upper half of the water column. This results in a gradient within the water column, since the bottom values remain at about 90 %. At high tide the surface values drop to 30-40 % and the bottom values to 50-60 %. During ebb current well-mixed conditions are re-established and the values rise continuously up to 95 % at the following low tide.

4 Turbulence parameters

Further blending the measurement data taken at the same time and location allows for Reynolds stresses as well as Turbulent kinetic energy (TKE) and gradient Richardson numbers (Ri) to be determined for these specific measurements. In total 17 mc rendered a blending possible. These parameters have been calculated based on the framework presented by LOHRMANN et al. (1990), STACEY et al. (1999a, 1999b), TRUCKENBRODT (2008), MCDOUGALL et. al. (2010) and LU and LUECK (1999). Results for the baseline measurements depict an evolution of the parameters over the course of the flood stream. Reynolds stresses develop the typical Reynolds stress profile over the water column described in (not shown here). For the baseline measurements the values range from 0.005-0.02 m^2/s^2. Values rise with the beginning of the flood stream and gradually sink again after mean tide. A similar behaviour was observed for the tidal control run, whilst the overall values where slightly larger ranging from 0.02-0.04 m^2/s^2.

TKE-values develop in a similar way, for the baseline measurements the values rise with the initial flood stream and gradually drop when mean tide is reached. Values range from 0,1-0.15 W/m^2. During the tidal control run the values, similar to the Reynolds stresses, are bigger and range from 0.17-0.21 W/m^2. Nevertheless, the course of development remains the same, where the values gradually drop once mean tide is reached.

Finally the Richardson number Ri has been determined as a means to evaluate whether the turbulent energy present suffices to overcome potential stratifications within the water column. Ri describes a ratio the potential energy to the kinetic energy. The critical value lies at $Ri_{crit} = 0.25$, above which too little energy is present and a stratification could form. Values below Ri_{crit} feature enough energy to overcome a potential stratification within the water column. Ri-values have been normalized in accordance with int. literature, with $\log_{10}(Ri/0.25)$ shifting Ri_{crit} from 0.25 to 0.0, facilitating the interpretation of plots (STACEY et al. 1999a, 1999b).

Ri-values determined for the baseline measurement data exhibit a similar behaviour as the other two turbulence parameters determined, in that the values increase with the beginning flood stream and decrease again when the mean tide is reached. Values for the baseline measurements range from -3.0 to -5.3, indicating sufficient energy to overcome a potential stratification. For the tidal control run, values also rise over the course of the flood stream and decrease with mean tide. Ri-values for the tidal control run are more negative, ranging from -4.3 to -6.0, implicating a shift of the ratio towards the kinetic energy. Fig. 7a shows the result for a Ri-profile for mc09c with its measurement location (Fig. 7b) and time frame (Fig. 7c).

Finally, all Ri-values obtained are negative, and feature no sudden, large variances within their profiles, thus can be depth averaged without losing any vital data for an easier visual assessment (cf. Fig. 7d).

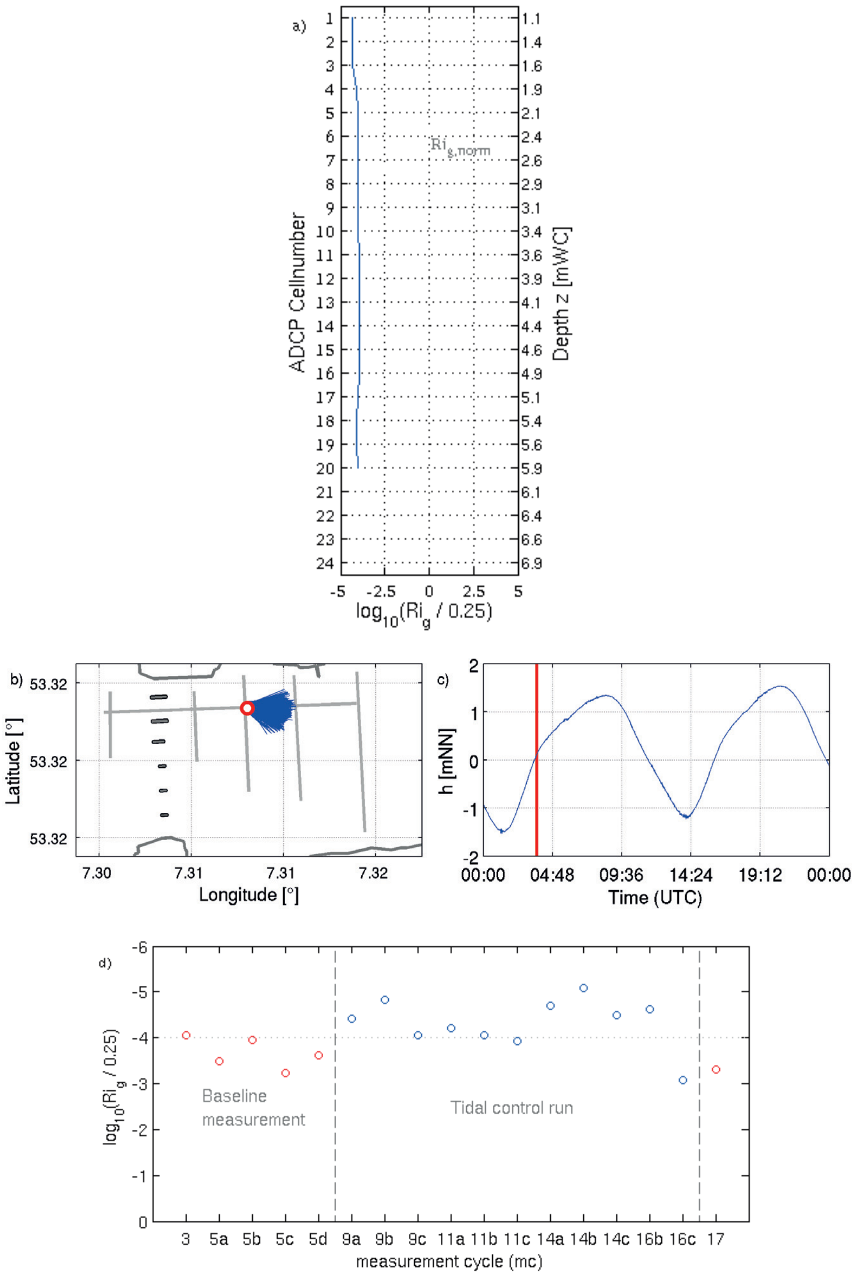

Figure 7: a) Normalized gradient Richardson number (—) plotted over the profile mc09a CTD: 14.07.2012, 02:17:21−02:24:01 | ADCP: 14.07.2012, 02:15:49−02:25:57 UTC. b) Locations of the measurements in regards to the barrage with the position of the CTD-probe (○) as well as the supplemental ADCP-measurements (—) c) Measurement period within the tide. d) Normalized depth averaged Gradient-Richardson-Numbers for the turbulence measurement cycles 3 to 17 originating from the blending of the ADCP-measurements with the CTD-data collected with the FI-boat on sight.

5 Discussion and Conclusion

During the tidal control experiment at the Ems barrage from the 14th to the 16th of July 2012, the Franzius-Institute conducted measurements of the 3D current velocities by ADCP as well as salinity and turbidity by CTD. Measurements were conducted from a mobile platform, operated in the fast flowing waters of the Ems river, and have successfully been evaluated. Measurement results presented here capture alterations in the local current field associated with the tidal control experiment.

Furthermore, collected data supports the calibration and validation of a hydro-numerical model of the Ems estuary developed and operated by NLWKN.

The ADCP measurements clearly depict an augmentation of the depth averaged current velocities by constricting the flow cross section to the navigation openings.

During flood current an eddy and backflow develop in the area of the closed secondary gates.

Vertical CTD measurements of salinity and turbidity showed a slight vertical gradient for water levels above mean water. The turbidity exhibits a maximum difference between top and bottom values of 30 %. Salinity values exhibit a maximum vertical gradient of 5 PSU.

Furthermore, in the area of the main navigational opening measurement deficiencies were encountered during baseline measurements due to non-detectable channel bed. This could be indicative of a near bed accumulation of suspended sediments or fluid mud is present within this area.

Turbulence parameters calculated by blending measurement data reveal an overall enhancement of already existent turbulences caused by the tidal control experiment. However, a significant increase in turbulence characteristics could not be detected. Nevertheless, the measurements help to assess the effects of the experimental gate operation procedure on hydrodynamics in the vicinity of the Ems barrage.

Finally, a new and mobile measurement method for turbulence parameters based on ADCP and CTD measurements, has been successfully applied.

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