OCEANOLOGICA ACTA · VOL. 23 – N° 3

Suspended sediments in a macrotidal estuary: comparison and use of different sensors

Michel LUNVEN *, Patrick GENTIEN

Ifremer, Centre de Brest, DEL/EC/PP, BP 70, 29280 Plouzané, France

Received 20 July 1999; revised 18 September 1999; accepted 18 September 1999

Abstract – Measurements made using an in situ particle-sizer (PSA) were compared to those of an optical backscatter sensor (OBS) in a macrotidal estuary. Both estimate the total volume of particles. After comparison with dry weight of suspended matter sampled in the study area, the different measurements were converted into dry weight. In three different kinetic energy regimes, times series were coherent for most of the observations. Discrepancies of suspended sediment concentrations estimated by both sensors appeared under specific hydrodynamic conditions: they were related to occurrences of definite particle populations. Overestimations and underestimations of measurements by the instruments depend on the optical principles of the sensors (backscatter and diffraction). Flocs appearing at low tide with low currents are detected by the PSA and not detected by the OBS which is more sensitive to finer particles and re-suspension of sedimentary particles from the bed, induced by high current velocities during flood tide. © 2000 Ifremer/CNRS/IRD/Éditions scientifiques et médicales Elsevier SAS

aggregates / suspended particulate matter / particle size

Résumé – Matières en suspension dans un estuaire à fort marnage : comparaison de différents capteurs. Des mesures acquises dans un estuaire à fort marnage par un analyseur de taille de particules in situ (PSA) ont été comparées aux mesures obtenues par un capteur de charge particulaire par rétrodiffusion (OBS). Tout comme ce dernier, le PSA estime le volume total de particules. Après comparaison des données acquises avec des mesures de poids secs de matières en suspension sur des prélèvements échantillonnés dans la zone d'étude, les séries temporelles issues des capteurs ont été converties en séries de poids secs. Pour trois coefficients de marnage différents, les résultats sont cohérents pour la plupart des observations. Des écarts de mesure de matières en suspension calculés par les deux capteurs apparaissent dans des conditions hydrodynamiques spécifiques et sont reliés à l'apparition de populations de particules précises. Les surestimations ou sous-estimations par les deux instruments dépendent des principes optiques des capteurs (rétrodiffusion et diffraction). Les agrégats, apparaissant à basse mer par courants faible, sont détecté par le PSA et invisibles à l'OBS qui est plus sensible à certaines particules plus fines et aux remises en suspension de particules sédimentaires du fond, générées par les forts courants de marée montante. © 2000 Ifremer/CNRS/IRD/Éditions scientifiques et médicales Elsevier SAS

agrégats / matières en suspension / taille de particule

1. INTRODUCTION

Understanding sedimentary transport in estuarine environments requires in situ acquisition of time series of particles quantities. Numerous methods and instruments have been developed to quantify suspended particulate matter in seawater. Among them, sensors such as the OBS [6] or transmissometers are well known and often used in hydrodynamic studies. They give satisfactory and reliable results in most cases.

However, in many cases, a quantitative study is not sufficient: it is recognized that the nature of the

* Correpondence and reprints : mlunven@ifremer.fr

PII: S0399-1784(00)00126-2/FLA

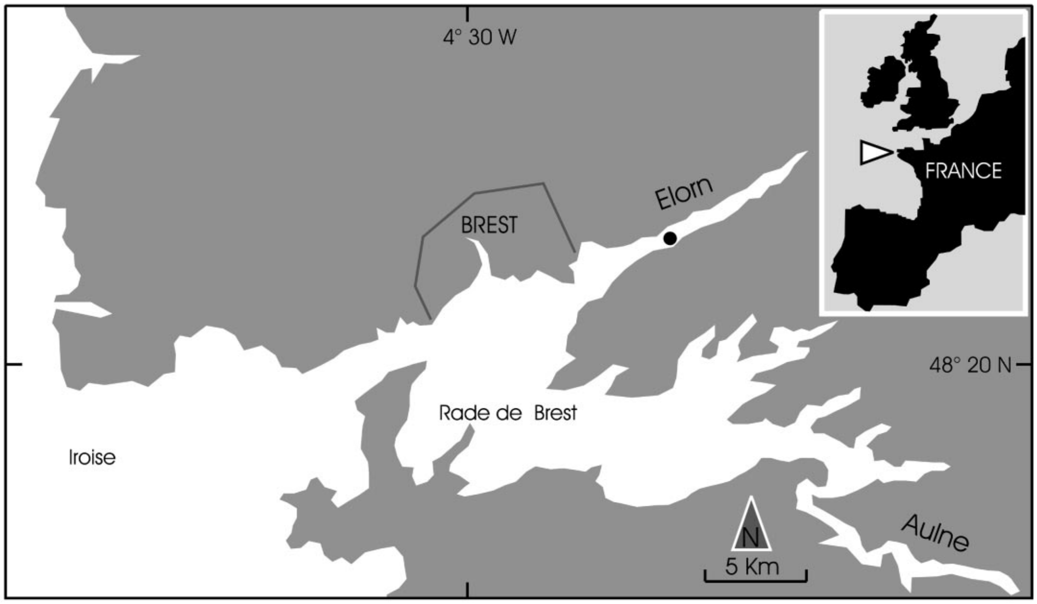

Figure 1. Elorn estuary and mooring locations (●).

particles varies according to the physical (current, salinity), and chemical (organic matter) environment. In estuarine waters, aggregates, consisting of organic and inorganic components, can be observed according to specific conditions [2, 7, 19, 22] or located within thin layers in the water column [25].

These large-size particles offer to bacteria a growing substrate. They also have an important role in the transport of hydrophobic contaminants. Such suspended particles aggregated into flocs, are very fragile and are often broken when sampled with a Niskin bottle [15]. Thus, it is very difficult to obtain representative granulometric measurements from samples analysed after collection.

In marine studies, investigation on particle sizes requires the use of sensors able to measure directly the in situ granulometric distribution [1, 2, 14]. Based on the principle of diffraction, those instruments investigate size spectra of particles without modifying their structures.

Recently, technological advances in photography and videomicroscopy have significantly improved our ability to study sedimentary transport and particles investigations in seawater. These techniques allow in situ visualization of the particles. Several scientific groups have already successfully applied these techniques in marine or coastal environments [8, 17, 18]. Digitalizations and data-processing treatment of the images obtained in the field allow a qualitative and quantitative evaluation of the particles. It is often essential to build a mechanical unit for slowing down the particles in order to obtain a good surface estimation [12, 23]. However, these techniques are not easily applicable to the detection of particles smaller than 20 μm diameter.

The development of new techniques has also led to problems of calibration and intercomparison. Eisma et al. [11] compared in the Elbe river, eight different methods for quantification of suspended particles. Their results showed that the response of the sensors was dependent on the characteristics (size, density, shape) of the particles. Laboratory studies showed the limits and the inaccuracies of the OBS for some categories of particles. For calibrated glass grains, an inverse relationship was found between OBS measurement and the size of the grains [5]. Gibbs and Wolanski [16] have shown an underestimation of 150 % by OBS due to flocs. For OBS, interferences may also be due to biological material in coastal waters [21]. Conversely, the diffraction method seems to be very sensitive to the presence of large size particles found in the stratified water column of coastal areas [14].

The present study describes in situ experiments showing measurement discrepancies between two sensors, OBS (backscatterance method) and the CILAS particle size analyser (diffraction method) [14]. Three time-series of granulometry and suspended sediment concentration have been acquired in three different kinetic energy regimes and total suspended sediment concentration estimated by optical backscatter sensor are compared to the results from the IFREMER-CILAS particle-size analyser.

2. MATERIALS AND METHODS

Experiments were conducted in the mid channel of Elorn river (Bay of Brest) which is oriented NE–SW (*figure 1*). Tidal range in this estuary is 7.4 m during spring tides and 2.3 m during neap tides. Tide is purely semi-diurnal. The drainage basin is 403 km^2 and its averaged annual flow is 5.7 $m^3 \cdot s^{-1}$. In this estuary, sediments are of alluvial origin and are mainly composed of quartz, mica, chlorite, kaolinite and illite. A large mud flat is located on the north bank of the river.

Size distribution of particles was measured by PSA [14]. Particles were analysed in a measurement cell, of 30 mm light pathlength. The radial dispersion of energy is measured by a 17-photosensor board which gives the relative abundance of 30 size classes (upper diameter limits: 0.7, 0.9, 1, 1.4, 1.7, 2, 2.6, 3.2, 4, 5, 6, 8, 10, 12, 15, 18, 23, 30, 36, 45, 56, 70, 90, 110, 135, 165, 210, 260, 320 and 400 µm). A detector in the optical axis gives a measurement of the laser beam transmission which can be related to particle load. From the total energy scattered in the angular sector, it is possible to compute an estimation of the total volume of particles. Calibrations with unimodal populations of calibrated beads have already been realized [14]. A good relationship was found between the total load criterion estimated by the PSA and the total volume of the particles present.

The PSA has a 48 h autonomy. Data, acquired at 15 s rate, are stored in a Save Random Access Memory with a total capacity of 8 MegaBytes allowing the storage of 190 000 particle-size measurements. PSA was placed at 0.5 m from the bottom. Additional sensors were also placed at 0.5 m from the bottom: a Seacat probe (Sea-Bird Electronics) provided synchronous measurements of temperature, salinity, pressure and OBS, and an electromagnetic current-meter (InterOcean S4) was moored at 10 m distance from the PSA and the SEACAT probe.

Sensors acquired data during 24-h periods during different tidal regimes. During spring 1994, 3 time-series were acquired:

13–14 April 1994: mean tidal range; 5 566 measurements

27–28 April 1994: high tidal range (spring tide); 5 636 measurements

2–3 June 1994: low tidal range (neap tide); 6 052 measurements

For sensors calibration and microscopic observations, water samples were taken near the mooring station with a horizontal Niskin sampling bottle, automatically closed at 0.5 m above the bottom. Samples were filtered on GF/F filters pre-combusted at 450 °C (2 h), pre-weighted and dried at 60 °C for 24 h.

3. RESULTS

Time-series (*figures 2–4*) were synchronised against tidal hour for improving data visualisation and interpretation. Large variations can be detected especially during high kinetic energy periods occurring during spring tide (*figure 4*). During neap tides (*figure 2*), the low energy induced very small variations in salinity between high and low tide into the bottom layer: vertical mixing was very limited. By contrast, during spring tide, due to increased vertical mixing, low salinities were observed in the bottom waters. A tidal asymmetry was observed with higher current speeds into the bottom layer at flood tide.

3.1. Measurement validation

Before any analysis, the data obtained from the particle size analyzer were validated. The computed grain size distributions are reliable when the transmission measurements are greater than 40 % [3, 14]. For lower values, particle load is too high and the calculated size distributions are skewed. Thus, some measurements obtained during the high tidal range were not taken into account in the analysis.

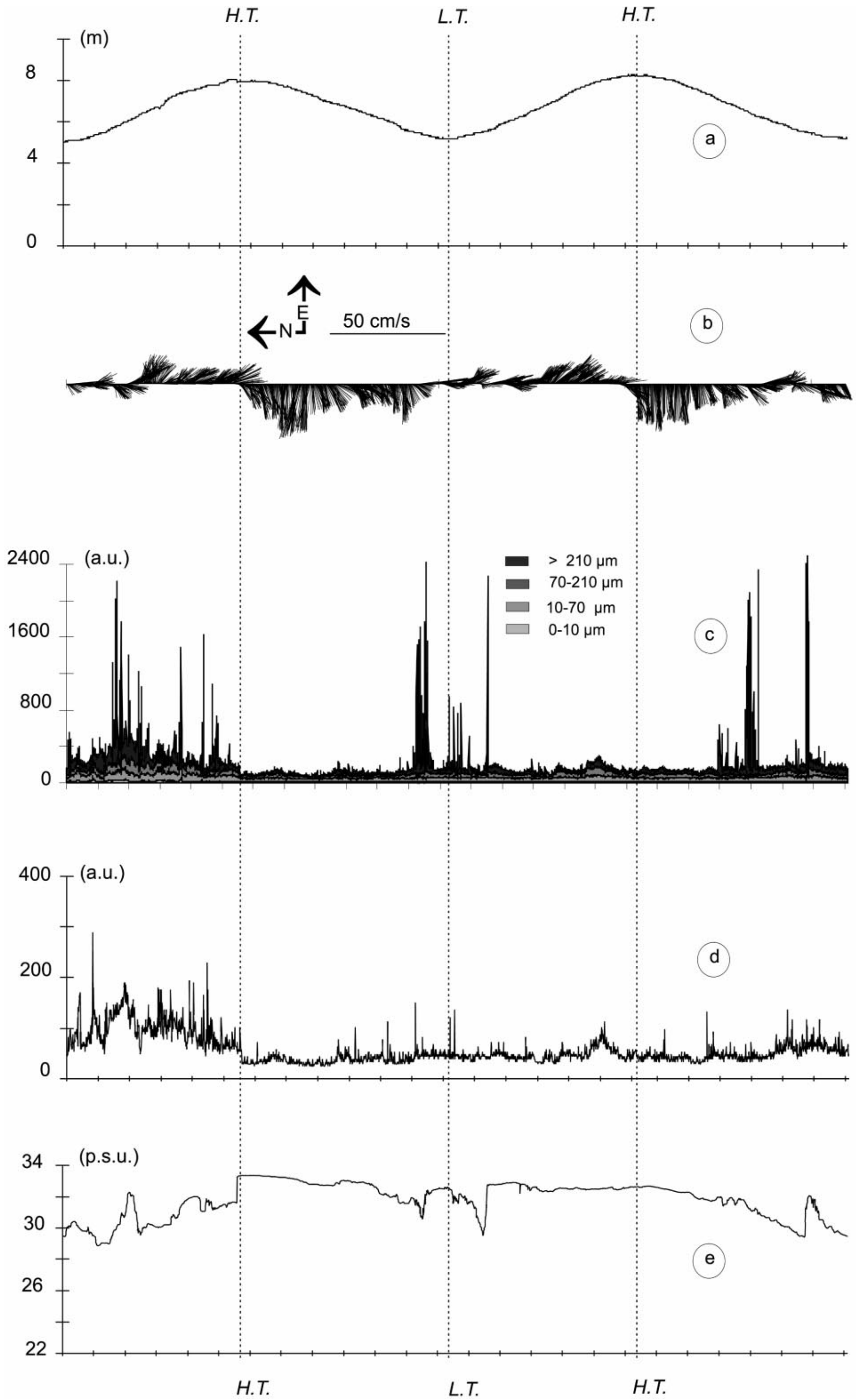

Figure 2. Time-series for a neap tide (tidal coefficient 45): (a) Water height, (b) Current speed at 0.5 m above bottom, (c) Cumulative volume of particles for 4 size classes $\phi < 10$, $10 < \phi < 70$, $70 < \phi < 210$ and $\phi > 210$ µm) (d) OBS, (e) salinity. (a.u. units are arbitrary units relative to each sensor).

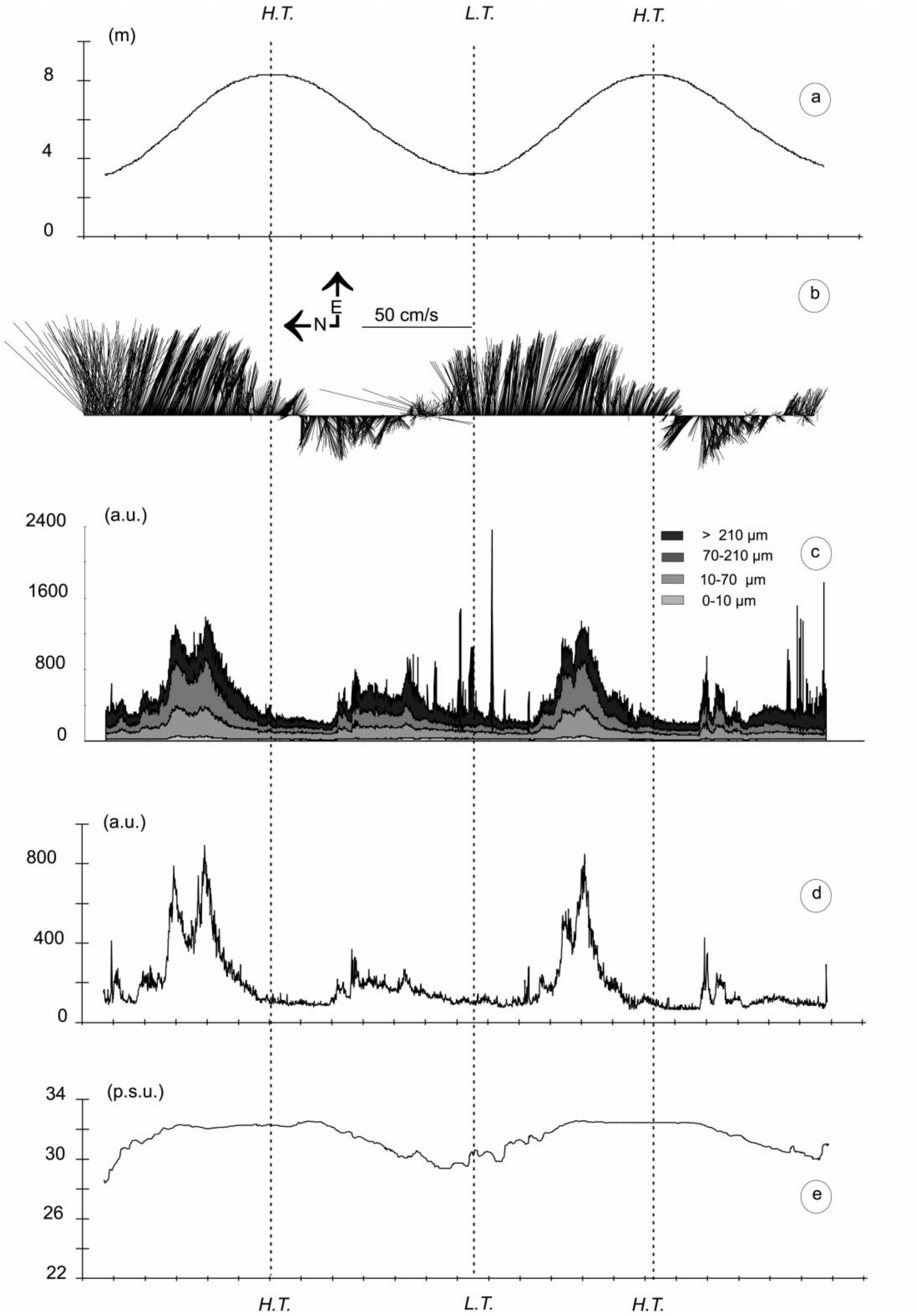

Figure 3. Average tidal coefficient time-series (80) (Same legend as *figure 2*).

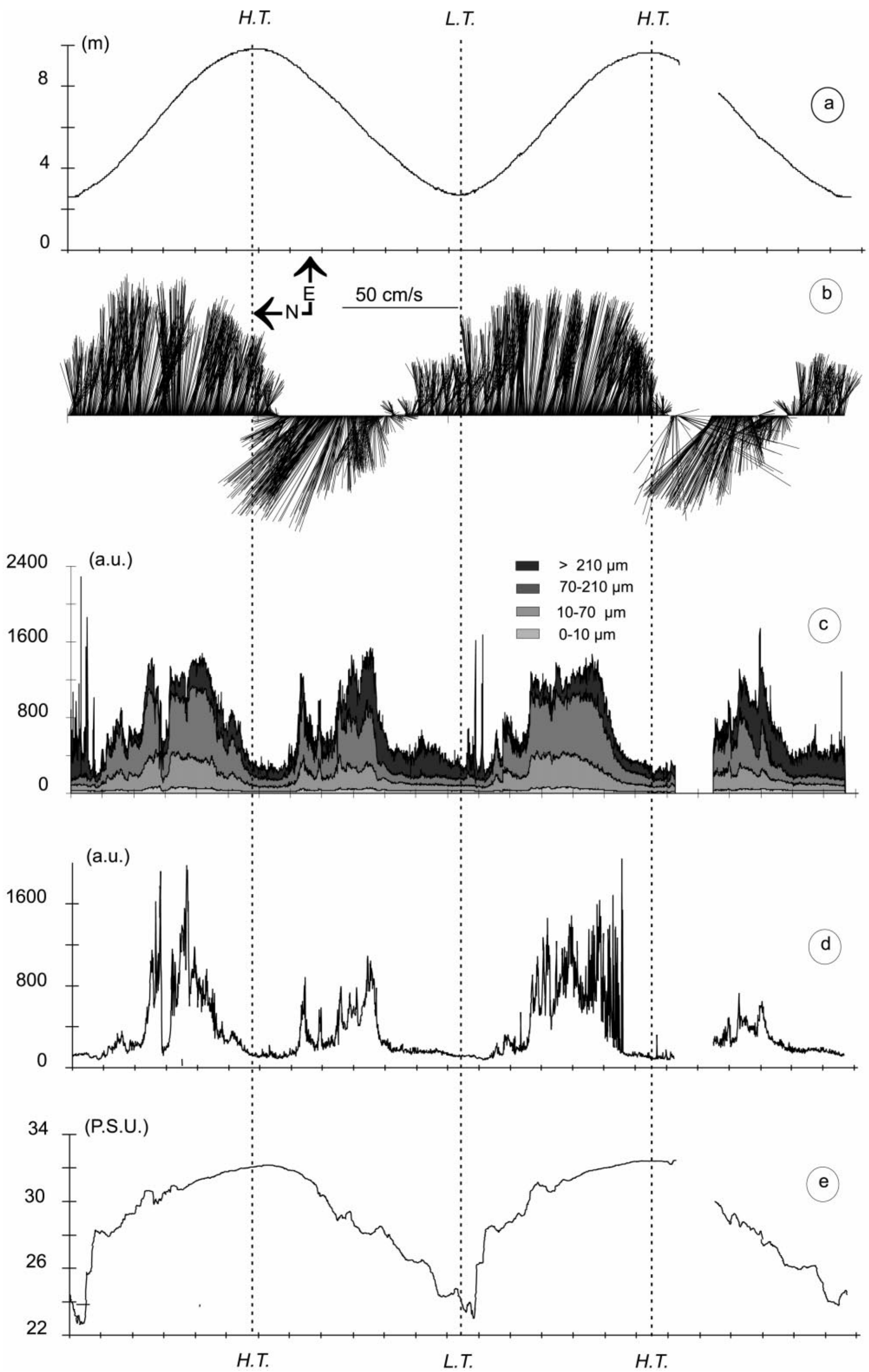

Figure 4. Spring tide time-series (Same legend as *figure 2*).

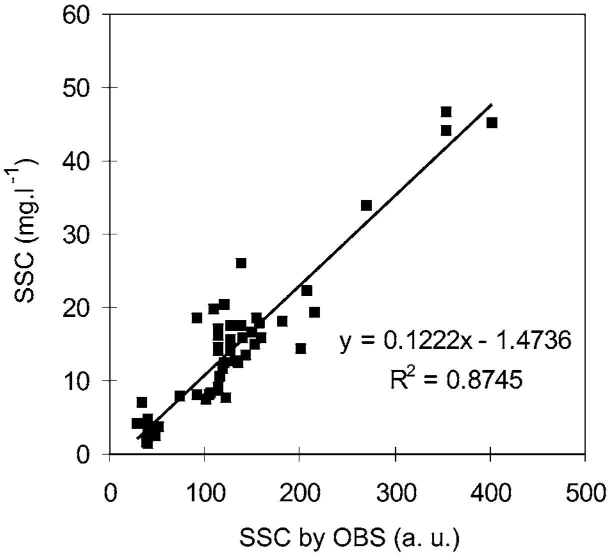

Figure 5. Suspended sediment concentrations and OBS estimates.

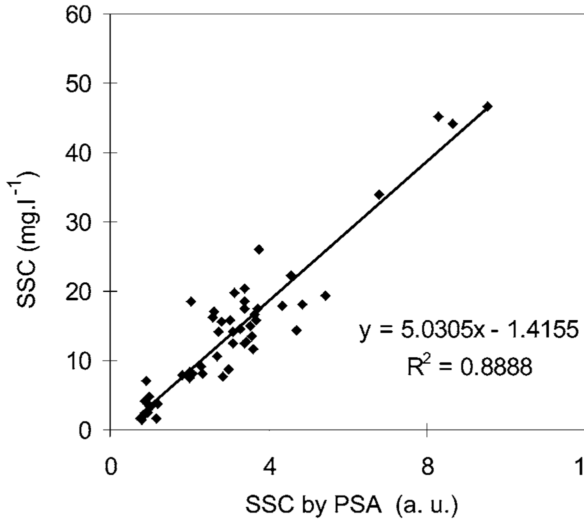

Figure 6. Suspended sediment concentrations and PSA estimates.

First data examination was made by grouping different size classes of particles. All data were gathered into four empirical classes: particles smaller than 10 µm because of their low settling rate, particles between 10 and 70 µm (silt), the largest particles were separated into two classes (above and below 210 µm) because of their different behaviours and occurrences.

3.2. Sensors calibration

Sensors were calibrated against the dry weights of 60 samples taken during data acquisition at regular time intervals (15 or 30 min depending on the time-series).

The following correlations between suspended sediment concentration (S.S.C.) and sensors data were established (*figures 5* and *6*) for the two methods:

for the diffraction-sensor (PSA)

S.S.C. ($mg \cdot L^{-1}$)

$= (5.03^* \text{ PSA})$

$- 1.42$ (corr. coeff: 0.89 – N samples: 60)

for the backscatter-sensor (OBS)

S.S.C. ($mg \cdot L^{-1}$)

$= (0.122^* \text{ OBS})$

$- 1.47$ (corr. coeff: 0.87 – N samples: 60)

These equations have been applied to the 3 time-series of acquired data in order to obtain calculated sediment concentration in $mg \cdot L^{-1}$, for both sensors. *Figure 7* represents a superposition of estimated dry weights time-series for the mean tidal range. These dry weight calibrations are simply indicative since bottle and sensor sampling are not related to the same scale. However, for ease of discussion, the two sensors are compared later from their results expressed in terms of equivalent dry weight.

3.3. Differences in calculated particle quantities

From the calculated dry weight series, it is possible to establish the differences in estimations by OBS minus estimations by PSA ($\Delta = SSC_{OBS} - SSC_{PSA}$) expressed in equivalent dry weight.

The results of the calculated differences are presented in *figure 8* for each tidal range. The corresponding water depths are also drawn on the graphs. The responses of both sensors are in accordance. Despite some differences in response, the two sensors give coherent results, the histogram of Δ (not shown) is symmetric and centred at -0.8 $mg \cdot L^{-1}$ equivalent, 80 % of the 16 200 measurements are comprised in the range ± 5 $mg \cdot L^{-1}$. This range is used as the operational significance level of the bias between the two sensors.

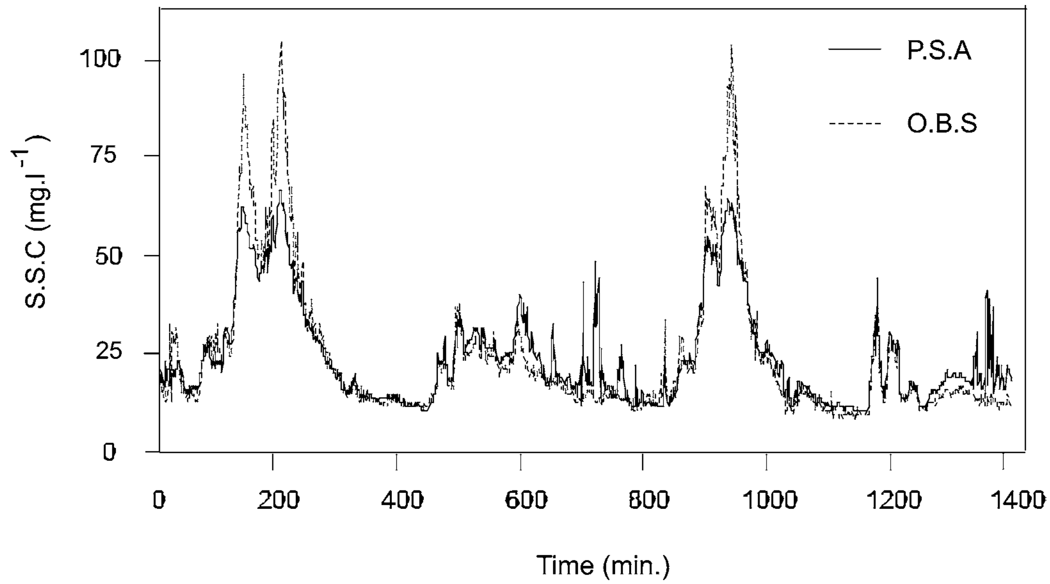

Figure 7. Comparison of OBS and PSA time-series at medium energy tide.

However, at times, either negative or positive differences occur:

1. Neap tide (*figure 8a*): OBS never over-estimates relatively to the PSA, but significant over-estimations by PSA appear throughout the cycle, especially around low tide.
2. Medium tidal range (*figure 8b*). For these series, the calculated differences are either positive or negative. OBS measures more particles than PSA during flood. PSA estimates more particles than OBS around the end of ebb tide.
3. Spring tide (*figure 8c*). The measurement cycle obtained at high tidal range, shows significant differences between the sensors: OBS gives higher measurements than PSA at the end of flood tide. As for the low tidal range, PSA detects more volume of particles than OBS around low tide.

Generally, the OBS over-estimation of particle concentration increases with the tidal energy. These over-estimations always occur at the end of the flood. On the other hand, over-estimations by PSA compared to OBS occur mainly around ebb tide. Over-estimations by PSA do not seem to be related to high tidal energy.

3.4. Particle quantities estimation and grain size distribution relationship

The differences in measurement by the instruments occur under special conditions related to the hydrodynamics and the hydrology of the estuary. They could be related to specific particle populations in the estuary.

Analysis of the grain-size distribution time-series revealed that differences in total quantity estimations were related to size classes histograms measured by PSA.

All measurements from the three time-series considered together, dry weight differences (Δ) were classified into 10 classes (*figure 9a*). Negative values of Δ correspond to an overestimation of PSA relatively to OBS and conversely, the positive values result from an overestimation of OBS sensor.

This graph highlights a good coherence between the two sensors, since the majority of the observations (80 %) gives a Δ comprised between ± 5 mg·L^{-1}. However, large positive or negative differences may occur.

An analysis of particle-size distributions allows us to classify Δ as a function of the average contribu-

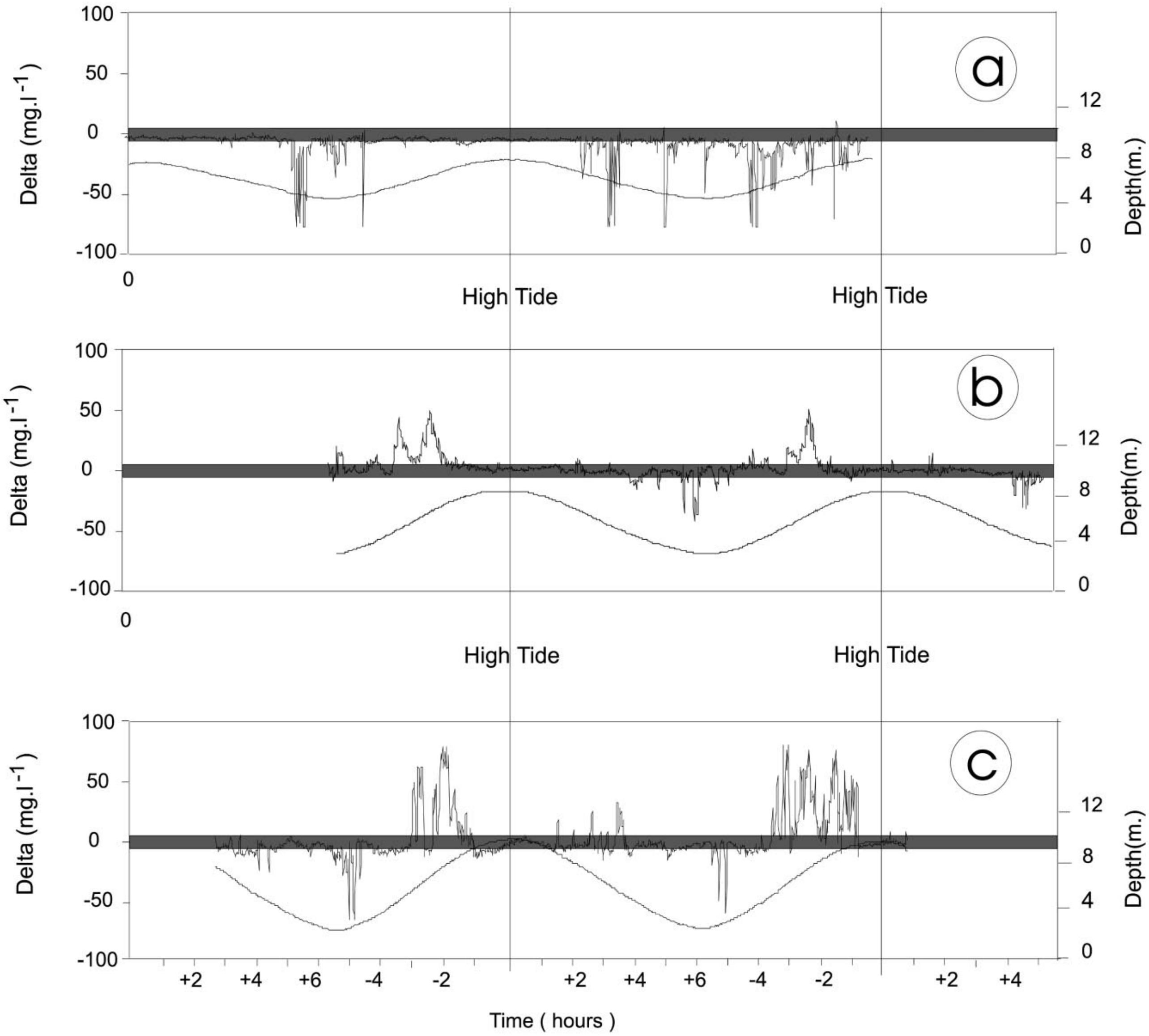

Figure 8. ($\Delta = SSC_{OBS} - SSC_{PSA}$) time-series and water height (lower line): (a) neap tide; (b) average tidal range; (c) spring tide. (Measurements of Δ in the shaded area are not significantly different from 0 at 80 % confidence.)

tions of the four main size classes defined above (*figure 9b*). The relative contribution of the 4 particle classes shows a smooth evolution from negative to positive Δ. Maximum overestimation by PSA corresponds to a high abundance of particles larger than 210 µm. Over-estimates by OBS are related to an increase in the quantity of the particles ranging between 10 and 210 µm.

3.5. Relationship between sensor differences, quantities of particles by classes, current speed and salinity

The occurrences of good or bad agreement between the two sensors vary according to the tidal kinetic energy. The discrepancies therefore, seem to be related to the strength of the marine currents generated in the estuary.

The relationship between the differences in estimation of quantity of particles by the sensors, current speed and salinity was studied (*figure 10*). This graph shows that over-estimates by PSA correspond to low currents (lower than 20 cm·s^{-1}) and low salinity periods, favourable to the appearance of large size particles higher than 210 μm. These periods mainly occur at low tide.

Reciprocally, over-estimates by OBS are associated with the strong currents of ebb (greater than 35 cm·s^{-1}) which resuspend, in the bottom layer, a large quantity of particles of size extending between 10 and 100 μm.

Figure 11 highlights the correspondance between the current velocity and the abundance of large-size

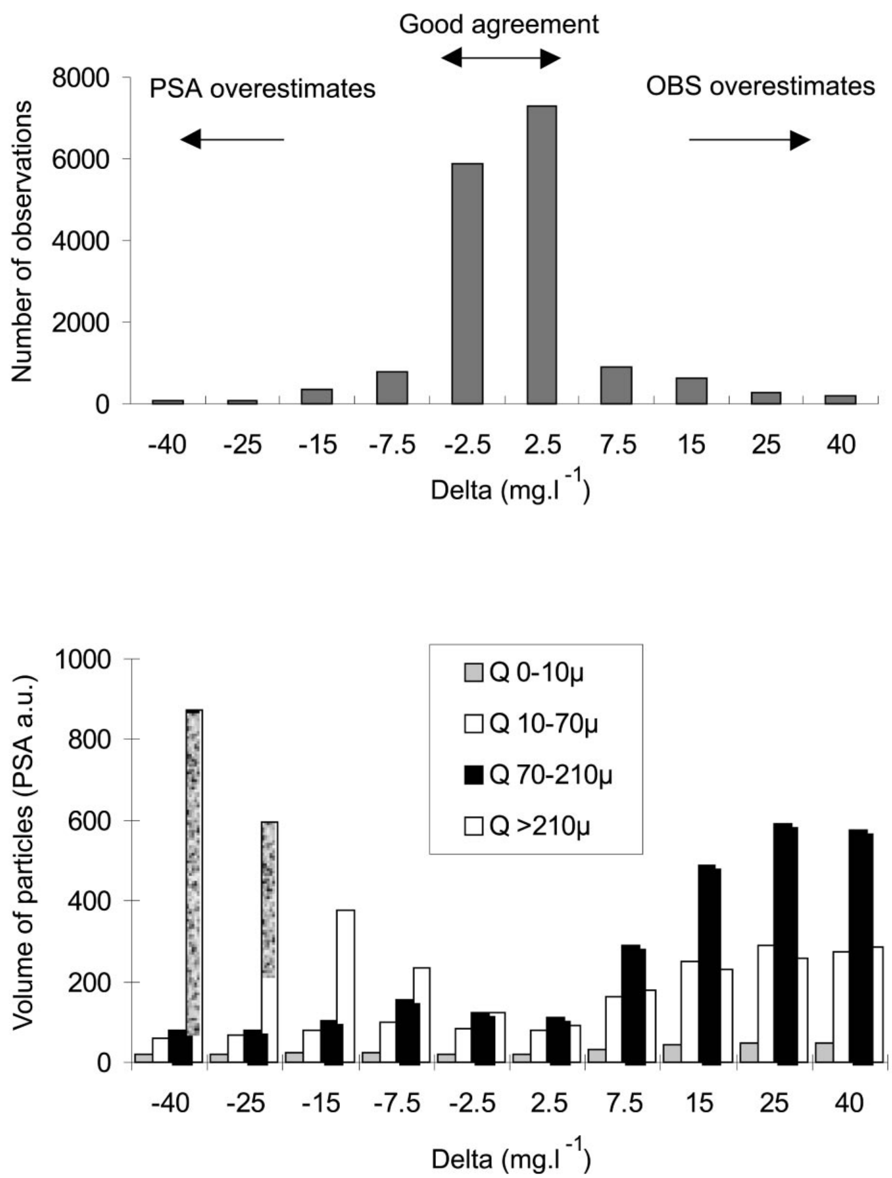

Figure 9. (a) Distribution of Δ (3 time-series pooled); (9) Distribution of particles in the 4 grain-classes vs. Delta (Δ).

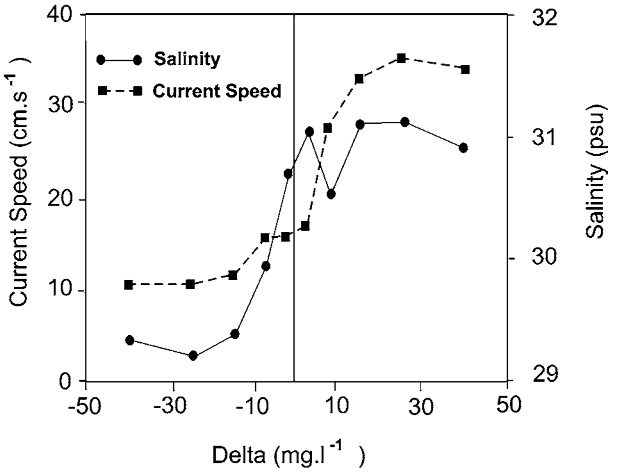

Figure 10. Plot of current speed (0.5 m above sediment) and salinity vs. delta (Δ).

particles under neap tide conditions. A current speed threshold (20 cm·s^{-1}) can then be defined. Below this value, a strong abundance of particles of size higher than 210 μm can be observed.

Inversely, for the spring tide time-series (*figure 12*), particles in the range size between 70 and 210 μm become abundant above a speed threshold of 20 cm·s^{-1}.

Figure 13 confirms the relationship between the current velocities and the differences in the estimation of suspended particulate matter by the sensors, for the three time-series. This graph presents a velocity threshold of 20 cm·s^{-1}. Below this value, the PSA over-estimates the values of quantity of particles compared to the OBS. For higher values, the OBS is more sensitive than the PSA to the types of the particles present in the estuary.

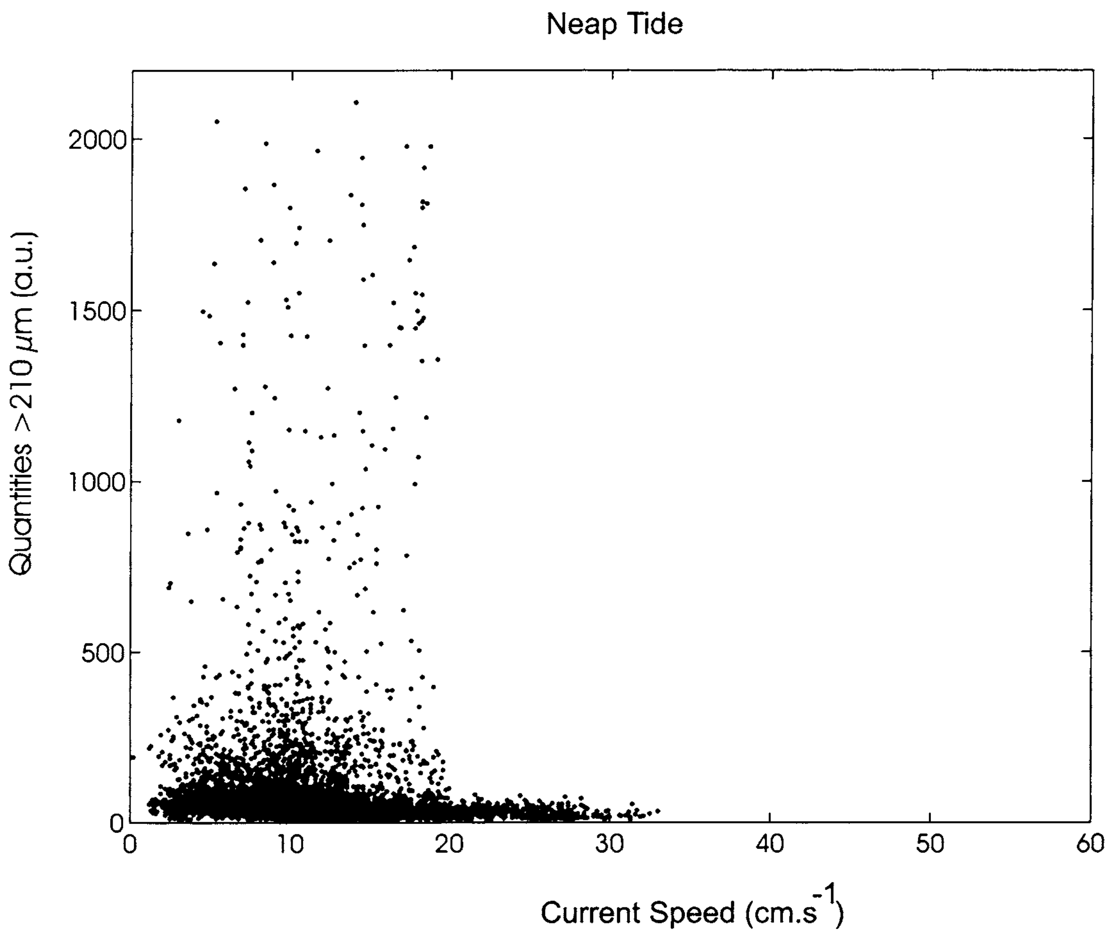

Figure 11. Volume of large particles above 210 μm vs. current speed (neap tide).

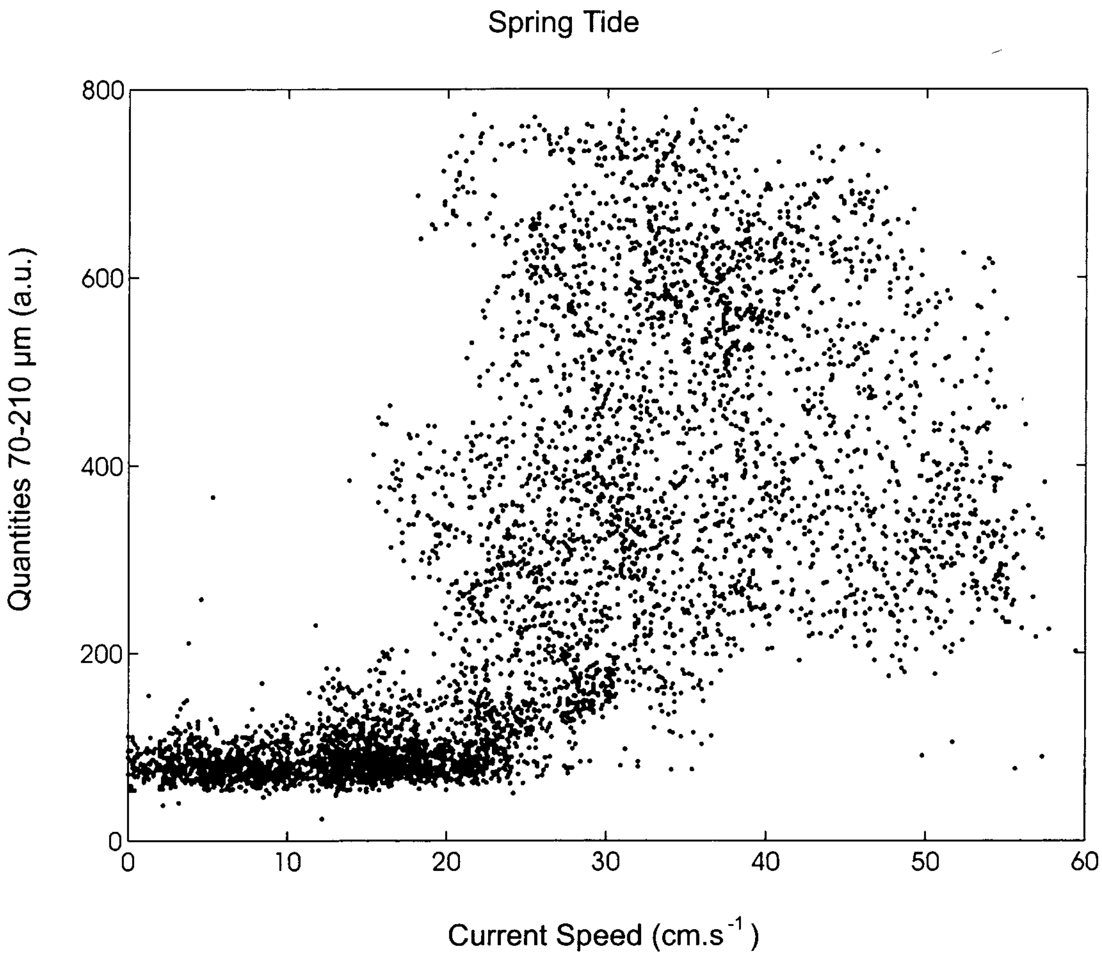

Figure 12. Volume of particles between 70 and 210 μm vs. current speed (spring tide).

4. DISCUSSION

Microscopic observations were performed from samples taken under various tidal conditions. A corresponding sample to the period of over-estimation by the OBS (*figure 14a*) was composed of sedimentary particles of small size (50–100 μm) with a large abundance of refractive particles. These particles are primarily micas: particles of high density re-suspended from the bed by strong currents. They have a high specularity, and thus, their abundance will be well measured by a sensor based on the principle of retrodiffusion like the OBS.

In the same way, microscopic observations were carried out on samples corresponding to periods of over-estimation by PSA (*figure 14b*). Morphometric measurements reveal the presence of organic aggregates of size ranging between 300 and 1000 μm. Gibbs and Wolanski [16] reported on the limitations of the backscattering sensors for translucent and not very refractive particles such as large flocs. PSA, on the other hand, is particularly sensitive to this type of particles. From our measurements, it appears that the favourable tidal times for the formation of organic aggregates are low current and low salinity periods which occur in the estuary around ebb tide. In the Elbe estuary, Pfeiffer [20], using a video system, reported that after ebb slack tide the number of the visible flocs increases. Using a video camera developed by the Netherlands Institute for Sea Research in the Elbe estuary, Eisma and Kalf [10] also detected the presence of large flocs in the bottom layer at slack tide in Elbe estuary. All the material is then concentrated in flocs with nearly clear water in between, resulting in the low turbidity and low weight. Those flocs are made of organic matter associated with mineral particles. They contain a high percentage of water. Thus they have a very low density. Individual floc data obtained with the in situ video camera INSSEV in the Elbe river show that the density of the particles is inversely proportional to their volume [13]. In our study, calculated dry weights of samples containing large amounts of aggregates are therefore overestimated. One solution to this problem could be the use of two calibration curves, one for small elementary particles and one for aggregates. However sampling for aggregates is difficult to realize.

Processes of aggregations and disaggregations of particles have been studied for several years. Our results are in agreement with the studies of Eisma [7, 9] and experiments of Burban et al. [4] which showed that the average size of the flocculates decreased when the current velocity and the salinity increased. In our case, during high tidal energy periods, mixing generated by the flood currents causes the re-suspension of sedimentary particles from the bed. Low salinity favours flocculation but high current velocities break up large aggregates (Van Leussen, [24]). These authors demonstrated a relationship between abundance and size of macroflocs and the variations in the Kolmogorov microscale.

In this study, we showed that large aggregates, in the bottom layer, disappear above a threshold of 20 cm·s^{-1} (0.5 m above sediment) probably in relation to the reduction in size of the smallest eddies allowed by the Kolmogorov microscale.

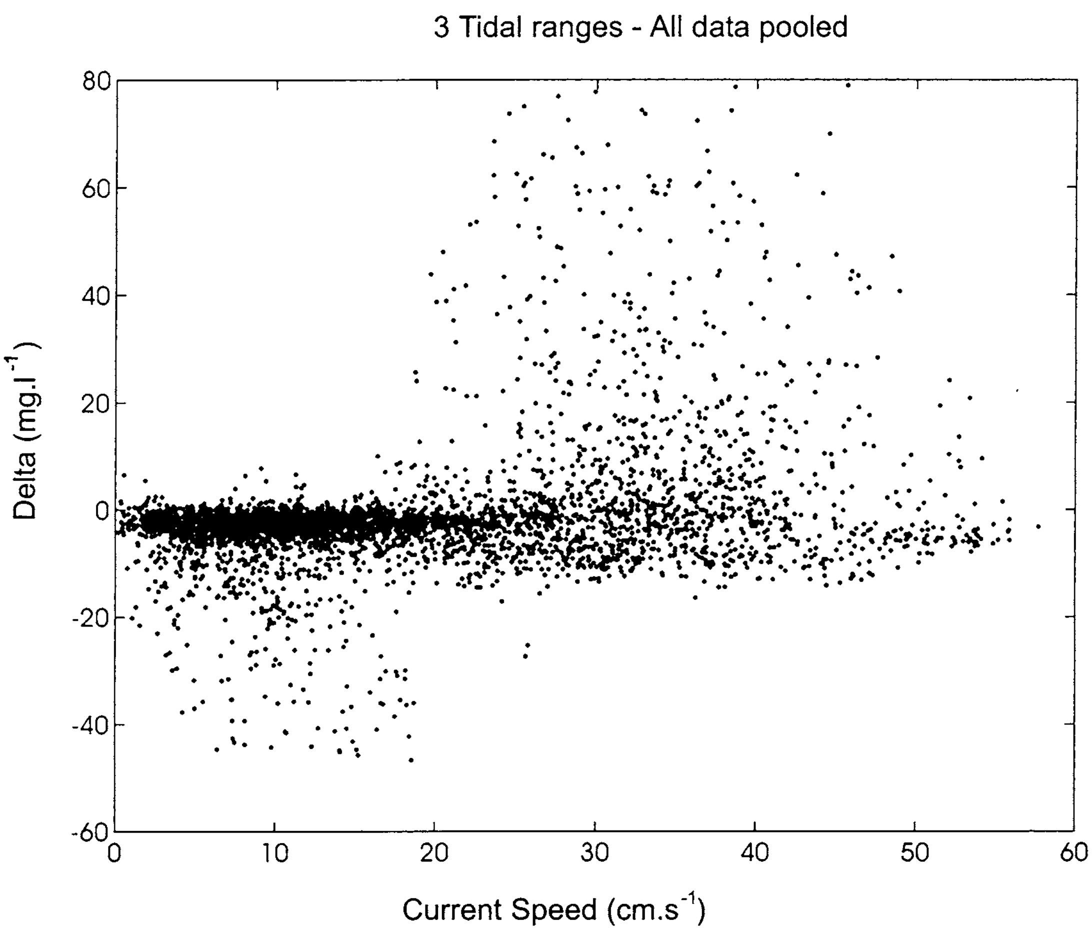

Figure 13. Scatter plot of Δ vs. current speed (all data pooled).

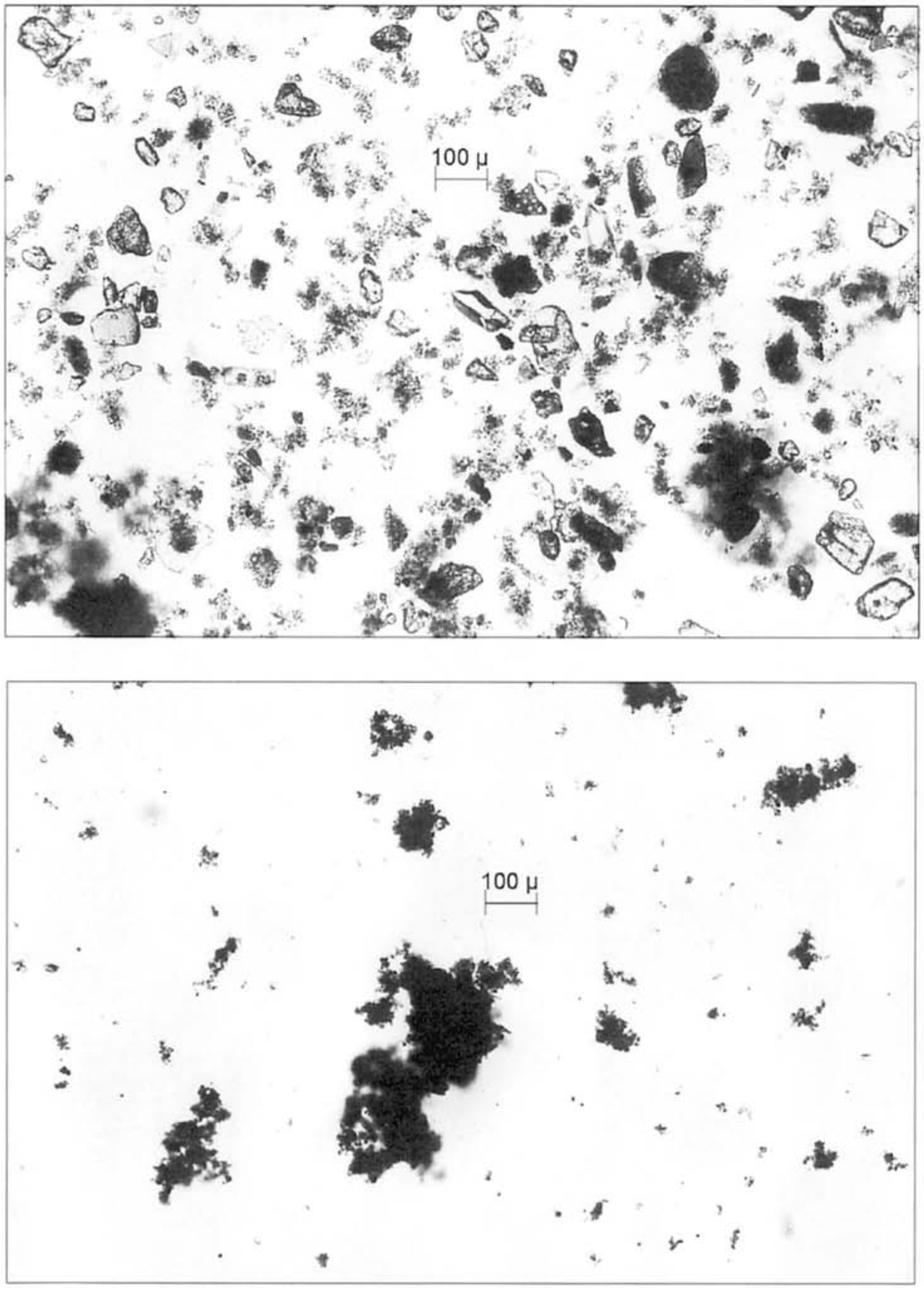

Figure 14. (a) sample collected during high current speed period; (b) organic aggregates sampled at low tide.

5. CONCLUSIONS

Generally, OBS and PSA gave comparable results. The differences in particle quantities appeared under conditions related to the hydrodynamics and the hydrology of the estuary. The OBS was particularly sensitive to some small sedimentary particles, while the PSA was sensitive to organic aggregates not detected by the OBS. This is due to the different optical principles. It is difficult to select the best probe according to the most realistic results. Quality and volume of particles have a great influence on the sensors' responses. This study shows that both instruments are complementary. The difference in suspended sediment concentrations estimated by OBS and PSA can be considered as a new parameter related to the types of suspended particles. This parameter allows the detection of the periods of resuspension of sedimentary particles from the bed by the currents and the detection of the flocculation periods. Tides and hydrodynamic conditions have an important effect on particle behaviour.

Results show that the observed discrepancies occur in specific hydrodynamic conditions. Differences observed are due to the optical principles of the instruments which are more or less sensitive to the size, the structure, the shape and the composition of the particles. Microscopic observations in water samples confirmed the relationship between the sensitivity differences of the sensors and the observed particles. The association of two different measurement methods (backscatterance and diffraction) offers an obvious benefit in estuarine field studies.

Further studies on covariances of the different size-classes could provide information on relationships of particles within a given size range with the hydrodynamical conditions, and therefore, on their densities and their types. These parameters are essential in view of modelling realistic particle behaviour [4, 24].

Acknowledgements

This study was funded by IFREMER. The authors thank Ms M.-M. Daniélou who performed the image analyses, Mr E. Le Gall and Ms A. Youenou for their contribution to the field work.

REFERENCES

[1] Agrawal Y.C., Pottsmith H.C., Autonomous long-term in situ particle sizing using a new laser diffraction instrument, Proc. Oceans 89 (3) (1989) 1575–1580.

[2] Bale A.J., Morris A.W., In situ measurements of particle size in estuarine waters, Estuar. Coast. Shelf Sci. 24 (1987) 253–263.

[3] Bale A.J., In situ laser optical particle sizing, J. Sea Res. 36 (1/2) (1996) 31–36.

[4] Burban P.Y., Lick W., Lick J., The flocculation of fine-grained sediments in estuarine waters, J. Geophys. Res. 94 (1989) 8323–8330.

[5] Conner C.S., De Visser A.M., A laboratory investigation of particle size effects on an optical backscatterrance sensor, Mar. Geol. 108 (1992) 151–159.

[6] Downing J.P., Sternberg R.W., Lister C.R.B., New instrumentation for the investigation of sediment suspension in the shallow environment, Mar. Geol. 42 (1981) 19–34.

[7] Eisma D., Flocculation and de-flocculation of suspended matter in estuaries, Neth. J. Sea Res. 20 (1986) 183–199.

[8] Eisma D., Schuhmacher T., Boekel H., Van Heerwaarden J., Franken H., Lann M., Vaars A., Eijgenraam F., Kalf J., A camera and image analysis system for in situ observation of flocs in natural waters, Neth. J. Sea Res. 27 (1990) 43–56.

[9] Eisma D., Li A., Changes in suspended-matter floc size during the tidal cycle in the Dollard estuary, Neth. J. Sea Res. 31 (2) (1993) 107–117.

[10] Eisma D., Kalf J., In situ particle size measurements with the NIOZ in situ camera system, J. Sea Res. 36 (1/2) (1996) 49–53.

[11] Eisma D., Bale A.J., Dearnaley M.P., Fennesy M.J., Van Leussen W., Maldiney M.A., Pfeiffer A., Wells J.T., Intercomparison of in situ suspended matter (floc) size measurements, J. Sea Res. 36 (1/2) (1996) 3–14.

[12] Fennessy M.J., Dyer K.R., Huntley D.A., INSSEV, an instrument to measure the size and settling velocity of flocs in situ, Mar. Geol. 117 (1994) 107–117.

[13] Fennessy M.J., Dyer K.R., INSSEV: floc population characteristics measured with INSSEV during the Elbe Estuary intercalibration experiment, J. Sea Res. 36 (1/2) (1996) 55–62.

[14] Gentien P., Lunven M., Lehaître M., Duvent J.L., In situ depth profiling of particles, Deep-Sea Res. 42 (1995) 1297–1312.

[15] Gibbs R.J., Floc breakage by pumps, J. Sediment. Petrol. 51 (1981) 670–672.

[16] Gibbs J.R., Wolanski E., The effects of flocs on optical backscattering measurements of suspended material concentration, Mar. Geol. 107 (1992) 289–291.

[17] Gorsky G., Aldorf C., Kage M., Picheral M., Garcia Y., Favole J., Vertical distribution of suspended aggregates determined by a new underwater video profiler, Ann. Instit. Oceanogr. Paris 68 (1992) 275–280.

[18] Honjo S., Doherty K.W., Agrawal Y.C., Asper V.L., Direct optical assessment of large amorphous aggregates (marine snow) in the deep sea ocean, Deep-Sea Res. A 31 (1984) 61–76.

[19] Kranck K., Flocculation of suspended sediment in the sea, Nature 246 (1973) 348–350.

[20] Pfeiffer A., In situ measurements of flocculated suspended matter with a video multi sensor system, J. Sea Res. 36 (1/2) (1996) 115–118.

[21] Schoellhamer D.H., Biological interference of optical backscatterance sensors in Tampa Bay, Florida, Mar. Geol. 110 (1993) 303–313.

[22] Trent J.D., Shanks A.L., Silver M.W., In situ and laboratory measurements on macroscopic aggregates in Monterey Bay, California, Limnol. Oceanogr. 23 (1978) 626–635.

[23] Van Leussen W., Cornelisse J., The underwater video system VIS, J. Sea Res. 36 (1/2) (1996) 77–81.

[24] Van Leussen W., The Kolmogorov microscale as a limiting value for the floc sizes of suspended fine-grained sediments in estuaries, in: Burt N., Parker R., Watts J. (Eds.), Cohesive Sediments, Wiley, New York, 1997, pp. 45–73.

[25] Vilivic D., Legovic T., Zutic V., Vertical distribution of phytoplankton in a stratified estuary, Aquat. Sci. 51 (1989) 31–46.