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# ProcED: A MATLAB PACKAGE FOR PROCESSING ADCP ESTUARINE DATA

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**ABSTRACT.** *ProcED* is a MATLAB based computational package designed to facilitate the handling of a large amount of data derived from mount vessel ADCPs that monitor tidal flows and discharge in estuarine cross-sections. The package routines were written to process water current information obtained with an RD Instruments Rio Grande ADCP and its *WinRiver* software – version 1.03. They are capable to eliminate bad ensembles, to extrapolate current velocities for the surface and bottom blanked areas and to smooth noisy cross-profiles, enhancing the visualization of the velocity field. By performing space and time correlation between cell velocities, *ProcED* allows for the computation of the residual velocity field, both in the entire cross-section and in the discrete vertical profiles. Results are provided in graphical and table formats, the latter also including a table with the main flow characteristics such flooding and ebbing time, tidal elevation and current asymmetry, tidal prism and computations errors. A comparison with computations performed by *WinRiver* shows that *ProcED* discharge calculations are in average 5.5% smaller. The apparent underestimation of *ProcED* computations is ascribed to interpolation of the cross-profiles and to its different bottom extrapolation method. In the bottom area there is a discharge overestimation by *WinRiver*.

**Keywords**: acoustic current meters, ADCP, current profiles, data processing, MATLAB, estuaries.

**RESUMO.** *ProcED* é um conjunto de rotinas computacionais para ambiente MATLAB, elaborado para facilitar a manipulação da grande quantidade de dados de correntes medidas em seção transversal com ADCP embarcado durante o ciclo da maré em região estuarina. As rotinas foram desenvolvidas para processar os dados de corrente obtidos com o ADCP Rio Grande da RD Instruments e o seu aplicativo *WinRiver* na versão 1.03. As rotinas têm a capacidade de eliminar dados inválidos, extrapolar as correntes para as áreas não medidas (superfície e fundo), bem como suavizar os campos de velocidade, destacando sua visualização. Estabelecendo a correspondência espacial e temporal das células de velocidade, o *ProcED* permite o cálculo das correntes residuais para toda a seção, assim como em posições específicas. As saídas do *ProcED* são geradas na forma gráfica e em arquivo texto, incluindo uma tabela que apresenta as principais características do fluxo, tais como o tempo de duração da maré enchente e vazante, as velocidades média e máxima da corrente, o prisma da maré e os erros das medidas do ADCP. A comparação com os cálculos efetuados pelo *WinRiver* mostra que as vazões determinadas pelo *ProcED* são 5,5% menores em média. A aparente subestimativa nas vazões obtidas com o *ProcED* é atribuída à diferença dos métodos de interpolação na seção transversal e na extrapolação das correntes para a região do fundo, na qual o *WinRiver* deve estar superestimando as vazões.

**Palavras-chave**: correntômetros acústicos, ADCP, perfil de correntes, processamento de dados, MATLAB, estuários.

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## INTRODUCTION

Acoustic Doppler Current Profilers (ADCP's) operated from moving boats have been largely used in the characterization of horizontal and vertical flow structures (Lane et al., 1997; Peters, 1997; Sylaios & Boxall, 1998; Rippeth et al., 2002; Reed et al., 2004; Sepúlveda et al., 2004; Piedracoba et al., 2005; Schettini et al., 2006; Stanev et al., 2007), in quantifying water exchange (Chadwick & Largier, 1999) and in the estimate of suspended sediment transport (Gartner, 2004; Hoitink & Hoekstra, 2005; Madron et al., 2005; Merckelbach, 2006; Zaleski & Schettini, 2006; Schettini & Zaleski, 2006; Schettini et al., 2009) in estuaries and coastal bays.

The monitoring of water fluxes in estuarine channels is generally done with multiple passages of the instrument along a pre-established cross-section. Due to problems associated with flow turbulence, navigation and the occurrence of bad ensembles, the position of the velocity cells in successive cross-profiles[1] are rarely coincident, thus causing computing problems. Computation becomes even more complex due to the amount of data gathered along the monitoring of a full tidal cycle. Several tens of ensembles in each cross-profile are summed up, resulting in many thousand velocity measurements seldom correlated in space. If the transport of solutes or suspended elements is also considered, it is still necessary to synchronize the time of current and concentration data acquisition (Chadwick & Largier, 1999).

In order to facilitate the data treatment and analysis, a MATLAB freeware package named *ProcED* (available at <http://www.mcirano.ufba.br/ftp/pub/matlab/proced>) was written to process water current information obtained with an RD Instruments Rio Grande ADCP and its *WinRiver* software – version 1.03 – through a tidal cycle. This article aims to explain the routine, to present its validation and to show the type of output generated.

## DATA PROCESSING

Processing water current data from a complete tidal cycle involves the following steps, modified from Chadwick & Largier (1999): i) preliminary data inspection of each cross-profile; ii) spatial data interpolation of each cross-profile; iii) spatial velocity interpolation at even steps of time between the beginning and the end of the tidal cycle; iv) measurement error estimates; and v) determination of the main characteristics of the tidal cycle, i.e., flooding and ebbing time, average and maximum flow magnitude and velocities, tidal asymmetry and tidal prism.

*ProcED* requires the definition, while in the field, of well established limits for the cross-section (fixed buoys), in order to maintain the cross-section width and orientation unaltered. Navigation between the limits must be kept as straight as possible. The left margin of the channel (seaward facing) is taken as a reference for cross-section orientation, whereas positive (negative) velocity values indicate seaward (landward) directed flows. *ProcED* data preparation involves the following:

a) Data inspection and selection of fully measured cross-profiles with *WinRiver* in playback mode, taking note of the profile orientation (left margin to right margin or vice-versa) and eliminating useless segments of cross-profiles (e.g. turns preceding the definite route towards the opposite margin).

b) Data exportation in P-file format using *WinRiver* version 1.03[2].

c) Creation of a four-column input file to the routine *ADCP_ProcED*, containing the P-file names (*p.000), the time of the cross-profile (hours and fraction), distance in relation to the cross-section reference buoy (in meters), and a flag indicating the need to invert the cross-profile orientation (0 = no, 1 = yes).

d) Definition of the angle between the channel axis (ebb orientated) and the true north. This can be done either through a map/satellite image or through the dominant ebb-flow direction measured during the monitoring.

The *ProcED* package is form by routines *ADCP_ProcED*, *rdpadcp.m* (Pawlowicz, 2004), *rot.m* (Beardsley, 2004), *smartmean.m*, *isoline.m*, *ADCP_ProcED_error* and *tidal_cycle_analysis*, allowing for:

(1) The computation of the along-channel component of the current velocity ($u$, henceforth referred to as current velocity).

(2) The elimination of bad ensembles through interpolation.

(3) The extrapolation of the alongshore current component to the upper and lower blanked areas (the same *WinRiver* layers).

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[1] A cross-profile refers to the velocity profiles (ensembles) acquired along a cross-section of the channel at a given time.

[2] Version 1.06 alters data location in the P-files generating unrealistic data in *ProcED* results. An attempt is being made to fix this compatibility problem, enabling the routine to read files in ASCII format, including the *WinRiver* version II.

(4) The smoothing of the raw data by averaging three adjacent horizontal cells (optional, if contrasting values between adjacent ensembles occur).

(5) The establishment of a regular grid (matrix i,j) with spatial correspondence between all cross-profiles in the tidal cycle.

(6) The computation of the average current value for each cell, in the case of more than one cross-profile exists for a given time.

(7) The computation of the total cross-section area and water discharge.

(8) The determination of the average cross-section velocity (U).

(9) The representation of the velocity field in non-dimensional depths.

(10) The computation of the residual velocity field.

(11) The extraction of velocity profiles, in non-dimensional depths, at the location of hydrographic monitoring stations.

(12) Smoothing of the output for visualization purposes.

The spatial interpolation provides the means to calculate the velocities for a same location $u(i, j)$ in every cross-profile, considering the need to invert the orientation of the cross-profile (Fig. 1a). The depths $(i)$ for each column $(j)$ are turned into non-dimensional depths, which is the base for time (t) integrations.

It is suggested that when running *ProcED* the user chooses the average ensembles number for the horizontal resolution and the same ADCP vertical resolution.

*ProcED* outputs include:

- The velocity fields for every time interval, in a graphic format and in a MATLAB file (.mat) (tidal_cycle_matrix).
- A text file with the depth-averaged velocity for each ensemble (dacv_res).
- A text file with the cross-sectional average velocity, area and total discharge for the tidal cycle (disch_res).
- A residual velocity field for the tidal cycle, in a graphic format and in a MATLAB file (residual_field).
- A MATLAB file with the velocity profiles along the water column (non-dimensional depths) for the positions occupied by the hydrographic station(s) (inf2ctd).
- An estimation of the velocity and discharge error for every time interval (error_res).
- A text file with characteristic values for the tidal cycle (tidal_synthesis).

Time interpolation is another important feature of the package. The velocity field is interpolated at even time intervals between the beginning and the end of the tidal cycle, thus allowing for the computational of the residual velocity according to (Kjerfve, 1979):

$$< u_{i,j} >= \frac{1}{n}\left[\frac{u_j(Z_i, t_1)}{2} + \sum_k u_j(Z_i, t_k) + \frac{u_j(Z_i, t_n)}{2}\right] \tag{1}$$

where: $j$ is the column position; $i$ is the line number ($i = 1, 2, \ldots, 11$ for $Z = 0$ to $Z = 1, 0.1$ spaced); $k = 2, \ldots, n-1$; $t_n - t_1 = T$; $T$ is the length of the tidal cycle; $n = T/\Delta t$ is the number of time intervals, and $\Delta t$ is the interpolation time interval. $T$ is determined by the routine through the interpolation of the computed discharges, defining the time when the discharge close to the end of the tidal cycle equals that at $t_1$. By default $n = 25$ in order to avoid underestimation of the velocity values close to the flood and ebb maxima.

Depth averaged velocity ($\bar{u}$), as well as the depth averaged of any water property (e.g. salinity, temperature or suspended sediment concentration), is calculated through the equation (Kjerfve, 1979):

$$\bar{p}(t) = \frac{1}{10}\left[\frac{P_{Z0,t}}{2} + \sum P_{Zi,t} + \frac{P_{Z1,t}}{2}\right] \tag{2}$$

where: $\bar{p}$ is the mean value for the property in the water column; $P$ is the value for the water property at the position $Z_i$ in time $t$.

The random error of the Rio Grande ADCP measurements depends on the ADCP frequency, the height of the cell, the number of averaged pings (WP) and the geometry of the sound beams (RD Instruments, 1996). The velocity standard deviation is proportional to WP$^{-0.5}$. The random error for each cross-profile estimated by the routine is based on the standard deviation of the "error velocity" given for each cell by *WinRiver* (RD Instruments, 1996). In accordance RD Instruments (2002), the standard deviation of the error associated to a single ping in measurement mode WM1 is 0.181 m/s for 0.5 m cells and 0.066 m/s for 1 m cells.

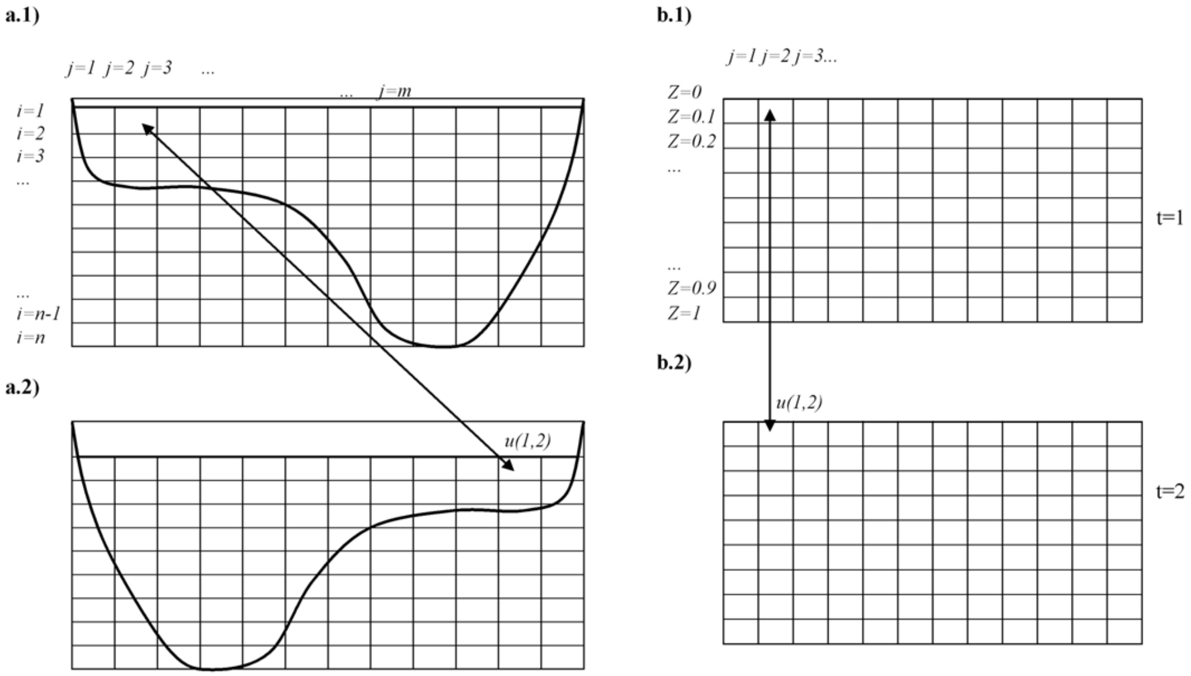

**Figure 1** – Scheme of spatial velocity cell correspondence in 2 cross-profiles (a.1 at high tide and a.2 at low tide). Profiles beginning at the right margin (a.2) are inverted. Space and time correspondence (b.1 and b.2) is done with all cross-profiles referenced to the left margin and to non-dimensional depths (Z). This procedure also applies to obtain an average condition when multiple cross-profiles exist for a given time.

To compute the mean random error for each cross-profile, the package uses the same computation method applied to the velocity, including time and space interpolations.

**Table 1** – Characteristic values for the two monitored tidal cycles in Paraguaçu River estuary. The parameters $t_f$ and $t_e$ were base on the variation of the average channel velocity $(\bar{u})$.

| | Spring | Neap |
|---|---|---|
| Tide height (m) | 3.15 | 1.32 |
| Cycle duration (h) | 12.13 | 13.06 |
| Ebbing time ($t_e$) (h) | 5.65 | 6.36 |
| $\bar{U}_e$ (m/s) | 0.54 | 0.15 |
| $\bar{U}_e \max$ (m/s) | 0.92 | 0.27 |
| $Q_e \max$ (m$^3$/s) | 23314 | 7163 |
| Flooding time ($t_f$) (m/s) | 6.48 | 6.70 |
| $\bar{U}_f$ (m/s) | -0.41 | –0.15 |
| $\bar{U}_f \max$ (m/s) | -0.61 | –0.27 |
| $Q_f \max$ (m$^3$/s) | –15816 | –7141 |
| $t_f/t_e$ | 15.0% | 5.3% |
| Maximum error $\bar{U}$ (m/s) | 0.029 | 0.018 |
| Minimum error $\bar{U}$ (m/s) | 0.014 | 0.013 |
| $AI_{DV}$ | 0.069 | –0.021 |
| Residual discharge (m$^3$/s) | 729.5 | –172.1 |
| Tidal prism (m$^3$) | $2.58 \times 10^8$ | $1.05 \times 10^8$ |
| Tidal prism error (%) | 3.0 | 7.7 |

As a final product, the package synthesizes the tidal cycle by providing the flooding and ebbing time, the average velocities, the tidal prism and an asymmetry index $(AI_{DV})$ (see Table 1). This asymmetry index is defined by Mantovanelli et al. (2004):

$$AI_{DV} = A_D + A_V; \tag{3}$$

$$A_D = (t_e - t_f)/(t_e + t_f); \tag{4}$$

$$A_V = (\bar{U}_e - |\bar{U}_f|)/(\bar{U}_e + |\bar{U}_f|) \tag{5}$$

where: $t_e$ is the ebbing time; $t_f$ is the flooding time; $\bar{U}_e$ is the average ebbing time; $\bar{U}_f$ is the average flooding time. The $AI_{DV}$ index considers the combined effect of the tidal asymmetries in duration $(A_D)$ and in mean velocity $(A_V)$ between the ebb and flood periods, since both asymmetries are important for determining net transports.

## VALIDATION AND DISCUSSION

The field data used here was obtained in flow measurements at Rio Paraguaçu estuary (northeast coast of Brazil – Fig. 2) on October 26 and November 02 2003, during semi-diurnal spring and neap tides, respectively. The cross-section was approximately 1200 m wide and 32 m deep. Detailed hydraulic and hydrographic information on the estuary was published by Genz et al. (2006) and Genz (2006). The flow was measured with an ADCP

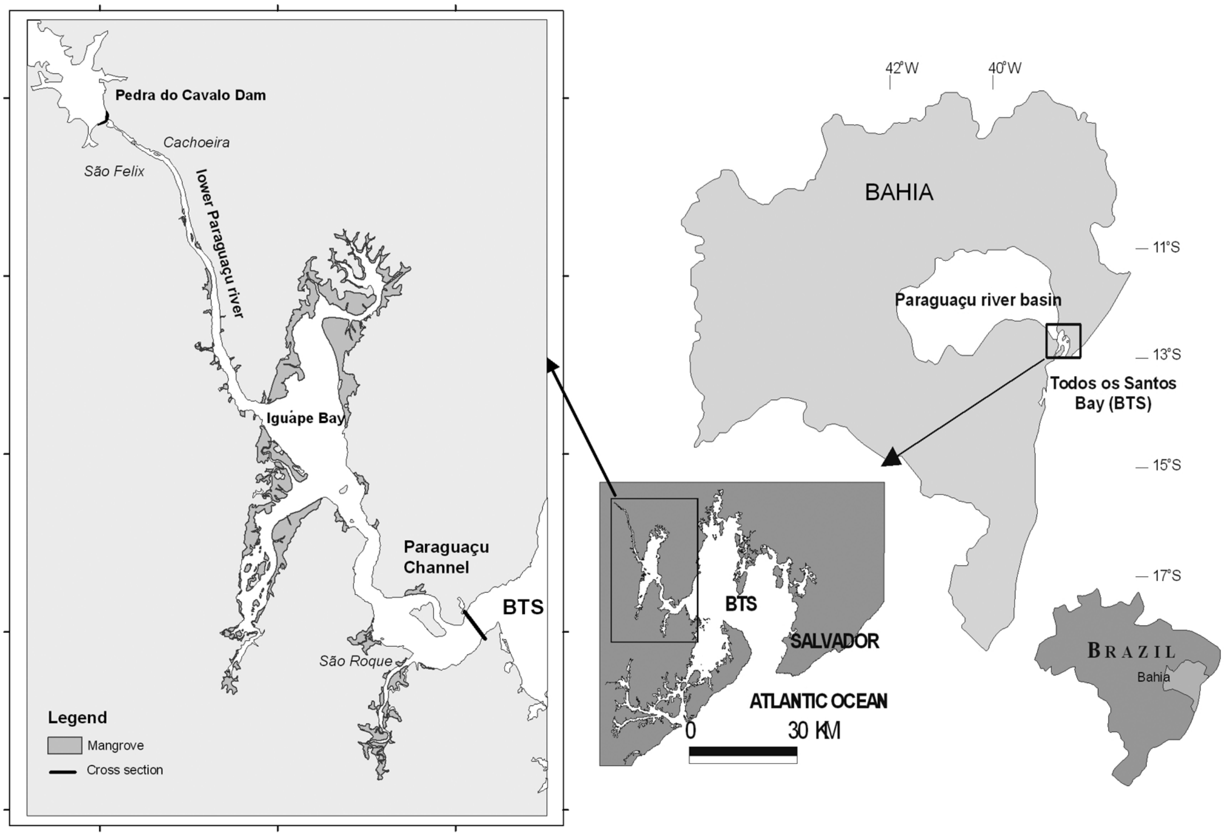

**Figure 2** – The Paraguaçu River estuary and cross-section localization.

Rio Grande 600 kHz with the following configuration: operation mode WM = 1; sampling frequency TP = 0.2 Hz; cell height WS = 1 m; pings per ensemble WP = 20; instrument depth ~1 m; vertical integration time TE = 5 to 7 s. Boat speed varied between 2.5 and 3 m/s, resulting in cross-profiles 8 to 12 minutes long and ensembles 8 to 15 m wide.

The validation was performed by comparing *WinRiver* and *ProcED* results based on the measured and the extrapolated surface and bottom discharges. It is reminded that *ProcED* does not extrapolate the discharge between the limits of the charted cross-section and the margins of the channel, such as *WinRiver*. Nevertheless, the uncharted area is close to the boundary and flow velocities are normally small. Extrapolated discharges computed by *WinRiver* for the two tidal cycles under consideration averaged 1.1% and 0.7% of the instantaneous spring and neap discharges, respectively.

The total spring-tide discharges measured by *WinRiver* varied between –16,000 $m^3$/s and 23,500 $m^3$/s with an average velocity magnitude of 0.45 m/s ± 0.26 m/s. The velocity error varied between 0.014 m/s and 0.029 m/s, averaging 0.019 m/s (Table 1).

*ProcED* discharges were smaller than *WinRiver's* with minimum and maximum differences in the spring cycle of 0.8% and 11.5% (mean of 5.5%). A larger difference of 51.7% (318 $m^3$/s) was observed during low-water slack, when discharge values are small enough to make differences negligible. By segmenting the cross-section into measured and extrapolated regions, the source of differences between the *ProcED* and *WinRiver* computations is identified. Smaller differences, between 0.1% and 6.5% (mean of 2.2%), occur when considering measured and extrapolated top discharges. Larger differences come about when comparing the extrapolations for the bottom blanked area. In this case estimated *ProcED* discharges were, in average, 45.6% lower than *WinRiver's*.

The total neap-tide discharges measured by *WinRiver* was around 7,200 $m^3$/s in both flood and ebb directions with an average velocity magnitude of 0.15 m/s and a standard deviation of 0.10 m/s. The velocity error varied between 0.013 m/s and 0.018 m/s, averaging 0.015 m/s (Table 1). Although nominal errors at neap tide were smaller than at spring tide, relative errors become higher due to the smaller velocity magnitude. Figure 3 shows that the error values increase exponentially with velocity magnitudes smaller than 0.15 m/s.

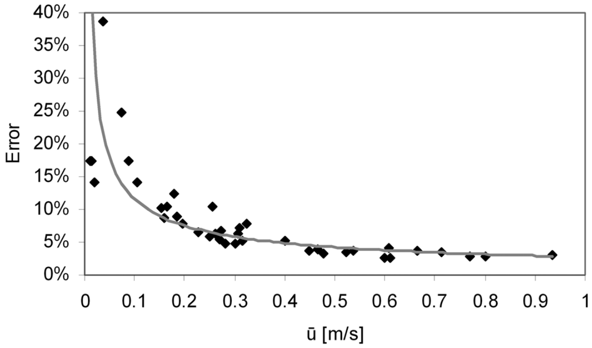

**Figure 3** – Variation of the velocity error relative to its magnitude in the spring and neap tidal cycles in Paraguaçu River estuary (cell height = 1 m).

*ProcED* neap discharges were smaller than *WinRiver's* with minimum and maximum differences of 1.7% and 8.4% (mean of 4.7%). Larger differences, as much as 48.5% (210 $m^3$/s), were observed close to slack water (discharges <960 $m^3$/s). If only the measured and extrapolated top discharges are considered, minimum and maximum differences are 0.1% to 2.1% (mean of 1.0%). In this case, slack water differences fall to a maximum of 3.7%. However, once again poor agreement exists between *ProcED's* and *WinRiver's* extrapolated bottom discharges. *ProcED's* discharge were in average 50.7% smaller than *WinRiver's*, with slack water differences reaching up to 1427%.

The discharge underestimation with *ProcED* is ascribed to: i) the data interpolation performed by *ProcED* to spatially adjust cross-profiles and ii) the *WinRiver's* extrapolation method to fill the bottom blanked area. Whereas the former causes the small differences observed in the measured and extrapolated top discharges, the latter causes major differences in the extrapolated bottom discharges. While *ProcED* interpolates a linear profile to a zero velocity at the bottom, *WinRiver* extrapolates a logarithmic profile based U* and $z_0$. For reasons yet unknown, the averaged extrapolated *WinRiver* bottom discharges are similar to those on the surface, with average velocities only 20% smaller than those at the surface (both for spring and neap data sets). *ProcED* results calculate bottom discharges half of that on the surface and average bottom velocities 60% smaller than those at the surface. Another important aspect about *WinRiver* calculations is that when depth velocity profiles are not unidirectional, as it was the case for stratified flows in many cross-profiles at the neap tide (also at slack water spring), it fails to fit a correct velocity profile through the data to properly calculate the bottom discharge (Fig. 4).

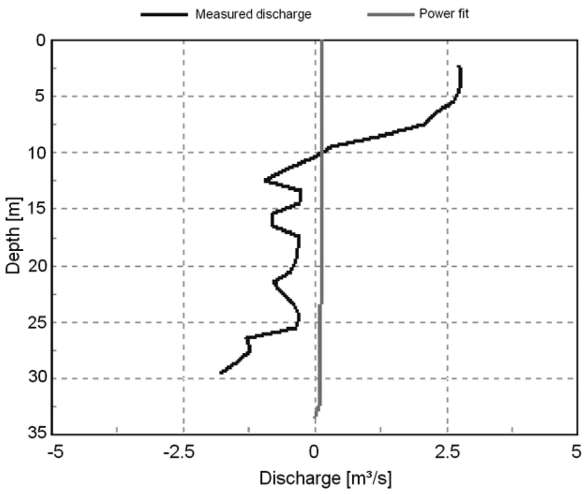

**Figure 4** – *WinRiver* measured discharge profile (dark thick line) and the fitted profile that allows for bottom discharge estimates (gray line).

Figure 5 shows a cross-profile produced by *WinRiver* and its counterpart computed by *ProcED*. Contrasting current directions and magnitudes are observed in neighboring ensembles in the *WinRiver* plots. This could be ascribed to excessive boat roll, water wave interferences or even the effect of eddies that were not eliminated with the short integration time (TE). These differences were smoothed after data filtering and interpolation in *ProcED* (Fig. 5c), allowing for an easier interpretation of the data.

The velocity profiles extracted for the position of the hydrographic station (Fig. 5c) are presented in Figure 6a in non-dimensional depths. The capability of *ProcED* to establish correlation between velocity cells both in space and time permits the computation of the residual velocity, as it is shown in Figure 6b for a single vertical profile and in Figure 7 for the entire cross-section in both tidal cycles.

Different patterns of residual circulation between the spring and neap cycles are clearly shown in Figure 6. During the spring tide (Fig. 7a), lateral flow shear is caused by the channel geometry that steers the main flow to different sides of the channel in the ebbing and flooding tide. During neap tides (Fig. 7b) density gradients along the estuary are strong enough to cause gravitational circulation.

## CONCLUSIONS

The *ProcED* package is capable of summarizing complex estuarine flow characteristics, which involve a significant amount of computation, in a few minutes. It allows the computation of the residual velocity field and discharge based on cross-profiles that are spatially non-corresponding. The package, and especially the *ADCP-ProcED* routine, performed well in discharge computati-

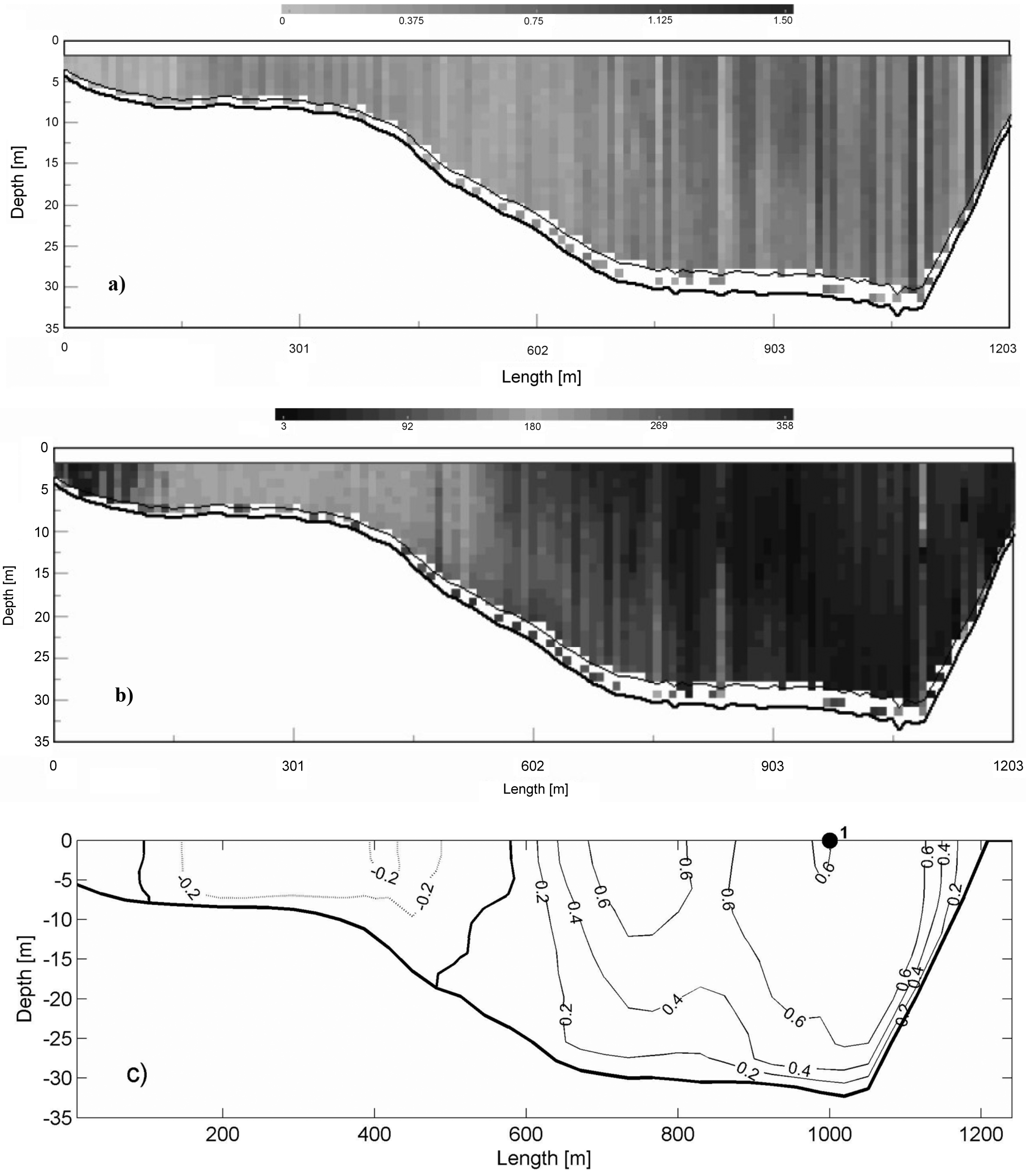

**Figure 5** – An example of a *WinRiver* cross-profile (a. magnitude and b. direction) and that computed by *ProcED* (c. – along-channel velocity component). Dot indicates the location of the hydrographic station. The measurement was performed approximately 1 hour before the spring low water. In c. the solid thin lines represent $u > 0$ m/s, dashed lines $u < 0$ m/s and solid thick line $u = 0$ m/s.

ons, presenting differences of 5.5% (in average) for two different tidal cycles, in relation to discharge values measured by *WinRiver*.

*ProcED* discharges were generally smaller than *WinRiver's*. This relative underestimation is ascribed to *ProcED's* interpolation of the cross-profiles and to its different bottom extrapolation method. The extrapolation method used by *WinRiver* relies on a power law fit of the velocity profile, which was not suitable for several neap cross-profiles where stratified flow existed.

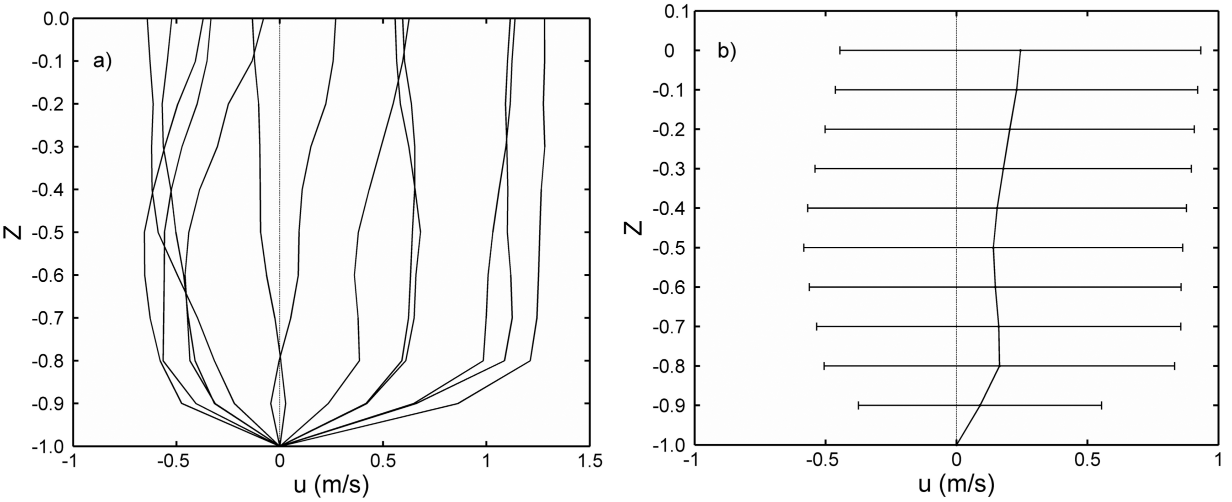

**Figure 6** – Velocity profiles (a) and the associated mean (residual) velocity profile with standard deviation (b) extracted from location 1 in Figure 5c.

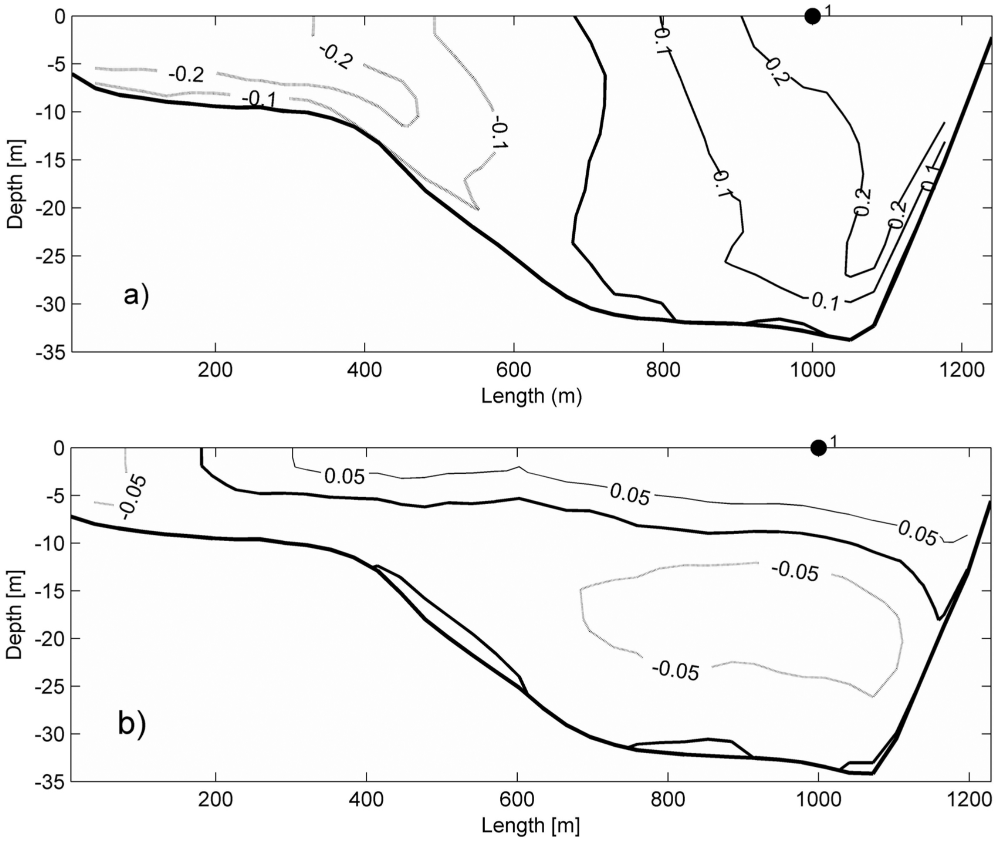

**Figure 7** – The residual velocity field for a cross-section at spring (a) and neap (b) tidal cycles.

Also, there is an apparent overestimation by *WinRiver* of the extrapolated bottom discharge.

Careful use of *WinRiver* for discharge estimates in estuarine environments is required, as partially mixed and stratified conditions leads to erroneous velocity profile extrapolations both in the bottom and the surface blanked areas with the power law method.

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