Particles in Europe (PiE)
7-9 October 2014
Esbjerg, Denmark

Organized by
Sequoia Scientific, Inc.,
MacArtney A/S,
University of Copenhagen

Program and Abstracts
**Monday 6th October 2014**

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<tr>
<td>18.00-20.00</td>
<td>Registration and Icebreaker at Café Frederik, Skolegade 46, 6700 Esbjerg</td>
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**Tuesday 7th October 2014**

<table>
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<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>8-8:50</td>
<td>Registration @ Esbjerg Conference Hotel (ECH), Stormgade 200, 6700 Esbjerg</td>
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<tr>
<td>8:50-9:00</td>
<td>Welcome</td>
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| 9:00-9:35 | **KEYNOTE**  
Daniel Hanes: The confounding effects of particle characteristics on acoustic backscatter measuring techniques |
| 9:35-10:00 | Guillaume Fromant et al: Acoustic inversion using two multifrequency profilers: the Aquascat 1000S and the TAPS |
| 10:00-10:25 | Yogi Agrawal et al: Sediment Acoustic Backscattering Cross-Sections in a River Column |
| 10:25-10:50 | Stefan Haun et al: Quantification of suspended sediment concentrations and particle size distribution in different water bodies by means of laser diffraction and acoustic backscatter |
| 10:50-11:10 | **Coffee Break** |
| 11:10-11:35 | Ulrik Lumborg et al: Monitoring of sediment dynamics during disposal of dredged harbour sediment in Port of Esbjerg, Denmark |
| 11:35-12:00 | Thomas Møskeland et al: Integrated Environmental Monitoring |
| 12:00-12:25 | Kevin Black: Using Particulate Tracers To Address Specific Sediment Management Issues: A New Tool in the Box |
| 12:25-13:25 | Lunch |
| 13:50-14:15 | Thor Markussen et al: Arctic fine-grained particle flocculation, the case of Disko Fjord, West Greenland |
| 14:15-14:40 | Michael Fettweis et al: Variability in concentration, size and settling velocity of muddy marine flocs from the southern North Sea |
| 14:40-15:05 | Thorbjørn Andersen et al: Flocculation in the water column or aggregation at the bed – LISST 100 used in a combined field and laboratory set-up |
| 15:05-15:25 | **Coffee Break** |
| 15:25-15:50 | Piers Larcombe: Particle dynamics in the marine environment - examples of measurements from NW Australia |
| 15:50-16:15 | Gael Many et al: Particles characteristics in front of the Rhône River during flooding conditions |
| 16:15 | End of day. On your own for dinner / drinks Tuesday evening. |
Wednesday 8th October 2014

8.30  Depart ECH for River Varde and the Skallingen Peninsula in the Wadden Sea National Park. Guide: Dr. Thorbjørn Andersen, University of Copenhagen

13.30 Lunch at MacArtney
14.30 Tour at MacArtney
15.30 Return to ECH
17:15 Welcome drinks at the Fisheries and Maritime Museum, Tarphagevej 2, 6710 Esbjerg V
17:30 Guided tour and conference dinner at the Fisheries and Maritime Museum

Thursday 9th October 2014

**Suspended Sediment Dynamics II**

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<thead>
<tr>
<th>Time</th>
<th>Speaker and Title</th>
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<tr>
<td>09:00-09:35</td>
<td>KEYNOTE  Colin Jago et al: SPM dynamics related to tidal straining in a Region of Freshwater Influence.</td>
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<tr>
<td>09:35-10:00</td>
<td>Suzy Jackson et al: Turbulence control of floc size in suspended particulate matter (SPM) in the river estuary transition zone (RETZ)</td>
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<tr>
<td>10:00-10:25</td>
<td>Eleanor Howlett et al: Particle size and its influence of fluxes through an estuary</td>
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<tr>
<td>10:25-10:50</td>
<td>Quentin Monnoyer et al: Assessment of suspended sediment properties from an optical settling column during a dam flushing event: the Arc and Isère rivers, June 2014</td>
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**New instruments and methods II**

<table>
<thead>
<tr>
<th>Time</th>
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<tbody>
<tr>
<td>11:10-11:35</td>
<td>Alex Nimmo Smith et al: MSS-HOLO: a free-fall particle microstructure profiler</td>
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<tr>
<td>11:35-12:00</td>
<td>Emlyn Davies et al: Combining technology to extend the limits of particle measurements in subsea blowouts</td>
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<tr>
<td>12:00-12:25</td>
<td>Christian Winter et al: PCam: Community camera system for the in-situ measurement of suspended matter size</td>
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**LUNCH**

13:50-14:15 Boudewijn Decrop: Challenges in the acoustic measurements of dredging plumes
14:15-14:40 Yogi Agrawal: What turbidity does not see, LISST reveals - sediment in a river water column

**Optics**

<table>
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<th>Time</th>
<th>Speaker and Title</th>
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<tr>
<td>14:40-15:05</td>
<td>Karolina Borzycka: One-year study on variability of suspended particles characteristics and inherent optical properties in the southern Baltic.</td>
</tr>
<tr>
<td>15:05-15:30</td>
<td>Aris Karageorgis: Schlieren effects in beam transmissometers and LISST-Deep observed in the stratified Danube River delta, NW Black Sea</td>
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15:30 Conclusion, coffee and goodbye

Rev. 02-10-2014
Sediment Acoustic Backscattering Cross-Sections in a River Column

Y.C. Agrawal¹, Ole A. Mikkelsen¹ ² and Wayne Slade¹

1. Sequoia Scientific, Inc., 2700 Richards Road, Bellevue, WA 98005, USA
2. Current affiliation: MacArtney A/S, Gl. Guldagervej 48, 6710 Esbjerg V, Denmark

In an accompanying paper by this group of authors, we have reported the rich detail in sediment dynamics in a column of the Cowlitz river, Washington. In this paper, we examine the contribution to acoustic backscatter at 3 frequencies, from different size components of particles.

The quantitative estimation of sediment size and concentration using acoustic backscatter in a water column remains a challenge today. Single-frequency acoustic backscatter suffers from insufficient information - the backscattering strength is a single measurement from a range cell, that depends on two unknowns: grain size and concentration. Multi-frequency systems do better with a single estimate of an equivalent grain size, along with concentration. The 'equivalent grain size' is a complex function of the true grain size distribution. Furthermore, acoustic backscatter strength depends on particles of all sizes, though the sensitivity to small particles (ka<1) is weaker than to larger particles (ka>1). The obvious question is which size dominates, if any size does. How does the relative contribution of the small particles compare to that from large grains? This is the question addressed in this paper using a uniquely detailed dataset on particle size distributions in a river column.

We model the acoustic scattering following the formulation used by Thorne and Hanes() and later Hanes(). The scattering by particles is both due to viscous and scattering processes, both are included. The scattering cross-sections of each size component depend on the particle area concentration, modified by the form factor (analogous to scattering efficiency in Radar and LIDAR). Because the locations, hence phases of scattering from individuals are random, the net backscattering pressure intensity that is sensed is proportional to the sum of squares of pressure contribution of each particle. This cumulative sum for all size classes is the key result. We have done this contribution for 3 frequencies: 1, 3, and 5MHz.
The results reveal that the fine wash-load component contributes significantly to the total scattering, but that the coarse resuspended load adds significantly to the total backscatter signal. In other words, in contrast to OBS which is blind to the coarse grains, acoustics responds measurably. This realization suggests combining OBS and acoustic backscattering to get a sense of the total sediment makeup.
What turbidity does not see, LISST reveals - sediment in a river water column

Y.C. Agrawal¹, Ole A. Mikkelsen¹² and Wayne Slade¹

¹. Sequoia Scientific, Inc., 2700 Richards Road, Bellevue, WA 98005, USA
². Current affiliation: MacArtney A/S, Gl. Guldagervej 48, 6710 Esbjerg V, Denmark

This paper presents one vignette from a rich dataset collected incidentally on a river column. While testing the LISST-SL instrument made by Sequoia, US Geological Survey (USGS) scientists collected data from a bridge at a cross-section of the Cowlitz river, Washington. The LISST-SL records optical transmission, particle size distribution, depth, velocity, temperature and a few auxiliary parameters. The -SL was operated in many modes - fixed depth, profiling, and fixed plus profiling. Treating the river flow as statistically stationary (in the absence of rain or significant changes in snow melt), we combined the 3-hour dataset into a single unit. As a result, the data are mostly at many fixed depths, but also fill gaps in between.

An examination of the data revealed this striking contrast: the optical transmission was nearly constant vertically, showing just the faintest hint of decrease towards the riverbed. In contrast, the concentration measured by LISST-SL showed a range of values at any depth, with a clear minimum concentration at each depth. This minimum value increased weakly toward the bed, but the variability in concentration increased greatly toward the river bed, increasing to a 4:1 range. Examination of the profile of grain size distribution revealed that there existed a well-mixed wash-load throughout the water column, of size around $\Phi \sim 6$. This corresponded to the minimum at all depths. In addition, the increase in concentration with depth, as revealed from the -SL data was clearly due to large grains - i.e. the suspended load. This clear separation of the wash-load and suspended load has not previously been reported in such extensive data. Recall that the transmission data of the LISST-SL (similar to data from turbidity measured by OBS) showed no such increase in concentration with depth. This so because the suspended load is coarse, several $\Phi$ values away from the wash-load, to which turbidity is less sensitive.

We will also show that profiles of concentrations of different size particles, when used to back-calculate the friction velocity in the river column, produced estimates that were consistent to within
20%. These estimates of the friction velocity, in turn, when used for estimating river slope, also produced slope estimates that match data of US Geological Survey for this river.

Prior studies of water columns have used OBS or acoustics, missing on this rich detail of river column dynamics.
Flocculation in the water column or aggregation at the bed – LISST 100 used in a combined field and laboratory set-up

Thorbjørn Joest Andersen¹, Thor Nygaard Markussen¹, Lars Chresten Lund-Hansen², Morten Holtegaard Nielsen³, Marianne Ellegaard⁴, Doan Nhu Hai⁵, Nguyen Ngoc Lam⁶.

1) Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark
2) Department of Biology, University of Aarhus, Denmark
3) Arctic Technology Centre, Danish Technical University, Denmark
4) PLEN, University of Copenhagen, Denmark
5) Institute of Oceanography, Nha Trang, Vietnam

Sediment aggregation in estuarine and marine environments is a subject which has been the focus of countless studies. The majority of these studies have focused on the flocculation taking place in the water column whereas the aggregation taking place at the sediment bed has received comparatively little interest. In the present study we examined the size of aggregates eroded from undisturbed natural sediment beds from a microtidal tropical lagoon and compared it to the size of aggregates suspended in the water column (fig 1).

The in situ particle size distribution (PSD) of material suspended in Nha Phu bay in SE Vietnam was measured using a LISST 100C. The PSD of eroded bed aggregates from the same site was measured on the suspension from EROMES erosion experiments carried out on undisturbed bed sediment from the bay. Water samples were gently transferred from the erosion chamber into a small chamber positioned at the optics-end of the LISST and measurements were made immediately after gentle stirring of the suspension.
The similarity of the grain size distributions of eroded and suspended sediment indicates that the size distribution of the suspended sediment of the lower water mass in the lagoon was controlled by aggregation taking place at the sediment bed rather than flocculation processes in the water body. The upper less saline water mass on the other hand showed evidence for flocculation taking place in the water column.

Figure 2: PSDs at different bed shear stresses. The aggregates appear to be relatively stable.
Measurements of PSD in the erosion experiments were carried out at varying bed shear stresses to examine the stability of the eroded aggregates (fig 2). The aggregates appeared to be quite stable as indicated by the similar PSDs for different bed shear stresses.

Our study demonstrates that the sediment aggregation taking place at the bed, e.g. as a result of biological activity, may have stronger impact on the size distribution of material in suspension than usually believed and is potentially quite important for the sediment transport in many estuarine systems.

Figure 3: EROMES erosion chamber with undisturbed sediment collected by divers from Nha Phu bay. Water samples are gently transferred from the eroded suspension using a pipette with a 6 mm opening at the suction end. Samples are transferred into the small chamber at the optics end of the LISST and measurements are made immediately after gentle stirring.
Using Particulate Tracers To Address Specific Sediment Management Issues: A New Tool in the Box

Kevin Black
Partrac, UK
One-year study on variability of suspended particles characteristics and inherent optical properties in the southern Baltic

Karolina Borzycka 1, Sławomir Sagan 2

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The Baltic, as a shallow inland sea, has a varied environmental condition from almost oceanic to the freshwater conditions. Most of water input comes from rivers, with marked seasonal and temporal variability. Therefore concentration of particles varies in the different year periods and at the different areas. There is still insufficient information about such variability. Main aim of this study is to show variability of particles and linked Inherent Optical Properties (IOP) characteristics throughout the year and indicate specific processes occurring in the Baltic Sea waters.

Spatial and vertical variability of characteristics of suspended matter in the southern Baltic waters were analyzed. The analyzes based on empirical data obtained during four research cruises in 2013 (cruises names: 201303, 201305, 201309, 201311). Cruises took place in different seasons like late winter (February, March), spring (May) as well as late summer and autumn (September, October, November). The study area covers the open waters of the southern Baltic as well as the coastal regions like the Gulf of Gdańsk. Study area with sampling stations are presented in Figure 1.

At each station measurements of the inherent optical properties of seawater (absorption, scattering and attenuation coefficients), temperature, salinity and volume concentration of particles were measured in situ from the surface to the bottom (vertical profiles). The inherent optical properties (IOP) were measured using in-situ spectrophotometer AC-9Plus, WetLabs. Absorption and attenuation coefficients were measured at 25 path length in nine wavelengths in the range of the visible spectrum (412, 440, 488, 510, 532, 555, 650, 676, 715 nanometres). Detailed description of the technology is provided by (Zaneveld et al., 1990). Particles Size Distribution and Particle Volume Concentration were measured in-situ with LISST-100X Type B. It allows resolving a particle size range from 1.25 to 250 micrometers in 32 classes (Gartner et al., 2001). Detailed description of the technology and its application is provided by (Agrawal, Pottsmith, 2000). All of the signals were processed further using software written in the Matlab® environment. This had
calibration procedures for all the sensors, and it merged all the measured geophysical parameters and calibrated values in physical units into a depth binned matrix. AC9 instrument was calibrated in pure water and routinely checked for stability with air-readings. Air and water offsets, temperature and salinity corrections were applied according to the manual. Since the ac-9 absorption signal needs correction for scattering, the ‘Zaneveld method’ was applied, which assumes zero absorption for 715 nm (Zaneveld et al., 1995). Particle Size Distribution (PSD), Particle Volume Concentration (PVC), particle number and particle mean size were obtain from LISST-100X data using standard procedures for randomly shaped model (Agrawal et al., 2008).

Obtained results showed significant differences in measured parameters values. These differences were presented in spatial as well as seasonal variability of all measured parameters. An overview of selected parameters values and its standard deviation are given in Figure 2.

Total particle volume concentration (Total PVC), which is a sum of particle volume concentration in all classes, varied in different seasons and in water column and was related to temperature and salinity condition. The highest values of total PVC were observed within the thermocline and just below it. Values in this layer were from 10 to 100 times higher than in the other layers. Examples vertical profile, on which this situation can be observed, is showed in Figure 3. Similar situation was observed at deep station (more than 70 meters depth), where strong salinity gradient was present. In this case total PVC increased 10-100 times within the halocline. In addition mean PVC were 10 times higher (36.0103 µl/l) in the mouths of Vistula and Oder River as well as well in Szczecin Lagoon. Seasonal variability were observed mainly in the mixed layer. In this layer values of total PVC were few times higher during 201305 and 201309 cruises, which was related to biological processes and freshwater runoff.

Second analyzed parameters was particle volume concentration in different classes. All classes were grouped into size range. Four groups were designated: pico (classes 1-3), nano (classes 4-17), micro (classes 18-30) and meso (classes 31-32). Groups range based on standard size range of plankton. Particle volume concentration in each group were expressed as a percentage of total PVC. Obtained results showed that smallest fraction of particles (group pico) had significant contribution to total PVC (more than 5%) only near surface (0-5 meters) and up to 10 meters under the bottom, what is shown in Figure 4. At the other hand this group had the smallest contribution to total PVC (mean value: 1%). The highest contribution to total PVC had micro group (mean value: 53%). In addition contribution of biggest group (meso) were higher within density boundary. Examples profiles were
shown in the Figure 5. Seasonal changes of volume concentration in the groups were significant. Nano and pico group had greater contribution in total PVC in 201303 (mean value nano 34% and pico 2%). The greatest contribution in total PVC had micro group, mean value exceeded 50% for 201305, 201309, 201311 cruises.

Another analyzed parameter was total particle number. The highest value and highest variability of total particle number were observed in the mixed layer (0-20 meter depth). In the layer mean total particle number were 40 times higher ($4.63 \times 10^{16}$ l$^{-1}$) than below the layer ($1.16 \times 10^{16}$ l$^{-1}$). At the same time total particle number in the mixed layer was higher near the coast and in river mouth than on the open sea. In the deep station (more than 50 meters depth) increase of total particle number was observed. Few meters (up to 10 meters) over the sea bottom, total particle number increased 10-100 times. Examples of this phenomenon is showed in Figure 6. Seasonal changes of total particle number were significant for mixed layer. In the layer mean total particle number was the highest during 201309 cruise ($7.28 \times 10^{16}$ l$^{-1}$) and lowest during 201311 cruise ($1.05 \times 10^{16}$ l$^{-1}$), which was related to biological processes freshwater runoff.

Inherent Optical Properties (IOP) showed similar variability to total PVC and total particle number. Absorption and attenuation coefficients were highest in the upper layers (0-40 meters) – mean values: $a_{gp}(532) = 0.284$ m$^{-1}$, $c_{gp}(532) = 1.257$ m$^{-1}$. Below thermocline values of absorption and attenuation coefficient were lower than in mixed layer (mean values: $a_{gp}(532) = 0.232$ m$^{-1}$, $c_{gp}(532) = 0.886$ m$^{-1}$). Seasonal changes were related to variability of water temperature and freshwater runoff. Values of IOP where relatively higher in spring and summer (cruises 201305 and 201309) as well as near the Vistula and Oder mouths. Obtained result are typical for southern Baltic Sea (Sagan, 2008). In the deep station IOP values increased few meters over the sea bottom, concurrently with increase of total particle number.

Summary of selected measured parameters and its season, spatial and vertical variability are showed in Figure 7. Considering all measured parameters together, three characteristic phenomenon were noticed. First one was high dynamic in upper layers of water. All measured parameters changed significantly for the depths from 0 to 40 meters. Influence of water temperature and rivers inflow was most noticeable for mentioned water layer. Second one was increase of total PVC in the thermocline. It showed accumulation suspended matter on density boundary. And the last, third noticed phenomenon was increase of analyzed parameters few meters over the sea bottom. This season independent feature is the result of sediments transport by the bottom currents.
Our empirical study documented high variability of particles characteristics and inherent optical properties. It showed vertical, spatial and seasonal changes of analyzed parameters. It also indicate processes influence on characteristics of suspended particles. Study showed that total PVC is correlated with $a_{gp}(676)$, especially in 201303 and 201305, what is showed in Figure 7. In addition total particle concentration is correlated with $c_{gp}(532)$. Worse correlation in 201309 can be related to different character (mineral/organic) of suspended matter during the cruise. Above mentioned relationships suggested that most of the year mineral particles dominated in Baltic waters and its contribution to total suspended matter changed during the year.

Acknowledgements

The study was financed by the Project „Satellite Monitoring of the Baltic Sea Environment – SatBaltyk” funded by the European Union through European Development Fund contract no. POIG 01.01.02-22-011/09

References


Fig. 1. Distribution of sampling stations in year 2013

Fig. 2 Summary of selected parameters values and its standard deviation.
Fig. 3. Examples of vertical profiles of temperature, salinity, total particle volume concentration and particle size distribution acquired during field studies in May (a) – station P115c and September (b) – station P140.
Fig. 4 Vertical profiles of PVC in pico group expressed as percentage of total PVC for all stations. Red dotted line represented 5% of total PVC.

Fig. 5. Examples of vertical profiles of temperature, salinity, meso group expressed as percentage of total PVC acquired during field studies in May (a) – station P104a and September (b) – station P116
Fig. 6 Examples of vertical profiles of total particle number acquired during field studies in September (a) – station P116 and September (b) – station P1
Fig. 7. Season, spatial and vertical variability of selected parameters for selected transect from coast in open sea direction (red box in the upper map).

<table>
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<th>cruise</th>
<th>Temperature [°C]</th>
<th>Total particle volume concentration [µl/l]</th>
<th>Total particle number [count/l]</th>
<th>$a_{gp}(676)$ [m$^{-1}$]</th>
<th>$c_{gp}(532)$ [m$^{-1}$]</th>
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<td><img src="image10" alt="cgp(532)" /></td>
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Combining technology to extend the limits of particle measurements in subsea blowouts

Emlyn John Davies*, Per Johan Brandvik¹, Frode Leirvik¹

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Measurements of the size distribution of oil droplets, gas bubbles, or the mixture of both is of critical importance in understanding the dynamics of subsea blowouts. This is due to the well-confined relationship between the turbulent energy at the point of release and the size distribution of the resultant droplets and bubbles (Johansen et al, 2013). Accurate knowledge of the particle size distribution is therefore a key requirement for predictive models of oil spill trajectories.

Laser diffraction is commonly used for measurements of the size distribution of suspended oil droplets, and the LISST-100 (Agrawal and Pottsmith, 2000) provides a good mechanism for undisrupted *in-situ* measurements. However, measurements of oil droplets using the LISST-100 are restricted by the measureable size range of the instrument (Davies et al, 2012) and limits to the maximum total volume concentration. Challenges associated with large volume concentrations can be overcome by effectively increasing the height of measurement above the release plume to enable sufficient dilution. Despite this, laboratory simulations of subsea blowouts used for calibration and validation of predictive models must still be scaled down such that the resulting droplet size distribution falls within the 500 µm limit of the LISST-100 (Brandvik et al, 2013; Johansen et al, 2013). Figure 3 shows two laboratory facilities (the 80 L Mini Tower and 42000 L Tower Basin) used at SINTEF for simulating subsea blowouts and evaluating dispersant effectiveness. The SINTEF Tower Basin is able to simulate larger-scale releases due to its 6 m height, which is needed in order to obtain sufficient dilution of the release plume for the LISST-100. However, there is a need to extend droplet measurements to larger sizes so that release conditions more closely coupled to realistic scales can be simulated and recorded accurately.
Figure 3: Photographs of subsea blowout simulations in the SINTEF Mini Tower (left) and Tower Basin (right).

The LISST-Holo (Graham and Nimmo-Smith, 2010) has recently enabled the extension of the 500 µm limit of the LISST-100 to provide measurements of oil droplets of up to just over 2 mm. Figure 4 shows a raw hologram of oil droplets created in the SINTEF Tower Basin and the processed image used for size distribution measurements. The adoption of the LISST-Holo has enabled new simulations of low energy releases and an assessment of dispersant effectiveness under these conditions, which was not previously possible using only the LISST-100.

A secondary advantage of the LISST-Holo is the ability to distinguish differences in droplet shapes and identify situations in which shedding of micro-threads or small droplets could occur. Figure 5 shows an image of an oil droplet that has micro-threads and is shedding small droplets due to super-saturation of dispersants.

Figure 4: Raw hologram of spherical oil droplets (left) and the associated reconstructed binary image (right), which has been coloured proportionally to the droplet distance from the CCD. The width of each image is 7 mm.
While the LISST-Holo provides a very substantial step forward in our ability to monitor droplets surrounding blowouts and has the ability to image individual objects up to approximately 4mm, the useable upper size limit for automatically processed images is closer to 2 mm due to over-segmentation of large particles during reconstruction and binerization (Davies et al, 2013). Under-sampling is also a challenge for measurements of large droplets, as only one or two droplets of mm-scale can fall within the sample volume at any one time. In addition, the path reduction module is required to reduce the likelihood of overlapping particles, but its use further exacerbates the problem of under-sampling. One method of reducing under-sampling errors is to increase the acquisition frequency of the instrument. The standard fastest fixed rate frequency of the LISST-Holo (0.1 Hz) has been increased to 1 Hz by reconfiguration of the instrument to continuously download holograms to a separate computer via the network, before the files are written to the internal instrument disk. This limit of 1 Hz has provided a substantial improved to the statistics that can be derived from in-plume measurements of large oil droplets and the added benefit of a near-real time display. Despite this improvement, however, experiments must often be run for at least 5 minutes (for median diameters above 1000 µm) before a suitable number of droplets have been sampled.

While concentrations are high and droplet sizes are large (mm scale), the advantages of a long path length and small pixel size are reduced, and as such we have developed a third imaging system to compliment the use of the LISST-100 and LISST-Holo. This is a backlit silhouette system with an adjustable path length (0.5-16 mm). The use of telecentric optics, with a 16 mm depth of field eliminates focussing and magnification errors and provides a field of view that covers a 25 mm x 35 mm area. A typical camera and lens configuration for this system will give a pixel size of 14 µm at full resolution – with the smallest particles intended for measurement by this system being just under 100 µm. An example of a sequence of images of a large oil droplet (~6000 µm) recorded by the silhouette camera is shown in Figure 6. This droplet was tracked by the camera system while rising through the water column. This is
approaching the maximum theatrical stable droplet size for a 0.2% dispersant treatment, and is subject to a large degree of deformation and oscillatory behaviour.

**Figure 6:** Three images of an oil droplet treated with 0.2% of chemical dispersant, as recorded by the silhouette camera.

The silhouette system can operate continuously at 15 Hz with a resolution of 2048x2448 pixels, can be configured for medium frame rate acquisition of 60 Hz at a 1200x1600 pixel resolution, or can run at a high frame rate using pixel binning – for example, a bin size of 5 horizontal pixels (and maintaining full vertical resolution) enables frame rates of 250 Hz continuously. This high-frame rate configuration has been used for tracking particle motion within gas blowouts, with asynchronous camera shutter and strobe lighting to provide a 5 µs illuminated exposure time that eliminates motion blur. Because this system provides sharp particle silhouettes, only very limited image processing is required and segmentation errors are small. Particle size distributions and motion tracking can be computed in less than 0.05 s per image pair, enabling near-real-time processing.

The most substantial challenges with the image acquisition from the silhouette camera are that there are large demands for data storage, the system must be tethered via a Catagory 5e Ethernet connection (which is limited to 100 m unless active repeaters are used), and data must be recorded onto a sufficiently large solid state disk. The smallest resolvable particle size is also relatively large, so there remains a need for the LISST-Holo to provide the high resolution images for particles below approximately 1.5 mm and to provide sufficient overlap between the LISST-100 and silhouette systems.

In a similar fashion to Mikkelsen et al (2005), the combination of multiple measurements of the particle size distribution from the LISST-100, LISST-Holo and silhouette camera can enable a span in accurate *in-situ* droplet or bubble size measurements from 5 – 9 000 µm. This presentation will demonstrate how size distributions of oil and gas bubbles recorded by multiple measurement techniques can provide a very large span in droplet sizes and volume...
concentrations that will enable the extension of laboratory simulations towards more realistic conditions.

References:


Introduction

The increase in the number of offshore and port development projects has led to rising dredging activity throughout the world. In order to minimise disruption of natural systems, environmental legislation regulating impacts of dredging works has become more extensive subsequently. Turbidity caused by dredging works with Trailing Suction Hopper Dredgers (TSHD) using an overflow is one of the main environmental concerns being assessed in the phases of planning, design and execution. At sensitive areas near the project, turbidity and sediment depositions rising above the allowed thresholds need to be prevented. Numerical modelling and in situ measurements are used at the present day to predict and monitor the fate of turbidity plumes (Figure 7). More recently, also remote sensing is becoming an integrated part of the plume monitoring systems.

![Example of an overflow plume](image)

Prediction of the increase in turbidity in the far-field is possible by means of large scale hydrodynamic and sediment transport models. These models, however, are not designed to solve the complex near field processes in the vicinity of the dredger and require a sediment source term to account for overflow in the form of a distribution of sediment flux over the water depth. Until today, the determination of this distribution has been rather arbitrary. Verification of the new generation of near field simulation models is one of the motivations for gathering in situ data of overflow plumes at close distance behind TSHD’s. Monitoring of
dredging plumes during project execution can usually be done at greater distance from the dredger.

**The measurement campaign**

A 120 m long TSHD with loading capacity of 12,000 m³ was dredging silty sand at a relatively shallow part of a tidal estuary. The mixture pumped into the dredger’s hopper contains a high percentage of water, sand and fine sediment particles. The sand settles in the hopper, while the excess water leaves the hopper through an overflow shaft. The water leaving the shaft at the vessel’s keel contains typically between 10 and 200 g/l of mainly fine sediments, which form a turbid plume behind the vessel. The goal of the measurement campaign is to relate the sediment distribution found in the plume behind the dredger to the sediment flux leaving the overflow shaft of the vessel.

Transects were sailed along the length of the plume as well as across the plume. The current and backscatter measurements in the plume were conducted using a Teledyne RD Instruments ADCP 1200 kHz Workhorse with beam angle 20°. For positioning, a DGPS was installed onboard the survey vessel. This 1200 KHz ADCP system was mounted on a steel moon pole at the centre of the back deck of the vessel. The transducer set was looking vertically downwards at the bottom. ADCP backscatter data was processed to suspended sediment concentration data using the Sediview® software, based on the sonar equation. See Thorne and Campbell (1992), Hay (1991) and DRL (2003) for more information.

As a backup for the acoustic system, a string of OBS-3A instruments was trailed behind the survey boat, with a heavy fish at the end of the string. One OBS-3A was logging online with a frequency of 1 Hz, two other OBS’s were logging to the internal memory with a frequency of 0.1 Hz. Further attached to the string is a tube connected to a centrifugal pump, permanently pumping water from near the middle OBS’s sensor. In this way water samples are collected every 5 minutes with increased frequency when entering and leaving the plume. Water samples are analysed for suspended solids and the results are used for calibration of the optical and acoustic turbidity acquisition systems.

In order to obtain complete profiles of sediment concentration between water surface and seabed, a SiltProfiler is deployed. The SiltProfiler was developed by IMDC and has the following general specifications. The data collection is executed locally (i.e. on the profiler)
by an integrated data logger. Sensor cables are kept very short and connect to the interfacing electronics of the data logger. The data logger collects the sensor signals and records the same in internal memory. The data can be retrieved upon recovery of the profiler via a short range wireless connection. As soon as the profiler breaks the water surface the data can be accessed and transferred to the operator's PC, whereupon the profiler is ready for a new profiling session. The retrieved profile data are visualised immediately in depth profile graphs. This operational mode requires no electrical cables to be attached to the profiler.

The mounted sensors are: (i) conductivity, pressure and temperature sensors with measuring ranges adequate for use in seawater; (ii) multiple turbidity sensors to cover the entire range of 0 to 55 000 mg/l suspended solids: 2 transmittance sensors (type FOSLIM) are used, in combination with a Seapoint turbidity sensor (0-400 mg/l).

As such the SiltProfiler is anticipated to rapidly profile the suspended sediment concentration as well as the salinity structure. The SiltProfiler can measure at variable speed up to 100 measurements per second (100 Hz).

The data collection rate is adjustable to optimize for the required vertical / temporal resolution. Further, the data acquisition rate will be depth dependent in such a way that the rate is low in the upper section of the profile and higher in the lower section. Both rates and the changeover depth are user adjustable. The duration of data retrieval depends upon the amount of collected data and the effective data transfer rate.

Figure 8 The free-fall SiltProfiler instrument
Results and discussion

The vertical profiles obtained using the SiltProfiler revealed clearly the bimodal structure of the turbidity plume (Figure 10). In the lower half of the water column, a highly concentrated layer was found containing the majority of the released sediments, while in the upper layers a more diluted secondary plume can be observed (background sediment concentration was <10 mg/l). In the surface plume (from a depth of 12 m to the surface), sediment concentrations of about 40 to 100 mg/l were found; in the near bed plume concentrations were up to a factor 10 higher.

Figure 10 Example of a SiltProfiler profile of suspended sediment concentration (SSC in mg/l) and salinity (ppt).

When looking at the sediment concentrations determined using the ADCP backscatter (calibrated using water samples), it seems only a 5 m thick surface plume is found and no dense bottom layer (Figure 11, top panel). When looking at the SiltProfiles taken along the course of the transect (lower panel), again the bottom plume is clearly visible. When two observers would use only one of both methods for plume monitoring, they would come to
radically different conclusions. It seems the acoustic measurements were disturbed by a substance inducing backscatter, which was not detected in the suspended solids analysis on the water samples, which served as calibration for the acoustics at several points along each transect.

![Figure 11 A 1.3 km transect while following the dredger at 100 to 200 m: Acoustic backscatter interpretation to suspended sediment concentration (top) and simultaneous SiltProfiler profiles (below). A discrepancy can be seen.](image)

Based on the OBS-3A string measurements while sailing laterally across the plume, the plume width could be determined. A range of plume widths was found between 80 m and 190 m, between 200 m and 800 m behind the dredger. The maximum distance at which the plume could be found was about 1,100 m behind the dredger. However, at some times, when the dredger was moving in the same direction as the current, no plume could be found behind the dredger. The current most probably kept it below the vessel.

From an environmental impact point of view, the surface plume is more relevant since it has the potential to move away from the dredging area with the current, potentially moving towards environmentally sensitive areas. For this specific case, the concentration levels found in the surface plume were about a factor 1000 smaller compared to the mixture released through the overflow shaft.
Conclusions

An offshore dredging plume monitoring campaign was successfully executed. The vertical and horizontal structure of plume behind a Trailer Suction Hopper Dredger at work was observed. Due to the limited water depth, two types of plume could be distinct: a dense benthic layer and a more diluted surface plume above. The dilution factor of the plume compared to the released mixture is about 1000 for the surface plume and about 100 for the more dense benthic layer. The plume length amounted to about 1 km, while the plume width varied between 80 and 190 m.

It was found that the acoustic backscatter method, which has been showed in the past to work well in river and offshore environments, did not produce reliable results in the vicinity of dredging vessels. Most likely, the presence of air bubbles is the cause of this unreliable acoustic output. Air bubbles can be generated due to air entrainment in the overflow as well as in the bow waves generated by the large vessel. Furthermore, pressure dips near the tips of propellers also generate gas and damp bubbles, from dissolved gases and cavitation. The acoustic backscatter was indeed sensing a particulate phase in the suspension, but a gaseous one instead of the sought after solid one. The backscatter is subsequently linked to the suspended solids found in the water column, resulting in an overestimation of the suspended solids in the acoustic data.

For this reason, it is advised to rely on additional direct measurements such as optical sensors. These instruments have a measurement volume close to the sensor, which avoids encountering air bubbles. Optical Backscatter Sensors are an option for capturing the horizontal distribution of sediments, but they lack a sufficiently high sampling rate to acquire a detailed vertical distribution. In order to obtain detailed vertical sampling of the sediment concentration structure, with a wide range of concentrations, the SiltProfiler instrument was successfully deployed.

References


Site-specific Conversion of Laser Diffractometer (LISST) Data to Suspended Sediment Mass Concentration (SSC)

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Abstract

This paper deals with a field investigation on measuring suspended sediment mass concentration (SSC) and particle size distribution (PSD) using a Laser In-Situ Scattering and Transmissiometry (LISST) device and bottle samples. The flowing water at the study site in a granite rock region in the Swiss Alps carries angular, elongated and flaky particles, as expected from the mineralogical composition and confirmed by microscope pictures. With such highly non-spherical particles, particle volume concentrations (PVCs) measured by LISST, and consequently SSCs, are overestimated (Felix et. al. 2013). For the particle mix at the study site, the overestimation was quantified by comparing SSCs calculated from (i) LISST measurements using a particle density of 2.77 g/cm\textsuperscript{3} obtained by pycnometer and from (ii) gravimetrical analysis of bottle samples up to 2 g/l. The LISST-based SSCs over four months in 2013 were found to be on average 68\% higher than the gravimetrical SSCs (R\textsuperscript{2}=0.89). If SSCs are to be calculated from LISST measurements, a site-specific calibration or validation by a mass-based measuring technique is recommended to account for effects of particle shape and density.

Introduction

Measuring concentration and size of suspended sediment particles is important for a better understanding and management of fine-sediment related processes in rivers, lakes, estuaries and seas and at hydraulic schemes for hydropower, irrigation and flood protection. Various direct and indirect measuring techniques are available (Wren et al. 2000). When quasi-continuous and real-time measurements of SSC and PSD are required, LISST devices are increasingly used. In such devices, the small-angle forward scattering and attenuation of light caused by suspended particles are measured and converted to particle volume concentrations
(PVCs) in certain size classes using a mathematical inversion algorithm (Agrawal & Potts-smith 2000). This inversion is based on the assumption of spherical or relatively compact particle shapes. If the shapes of natural particles differ widely from spheres, PSDs and PVCs measured by LISST, and consequently SSCs, are biased. This is a physically-based general feature of laser diffraction instruments. Felix et al. (2013b) experimentally quantified the bias for selected particle types and reported that PVCs or SSCs of highly non-spherical particles can be approximately corrected by applying particle type-specific factors.

For the conversion of PVC to SSC, the particle density has to be known, which can be assumed or measured with another device, typically a pycnometer. The particle density may deviate from the solid density of the particle material due to conglomerated particles (flocks) and may also change in time, e.g. due to variations in the mineralogical composition of the particle mix caused by particle sorting during sedimentation or re-suspension.

In a present research project on monitoring of suspended sediment and hydro-abrasive wear at turbines of hydroelectric power plants (HPPs), an *in-situ* laser diffractometer *LISST-100X*, Type C, has been used to measure SSC and PSD of the mineral particles in the power water-way of HPP Fieschertal in the canton of Valais, Switzerland. The SSCs (i) calculated from LISST measurements using a particle density determined by pycnometer and (ii) from gravimetrical analysis of periodically taken bottle samples were compared in order to quantify the particle shape effect on SSCs calculated from LISST measurements.

**Set-up, devices and methods**

Among other devices, the LISST was installed in July 2012 in a flow-through bucket at the top of the penstock at the study HPP (Fig. 1). A sampling pipe feeds the bucket with sediment-laden water drawn from the level of the penstock axis. An automatic water sampler was used to collect bottle samples (0.5 l). The sampler was programmed to take a sample every 3 days or more frequently if certain turbidity thresholds were exceeded. From the bottle samples, SSCs were gravimetrically measured in the laboratory (weighing of dried residues).

In order to extend the range of measurable SSCs the optical path length of the LISST was reduced from 50 mm to 5 mm by insertion of a 90%-path reduction module. Since 2013 the LISST was programmed to run in burst mode: 10 measurements at 1 Hz are followed by a break of 50 seconds.
The LISST with the corresponding software provides PVCs in 32 log-spaced size classes called bins 1 to 32. The inversion mode for so called ‘random’ shaped particles (Agrawal et al. 2008) was employed. Using this mode termed IMR in this paper, the nominal range of measurable particle sizes is approx. 2 to 380 μm (Sequoia 2011). As reported by Andrews et al. (2011) and Felix et al. (2013b), PVCs measured by LISST in bins of small particle sizes may be unrealistically high in some cases (‘raising tail’ in the PSD, e.g. due to ‘fine out of range particles’ or particle shape effects). This was also observed in most LISST measurements in the present study. Thus, the PVCs of bins 1 to 3 were omitted in the calculations of the PSDs and SSCs, as described in Felix et al. (2013b). The lower limit of the range of measurable particle sizes is slightly shifted from approx. 2 to 3 μm.

Fig. 1: Schematic longitudinal profile of the HPP Fieschertal, Switzerland, showing the measuring location at the power waterway (modified from Felix et al. 2013a)

**Results and Discussion**

**Mineralogical composition and particle shapes**

Rietveld X-ray diffraction analysis of three bottle samples taken in August, 2012 showed that the suspended sediments at the study site were composed of the following minerals:

- 65 to 80% of quartz, feldspars and epidote (Mohs hardness: 6 to 7), and

- 20 to 35% of muscovite, biotite, chlorite and smectite (Mohs hardness: 1 to 3).

Muscovite and biotite are typical mica minerals and belong together with the other soft minerals to the group of sheet silicates. According to their crystallographic structure, 20 to 35
mass percent of the particles at the study site are expected to have a flaky shape. The scanning electron microscope picture in Figure 2a confirms that flakes are not dominant among the particles at the study site. The picture shows that most of the particles are angular and some are elongated. Evidently, a considerable fraction of the particles at the study site has highly non-spherical shapes.

Fig. 2: Microscope pictures of the particles a) from the Fieschertal study site (picture: ETH Zurich), b) feldspar and c) mica powders used in laboratory tests by Felix et al. (2013b), and d) particles used for the development of IMR by Agrawal et al. (2008); for comparison of shapes (at different scales)

Particle density

The density of the particle mix at the study site was measured with a Helium pycnometer. A solid density of 2.77 g/cm$^3$ was obtained from dried and ground particle material. As expected, this value lies between the densities of quartz and muscovite. This value was used for the conversion of PVCs to SSCs.

Particle shape effect on SSCs calculated from LISST data

The SSCs obtained from gravimetrical analysis, SSC(G), and from LISST and pycnometer, SSC(L) at corresponding times are shown in Figure 3. A linear fit through the origin yields that the SSC(L)s are on average 68% higher than the SSC(G)s. Possible reasons for the scatter in Fig. 3 are: (i) temporal variations in particle density and shape, and (ii) less importantly measurement errors in SSC(L)s and SSC(G)s. The overestimation is mainly attributed to effects of highly non-spherical particle shapes. Many particles from the study site (Fig. 2a) deviate more from spheres than those used for the development of IMR (Fig. 2d), in which
according to Agrawal et al. (2008) no elongated or platy particles were considered. In the laboratory investigation by Felix et al. (2013b) SSC(L)s were also found to be overestimated with factors of 1.38 for angular feldspar and approximately 8 for flaky mica (muscovite) particles (Figs. 2b and 2c), using also the PVCs in size bins 4 to 32. For a mixture of 70% feldspar and 30% mica powders an overestimation factor of 3.3 was found in the laboratory tests.

Since the flaky particles have a strong effect on the overestimation, it is concluded that mainly the shapes of flaky particles at the study site differ from the shapes of the mica particles used in the laboratory. The smaller overestimation in the present field study fits to the comparison of flake shapes: the sheet silicate particles at the study site (flaky particles in Fig. 2a) are thicker in relation to their size than the mica particles used in the laboratory (Fig. 2c). As reported by Felix et al. (2013b), the shape of mica particles depends on their size, since their thickness tends to vary less than their size. Overestimation factors of flaky particles are thus not easily transferable among various studies and sites, unless the size-dependent shape of flaky particles would be parameterized and known.

![Graph showing SSCs comparison](image)

**Fig. 3:** SSCs calculated from LISST PVCs (in bins 4 to 32) with a particle density of 2.77 g/cm³ in comparison to gravimetical SSCs at HPP Fieschertal from June 3 to October 10, 2013 (65 samples)

**Conclusions and Recommendations**

The present study deals with the application of a LISST for suspended sediment monitoring in a granite rock environment. The comparison between the data obtained from (i) LISST and
pycnometer and (ii) gravimetical analysis of bottle samples indicates that the LISST overestimated PVCs and consequently SSCs by 68%, which is attributed to flaky, elongated and angular particle shapes.

If SSCs are to be calculated based on LISST measurements, we recommend accompanying measurements of SSC by a mass-based method, i.e. gravimetical analysis of bottle samples, to determine a site- and possibly time-specific conversion factor from LISST PVCs to SSCs accounting for both particle shape and density. Even if this factor is found to correspond to the assumed particle density, i.e. showing no bias by highly non-spherical particles, such measurements are still valuable to validate the assumptions on particle shapes and density.

**Outlook**
The data on suspended sediment at the study site obtained in the years 2012 to 2014 will be further evaluated to investigate the characteristics of the various measuring devices, to further examine the LISST PVC to SSC conversion factor described above and to quantify the sediment mass flux and PSD in the turbine water.

**Acknowledgements**
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**References**


Seasonal variations are characteristic for bio-geochemical processes on tide-dominated mid-latitude continental shelves. They are primarily caused by the seasonality of solar forcing that drives physical (e.g. weather conditions, thermal stratification, light) and biological (e.g. primary production) processes. Suspended Particulate Matter (SPM) concentration in the North Sea has a seasonal variation with high values in winter and low values in summer. Very often the seasonal pattern in wind and waves, with more storms in winter than summer, is put forward to explain the seasonality (Eleveld et al. 2008; Dobrynin et al. 2010). However, the decrease in SPM concentration corresponds well with the algal bloom. Measurements of particle size distribution (PSD), SPM and Chl concentrations from the Belgian nearshore area has indicated that the frequency of occurrence of macroflocs has a seasonal signal, while seasonality has little impact upon floc size (Fettweis et al. 2014). These data suggest that the maximum size of the macroflocs is controlled by turbulence and the available flocculation time during a tidal cycle, but the strength of the macroflocs is controlled by the availability of sticky organic substances associated with enhanced primary production during spring and summer. The data have highlighted the shift from mainly microflocs and flocculi in winter towards more muddy marine snow with larger amounts of macroflocs in spring and summer. The macroflocs will reduce the SPM concentrations in the turbidity maximum area as they settle faster.

Is the lower SPM concentration in the water column in summer compensated by a higher near-bed SPM concentration and by more frequent layers of fluid mud and vice versa in winter? To answer this question we have used 2300 tidal cycles of ADP and OBS data and 1235 of LISST data collected with a benthic lander in the Belgian nearshore area between 2005 and 2013. The ADP backscatter signal was calibrated with OBS data and was used to investigate the near-bed SPM concentration. The tidal cycles were classified according to their tidal amplitude and the seasons.
The results show that SPM concentration in the water column is lower in summer than winter. Near the bed, however, the seasonality is opposed with higher values during summer and lower ones during winter (Figure 1). With increasing distance from the bed the seasonal signal is decreasing and from about 1.8 m above the bed the SPM concentration is lower in summer than winter. The seasonality in SPM concentration differs during the different parts of a tidal cycle. Near-bed SPM concentration is higher at maximum currents (occurring at about 1 h before LW and around HW) during summer than winter, whereas at slack water (3 hours before and after HW) the near-bed SPM concentration is higher in winter. The normalized particle size distribution (PSD) for both season are shown in Figure 2. The data indicate the percentage of each LISST class in the total volume concentration. The highest frequency of large particles is observed during slack water – as expected. A clear difference between summer and winter occurs. During winter the difference between eb and flood is less pronounced. These findings are also visible in the averaged PSD in Figure 3, were we see that the volume averaged particle size is always lower in winter than summer.
Figure 1: Mean SPM concentration (g/l) profile (from about 0.5 to 2 m above bed) during a tide in winter (above left) and summer (above right). The difference is shown below; negative values point to higher concentration in summer. The black lines indicates a zero difference.

Figure 2: Normalized volume concentration (%) in the 32 LISST classes during a tide in winter (above left) and summer (above right). The difference is shown below; negative values point to higher relative concentration in summer. The black lines indicates a zero difference. The measurements have been taken at 2 mab.
The main conclusions are:

The SPM concentration in the water column is higher during winter than summer. This is in contrast with the lower 1.5 m, where the SPM concentration is higher in summer than winter.

The near-bed SPM concentration is higher during maximum currents in summer as compared to winter. During slack water the opposite is observed. The highest SPM concentrations occur during maximum currents in summer. This is explained by higher biological activity in summer, which results in a high concentration of sticky organic molecules (TEP), in more macroflocs, higher settling rates and in higher near bed SPM concentrations. This results in a reduced mixing of the SPM in the water column during summer than winter.

The lower SPM concentrations in the water column are compensated by higher concentrations near the bed. We argue therefore that the total mass of SPM in the area does not has a distinct seasonal signal in contrast with its distribution in the water column.


Acoustic inversion using two multifrequency profilers: the Aquascat 1000S and the TAPS

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1) Introduction

The multifrequency theory has recently been subject to several advances in the field of acoustical oceanography. Either to estimate zooplankton biomass and trophic activity (Holliday et al. 1989, Holliday and Pieper 1995, Lebourges-Dhaussy et al. 2013) or sediment size distribution and concentration (Crawford and Hay 1993, Thorne and Hanes 2002, Thorne et al. 2011), the use of multifrequency systems has steadily evolved in a concern to widen our vision of the oceans and rivers. Multifrequency inversion methods were thus developed in order to improve the ecosystem description and stock assessments (Greenlaw 1979, Holliday & Pieper 1995). Given a specific backscattering model that provides the acoustical signature of a particle (mineral or organic), several attempts were made to retrieve both concentration and size distribution of Suspended Particulate Matter (SPM) through Acoustic Backscatter System (ABS) in situ measurements. The present study focuses on the resolution of the inverse problem from acoustic multifrequency data, more precisely using the Non-Negative Least Square (NNLS) inversion algorithm proposed by Lawson and Hansen (1974), then used for swimbladder fishes by Johnson (1977) and later implemented in the method for zooplankton populations characterization designed by Greenlaw (1979).

In the vicinity of Moroccan coasts, a series of measurements was collected in a zone of high upwelling activity, using both an Aquascat 1000S (4 frequencies ABS ranging from 0.5 to 4 MHz) and a Tracor Acoustic Profiling System (TAPSTM - 6 frequencies ABS ranging from 0.26 to 3 MHz: the lower was discarded in the analysis due to malfunctioning) attached to the same downcasting structure. A complementary set of instruments was also present on the downcasting structure: LISST 100-X, CTD (Fluometer, Turbidimeter, Dissolved Oxygen).
The aim of the presentation is to assess the possibility to combine both instruments frequencies in order to obtain a better biomass and size distribution estimate of the organisms present in the water column via the NNLS algorithm. A preliminary work of comparison between similar frequencies from both instruments was a necessary first step.

If the TAPS is well known for zooplankton biomass measurement applications and qualified as a *zooplankton profiler*, the Aquascat 1000S, commonly known as a *sediment profiler*, is almost exclusively used to tackle suspended sediment related problems. Amongst a wide set of existing backscattering models (Stanton 1989, Stanton 1994), the Truncated Fluid Sphere model -TFS- (Holliday 1992), designed for copepods, was chosen given the physical context (upwelling zone) of the field study (S. Salah *et al.*, 2012).

**Methods**

A total of 50 profiles were collected using the TAPS and Aquascat mounted on the same down casting structure off the Moroccan coasts. Both instruments were located at the same level on the structure and looking horizontally in opposite directions.

The ABS data consist of the measurement of the volume backscatter ($S_v$) recorded at a precise depth. In order to assess the possibility of combining the instruments frequencies and performing the inversion on the entire set of acoustic data, we realized a pairwise comparison of the profiles obtained with similar frequencies by the two instruments.

The NNLS algorithm used to inverse the acoustic profiles is based on the hypothesis that the measured backscattered intensity is linearly related to the abundance of particles and organisms in presence into the sampled volume. The measured volume backscatter $S_v$ at the frequency $f$ can thus be expressed as follows:

$$S_v(f) = \sum_i \sigma_{bs}(a_i, f) * N_i$$

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<thead>
<tr>
<th>Frequencies compared</th>
<th>TAPS</th>
<th>Aquascat</th>
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<td>0.42 MHz</td>
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<td>1.1 MHz</td>
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Table 1: Couples of frequencies used for comparison of the measured
\( \sigma_{bs} \) being the theoretical backscattering cross-section of one particle with an equivalent radius \( a_i \) calculated at the frequency \( f \), and \( N_i \) being the abundance of particles with an equivalent radius \( a_i \), (count/m\(^3\)).

Given the measured \( Sv \) at several frequencies, the latter equation leads to a linear system that can be inverted, the abundance being the unknown of the problem. The NNLS method guarantees a positive outcome of the abundance by minimizing the residual error of the positive solutions. Using numerical methods (Lawson and Hanson 1974, Lebourges-Dhaussy 1996), this algorithm allows solving under-determined problems, i.e. in this case, problems where the number of size classes exceeds the number of frequencies in the equations system. This facilitates highlighting the main size modes. After characterization of the modes, the size range is finally divided into classes around the modes, with a number of modes no higher than the number of frequencies. Then, the calculated abundance vectors corresponding to the size vectors can be converted to concentrations or biovolumes and are summed within the size classes.

2) Results
   a) Inter-instrument closest paired frequencies correlation

   A typical example of the results derived from the inter-instrument comparison is shown in figure 1. \( Sv \) is varying accordingly to the structure of the water column and its composition. The correlation for the higher frequencies pairs (over 1 MHz) is good, ranging from 0.70 to 0.95 for most of the profiles, despite some artefacts that are assumed to come from heterogeneities observed by both instruments and differences in measurements smoothing. The correlation for lower frequency pair (0.42-0.5 MHz) is more difficult to evaluate. There is no apparent correlation between the pairwise values of \( Sv \) collected at those low frequencies. This phenomenon is observed in all profiles, and has to be related to the larger scatterers present in the water column.

Figure 1: Comparison of the behaviour or the measured \( Sv \) at similar frequencies for the same profile. From top to bottom, 0.5-0.42 MHz pair comparison, 1-1.1 MHz pair comparison, 2 – 1.85 MHz pair comparison and 4 – 3.04 MHz pair comparison. For each graph, the associated correlation coefficient between the two profiles is indicated in the right-hand corner.
b) Combined-instruments multifrequency inversion

The figure 2a compares the measured $S_v$ values with the TFS model output for the 9 frequencies combined. The more frequencies we use for the inversion, the harder it is to fit exactly the model: the latter becomes more and more constrained. On the figure 2a, there is good fit between the data (dots) and the model (curve) calculated for a possible zooplankton population resulting from the inversion algorithm: the possibility to find a plausible population from the 9 frequencies data, added to the overall good correlations observed in the upper paragraph, justifies the inter-instrument inversion attempt.

![Figure 2a](image)

**Figure 2:** From left to right: - a) Comparison between values of $S_v$ measured at the 9 frequencies with those predicted from the TFS model (small organisms) for a given depth. - b) Residual error of the inversion for each frequency for all depths (the 265 kHz TAPS frequency was dismissed due to malfunction). - c) Biovolumes calculated for all depths using the TFS model. The black dotted line locates the mixing layer. All the data shown are taken from the same profile as in figure 2.

In term of residual error (difference between the measurements and the volume backscattering calculated from the model for the estimated population), expressing the quality of the solution in term of biovolume, the model chosen provides particularly reliable results for the first 30-40 m of the water column (residual errors smaller than 0.1), after which the measured $S_v$ tends to deviate from the TFS model (figure 2b) for certain frequencies. The global residual error remains nonetheless low for the set of 9 frequencies, relatively to current maximum errors on the order of 1 that are obtained with 6 frequencies. Several attempts were made to find the best under-determination factor that provides the best fit to the model, the latter mostly depending on the SNR of the measurements (Lebourges-Dhaussy 1996). The results of such an inversion on an entire profile are given in figure 2c, where a clear dominance of organisms with an equivalent sphere radius of 2 mm is observed. For the first 20 m, bubbles created by the boat and the swell corrupt the acoustical data that are thus unusable, hence some high
residual errors for the first bins on figure 2b. The total biovolume calculated with 5 or 9 frequencies inversions are moreover consistent, and both vary in accordance with the fluorescence measurements and the thermocline location.

3) Discussion and conclusion

The comparison between the similar frequencies of both TAPS and Aquascat 1000S showed a good correlation, which enabled us to combine the instruments frequencies in order to perform an inversion. On the dataset we examined, the 9-frequency inversion (dual TAPS and Aquascat 1000S) reveals to be more efficient than a usual 5-frequency inversion for the first 40 meters of the water column. Below 40m, the measurements tend to deviate from the TFS model even if the residual errors still remain low. No deviation of the sort was noticed when using the 5 operating frequencies of the TAPS. Notably, the set of channels where the measured $S_v$ deviates from the model does not belong to the same instrument but is always spread between the two of them. A change of organism type may well explain the increase in residual error observed for deeper waters, consistently with the decrease in the quality of the fit between measurements and model predictions. Instead of a truncated fluid sphere, the fluid bent cylinder model (Stanton 1994) could yield better estimates of biovolumes. This potential ability to detect such a scatterer-specific signal with the 9 frequency inversion is encouraging for a separation of species, or even the distinction between organic and mineral particles.

A question to be raised concerns the calibration procedures of both instruments. Indeed, the Aquascat is calibrated according to the backscatter of a suspension of sediment perfectly known given the experimental results obtained by Betteridge et al 2008. As for the TAPS, it is placed vertically in a clear water basin and each transducer is calibrated independently in transmission and reception using three hydrophones. We have shown both instruments have a similar response when placed in the same environment, in spite of these different calibration procedures. Further attention should be placed regarding that matter as well as a possible smoothing of the Aquascat data compared to the TAPS ones.

Our data shows that both instruments provide consistent measurements, and a way to combine them is under examination to further obtain a more robust estimate of the size distribution and mass concentration of suspended particulate matter.
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References


The confounding effects of particle characteristics on acoustic backscatter measuring techniques

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The basic principles and techniques for using acoustic backscatter to measure the concentration of suspended sediment in water will be reviewed, and some recent developments in this area will be presented. The principal advantage of using acoustic backscatter is that concentration profiles can be estimated with high spatial temporal resolution a sufficient distance away from the instrumentation such that the flow and suspended sediment field is minimally disturbed in the region of the measurements. The principal challenge, and shortcoming of these techniques, is that inversion techniques are usually required to estimate the sediment concentration along the acoustic propagation path. The inversion is not very robust; rather it is sensitive to sediment characteristics, their spatial variations, the possible excessive attenuation of the signal, and the scattering and absorption of acoustic energy by air bubbles, particles, or objects other than those that are intended to be measured.

Some example of the successes and challenges of using acoustic backscatter in various environments and with various sediment characteristics will be presented. Much of the early progress in using acoustic backscatter for suspended sediment measurements was related to studying the temporal and spatial variations of well sorted sand suspended by surface gravity waves. More recently, acoustic backscatter techniques have been applied in a variety of natural aquatic settings and also in some industrial applications. Field and laboratory studies of the suspension of sand by waves have resulted in detailed examination of suspension processes, the relationships between suspended sediment and bedload, and the role of wave groups in enhancing local suspended sediment concentration. Single frequency backscatter has recently been used successfully to measure the concentration of suspended clay and sand in rivers. A theoretical explanation of how a single frequency backscatter system is capable of such measurements will be presented for a uniform concentration mixture of sand and clay. Finally, some recent progress in measuring flocculated sediments, such as those encountered in estuaries and brackish waters will be described.
An increasing demand on suspended sediment data is given for getting a better understanding of the sediment transport mechanisms in water bodies. However, the collection of suspended sediment data is still challenging, cost intensive and as consequence, numerous rivers and reservoirs are unrated or show gaps in the existing data. Where in most cases simple methods like taking physical samples or time integrated sampling are conducted, very few rivers are investigated by means of acoustic backscatter, laser diffraction, digital optical imaging or turbidity (Gray et al., 2010). One of the most sophisticated methods, the laser diffraction method (Sequoia Scientific Inc. 2011 and 2013) was already successfully used by the Department of Hydraulic and Environmental Engineering and its research partners in the rivers Danube (Hungary), Rhine, Elbe and Oker (all Germany) as well as in the reservoirs Angostura, Peñas Blancas, Sandillal (all Costa Rica) and in Wasserfallboden (Austria). All measurements were conducted from quasi-stationary vessels with the purposes of further investigation of suspended sediment transport in the rivers/reservoirs and in addition for allocating data which was further used as input for numerical simulations. Figure 1 shows e.g. the simulated depth averaged concentrations in the Angostura reservoir in Costa Rica during the wet season with the affiliated measurement points. The SSC are simulated with the 3D hydrodynamic model SSIIM (Olsen, 2012), which is directly coupled with a sediment transport model, A comparison of the results showed good agreement between the measurements and the simulation (Haun et al., 2013).
During the above mentioned field campaigns the LISST-SL instrument was used predominantly. It is streamlined, needs no calibration and samples iso-kinetically correct due to the implemented pump, which is regulated based on the measured flow velocity by built in pressure sensors (Agrawal et al., 2011). The device measures time averaged characteristics of the suspended sediment concentration (SSC) and of the particle size distribution (PSD) in real time. The measurement time per measurement point was usually set between 1 and 2 minutes. An evaluation of SSC and PSD (mainly the $d_{50}$) within the Peñas Blancas reservoir in Costa Rica is presented herein. Results are shown for measurements during low and high flow conditions, where the discharge increased from about 22 m$^3$/s to 142 m$^3$/s. The SSC shows for the high flow conditions about 30 – 40 times higher concentrations.

One of the few known disadvantages of using a LISST device for an evaluation of larger river reaches or reservoirs is that the LISST is limited to point measurements, only. This may lead to a time consuming field campaign in cases where e.g. detailed profiles over the depth are needed.

Therefore, a profiling method is presented herein for the evaluation of SSC in a water column. The method is based on the evaluation of multi-frequency acoustical backscattering data (Guerrero et. al, 2011). The advantage of using an acoustic backscatter method is that due to an indirectly quantification of the SSC a detailed spatial pattern of the SSC and the average
grain size can be achieved within the same time. In this study, a method using two ADCPs working at different frequencies (600 and 1200 kHz) is presented. The method was already successful tested in a tower tank at the laboratory in Bologna (Guerrero et al. 2012) and further validated in a research flume at the Hydraulic Laboratory at the Norwegian University of Science and Technology in Trondheim (Guerrero et al. 2014). The results of an investigation presented herein are the quantification of the SSC and the average grain size in the river Danube (Hungary) in several points along two cross sections. In the investigated transect, the Danube can be considered as free-flowing with a mean flow of 2000 m$^3$ s$^{-1}$ (Baranya et al., 2012), with an average width of about 500 m and an average depth of about 6 m. The measurements were performed during a 1-year flood event. In addition to the multi-frequency acoustical backscattering evaluation, LISST-SL device was used for a comparison of the results. The measurements were conducted along two transects, where in one transect 5 verticals and in the other one 7 verticals were measured. Figure 2 shows the configuration and facilities for the measurement campaign at the river Danube in Esztergom, Hungary. The measurements were conducted as stationary measurements from an anchored vessel, where time averaged characteristics were collected with the ADCP over the water column and with the LISST-SL in different depths.

![Figure 2: Measurement facilities during the field campaign at the river Danube in Esztergom, Hungary](image)

The results of the LISST-SL measurements showed a rather uniform distribution over the depth, with a major part of medium and coarse silt and with only slightly coarser sediments close to the river bed. The PSD measured by the LISST-SL is shown in figure 3.
The measurements with the multi-frequency ADCP were conducted simultaneously and were evaluated in the same depths as average concentration and particle size for each meter in depth. The investigated results showed good agreement compared to the LISST-SL measurements in the range between 86–200 μm in several depths and in several verticals along a cross section, which corresponded to the suspended sediment from the river bed, i.e., with larger concentrations near the bottom.

Due to a fast and efficient development of new measurement devices, it will be in the future possible to increase the amount of information, which can be collected during a field survey. However, also if previous conducted studies showed that an extensive field survey with the LISST is time consuming, information regarding the PSD over the whole range of grain sizes will be available.

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References


**Particle size and its influence of fluxes through an estuary**

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**Introduction**

As part of the wider NERC (Natural Environment Research Council) Macronutrients programme, we aim to examine sedimentary processes and their impact on nutrient fluxes and pathogen survival through an estuary. Nutrients and pathogens become incorporated into particles (Fugate and Friedrichs, 2003) as they travel down the river; thus, unravelling what happens to those particles within an estuary becomes a key issue, determining how much pollution reaches the ocean.

As fine particles enter an estuary, they begin to flocculate when they encounter salt water (Jay et al., 2007). The larger particles settle more quickly to the bed, to be carried back up-stream with the estuarine circulation. Further up-stream, where the turbulence is greater as the channel is narrower, the particles are broken up and re-mixed throughout the water column. Thus the net transport of particles is complicated by this pattern of flocculation, disaggregation and turbulence. In this study, we aim to: 1) examine the influence of along-channel turbulent kinetic energy on the mean particle size; 2) examine the net flux direction of different size classes of particles. We hypothesise that larger, faster settling particles will be imported up-river with the estuarine circulation at the river bed while smaller, slower settling particles will, potentially, be exported (Figure 1). Also, we speculate that tidally-averaged particle size will become smaller up-river where the turbulence is stronger (see Figure 1).
Methods

Moorings, consisting of a LISST-x, ADV (Acoustic Doppler Velocimeter), CTD (Conductivity Temperature Depth) and ADCP (Acoustic Doppler Current Profiler), have been deployed on four occasions between 2013 and 2014 in the Conwy estuary and tidally-influenced river. Tal Y Cafn (TYC) is located in the estuary and is subject to large semi-diurnal variations of salinity (20-30 psu) and water depth (4.5 m) at springs; Dolgarrog (DOL) is located further up-stream and is subject to only small semi-diurnal variations in salinity (1-3 psu) but has a 3 m tidal range. Each site was manned for two consecutive days to supplement the mooring data with water column profiles and water samples. Transects, from DOL to the estuary mouth, were also conducted once on each deployment at high water to obtain water column profiles and water samples.

Turbulent kinetic energy (TKE) dissipation rate ($\varepsilon$) has been calculated using the structure function (see Wiles et al., 2006) and inertial dissipation methods (see Voulgaris and Trowbridge, 1998). Tidal fluxes were calculated using a combination of moored LISST-x data, profiling LISST data and ADCP/ADV data. Fluxes were calculated as:

$$V = \int_{t}^{T} \int_{0}^{h} u(z)c(z)dzdt$$

where $u(z)$ is major-axis velocity variation with height $z$ above the bed, $c$ is the concentration of suspended sediment, $h$ is water depth, $T$ is the tidal period used to calculate the net flux and $t$ is time. Where only near-bed sediment concentration is used from the moored instruments, the vertical profile has been assumed to be constant though we recognise this is not the case in reality.
Results

Along-channel particle size does appear to increase with distance toward the coast. Transect measurements acquired around high water indicate that smaller particles are found at DOL than at the estuary mouth. Comparing tidally-averaged TKE dissipation rates between two sites (Figure 3a), DOL and TYC (TYC being further seaward with a wider channel than DOL), we find that the narrower site contains more TKE than the wider one. In contrast to our theory, the narrower site with higher TKE does not have lower tidally-averaged particle sizes. Over the course of a spring-neap cycle, the average mean particle sizes at both sites are approximately equal. We do, however, find larger particle sizes toward the coast when transects are performed at high water from DOL to the estuary mouth.

In contrast to our hypothesis pertaining to fluxes, we find that the net transport of medium-large particles is out of the estuary at TYC whilst small-medium particles are imported (see Figure 15a). Calculations using the moored LISST provide a similar pattern (not shown here). However, we find that at DOL (Figure 15b), where semi-diurnal salinity variations are smaller, there is predominantly a net flux of small-medium sized particles up-river. Moored LISST-derived fluxes for this site provide a slightly different picture with a negative net flux (export) of particles greater than 157 µm.
Discussion and Conclusions

As the fluxes we observe show a different trend to those hypothesised, we examine phase-averaged spring tides from each site (Figure 16). Data from TYC indicate that small to medium sized particles are suspended on the flooding tide and early ebb (Figure 16, left panels); on the late ebb as the saline front passes, a high concentration of particles with a large size (D = 238 µm) is observed. It is interesting to note that during the period of intense dissipation near the bed on the ebb at TYC there is a decrease in sediment concentration. Due to this cycle of resuspension and flocculation, the net flux per particle size is calculated as being opposite to our theory: smaller particles are imported and large ones are exported. Similarly at DOL (Figure 16, right panels), a high concentration of small-medium sized particles is resuspended on the flood while medium to large particles are resuspended on the ebb. Again this provides the opposite pattern of net fluxes to that expected from estuarine circulation theory.

The vertical profiles of fluxes, calculated using LISST profiles, indicate different net flux orientations at both sites. At DOL, LISST-derived fluxes are predominantly landward at all depths whilst at TYC they are predominantly seaward. However, fluxes calculated via calibration of ADCP backscatter signals (to provide an estimate of the suspended particulate matter concentration) yield a result which suggests there is an import of sediment near the bed and an export further toward the surface. Similarly, there is some disagreement between ADCP-derived, moored-LISST-derived and moored-CTD derived fluxes over a spring-neap cycle; for the most part net flux orientations agree though on occasion they do not. However,
in the case of the moored instrument-derived fluxes, differences may be due to height variations of data collection. These differences in flux orientations from different instruments require further analysis.

In terms of along-channel particle size, the transect measurements are, most likely, misleading. Transects were obtained by using a boat to sample at 10 stations from DOL to the estuary mouth, starting the transect slightly before high water at DOL and finishing at the mouth just over an hour later. The phase-averaged measurements (Figure 16) indicate that the maximum particle size observed occurred 10-30 minutes after high water suggesting any profiles obtained prior to or at high water may be smaller. High water at the mouth is approximately half an hour before that at DOL so by the time the boat reached the mouth, it is likely that the mean particle size had started to decrease. Additionally, the average mean particle at both sites is approximately equal over a spring-neap cycle. Thus, there is no clear evidence here that particle size is larger at a less turbulent site.

Figure 16 – Phase-averaged TKE dissipation rates (top panels) calculated via the structure function method with ADCP data and volume concentration per particle size (bottom panels) from the moored LISST-x relative to high water (t = 0) in September 2013. The panels on the left are for TYC, while those on the right are for DOL.

References


Turbulence control of floc size in suspended particulate matter (SPM) in the river estuary transition zone (RETZ)

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The majority of terrestrially derived suspended particulate matter (SPM) is transported to the open ocean by rivers, therefore the river estuary transition zone (RETZ) represents a globally significant boundary separating the riverine and coastal regimes. The RETZ is comprised of the Tidally-Influenced River (TIR), found above the limit of salt intrusion and the upper part of the estuary including the Estuarine Turbidity Maximum (ETM). The fate of SPM in the RETZ depends on its physical properties which are likely to be extremely variable in the RETZ which is characterised by large temporal and spatial gradients in hydrodynamic properties. Therefore, quantifying SPM properties in relation to physical forcings is key to determining the transfer flux of SPM and associated biogeochemical components from the catchment to the coastal ocean. This study aims to identify the role of turbulence in determining particle properties and how the origin of SPM can affect this relationship.

SPM is commonly observed as collections of particles known as flocs. Flocs are fragile in nature and their properties fluctuate on short spatial and temporal scales; therefore observations of floc development require high resolution data and non-invasive techniques. Two mooring configurations were deployed in the RETZ. *In situ* optical instruments (LISST-100X and transmissometers) were deployed to obtain particle size distributions, volume concentrations and mass concentrations of SPM, thus providing floc effective density. The hydrodynamic parameters were determined via acoustic methods using ADCP and ADV instruments. TKE dissipation rates were calculated via the structure function method using ADCPs. This enabled the direct comparison between near-bed floc properties and local turbulence in the RETZ. Data was collected over one spring to neap cycle for 5 periods during two years, thereby allowing the opportunity to sample a large range of tidal and river discharge conditions in addition to seasonally variable biological conditions.

Diurnal and semi-diurnal signals in floc properties in the RETZ were observed: resuspension occurred at peak tidal flows, usually on the flood tide; the maximum floc sizes corresponded with minimum effective densities and largely corresponded with high water, as a result of particle flocculation during low turbulence conditions.
Turbulence dissipation did not simply scale on tidal current velocities due to the additional contribution of wind stress and direction to the turbulence field. The Kolmogorov microscale did not represent a clear upper limit for floc growth when considering multiple tidal cycles, however analysis on a tidal scale indicates terrestrially derived SPM and SPM of a marine origin display differing relationships with the local turbulence regime. The Kolmogorov turbulence microscale correlated significantly with floc size during periods of marine conditions (i.e. the flood and early ebb tides) but showed a variable relationship during the late ebb when the RETZ was dominated by fluvial conditions and particles. This was most evident in the ETM where marine influence was greater compared to the TIR where it occurred only on larger tides. Thus floc size was related to the turbulence microscale but differences between flood and ebb relationships were most likely due to different floc strengths of marine and terrestrial particles. During the lunar cycle, the variations observed on springs were repeated on neaps except that the flocculation signal occurred late in the flood rather than at high water. These tidal and lunar variations of particle properties in the RETZ were observed at all seasons.

The RETZ is a complex and challenging environment to study however it is essential to gain understanding and quantify the relative importance of hydrodynamic and biological implications controlling SPM characteristics and thus the fate of the transfer of terrestrially derived organic matter to the coastal ocean.
SPM dynamics related to tidal straining in a Region of Freshwater Influence.

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The coastal boundary zone constitutes a transition zone which all particulate biogeochemical components derived from the land must traverse if they are to enter the shelf seas. Exchanges and fluxes across this boundary zone govern water quality and ecosystem sustainability in shelf seas. Biogeochemical components are attached to suspended particulate matter (SPM) so the properties and flux of SPM are important in this context; biogeochemical components can escape the coast only if SPM moves seawards through the coastal boundary zone. Since most particulate matter from the continents reaches the coast via rivers, particles must escape Regions Of Freshwater Influence (ROFIs) before they enter the shelf sea environment proper.

Observations of turbulence dissipation $\varepsilon$ (using a FLY profiler) and SPM properties (using LISST 100) in the ROFI of Liverpool Bay, Irish Sea show that SPM dynamics and flux are strongly influenced by asymmetries deriving from tidal straining. Vertical profiles over spring and neap tidal cycles were made at a site in 35m water depth; horizontal gradients were determined from 2 supplementary moorings adjacent to the primary site. The vertical structure of $\varepsilon$ shows $M_4$ periodicity in the lower part of the water column but $M_2$ periodicity in the upper part with the transition at c.5 and 15 mab on a neap and spring tide, respectively. Harmonic analysis of velocity $u$ and $\varepsilon$ shows that the $M_4$ phase corresponds to peak flow and the $M_2$ phase to peak flood, indicative of flood-ebb asymmetry with peak $u$ and $\varepsilon$ on the flood. The ratio of $M_2$ to $M_4$ amplitudes is a measure of asymmetry: for $u$ the ratio reduces upwards from the seabed, for $\varepsilon$ it increases upwards. The increased asymmetry of the turbulence field is due to flood turbulence generated as the potential energy anomaly caused by tidal straining is eliminated. The SPM field is due to resuspension superimposed on a lateral gradient. The concentration of coarse particles (>40$\mu$m) is much greater than the concentration of fine particles. Resuspended coarse particles are moved upwards by enhanced flood turbulence, where they are entrained by faster currents and moved eastwards along the tidal stream. The net mass flux of SPM due to this tidal pumping is nearly a half of the net point flux. Tidal
straining also creates a barotropic flow on the flood which is normal to the tidal stream and which in turn causes a net southwards SPM flux; in this case the contribution of tidal pumping is negligible. Because of the geometry of Liverpool Bay, both eastward and southward net SPM fluxes are towards the coast. These observations suggest that, within the confines of the ROFI, and in the absence of other mechanisms, there is no seawards escape for the coarser components of SPM.
Schlieren effects in beam transmissometers and LISST-Deep observed in the stratified Danube River delta, NW Black Sea

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Abstract
The term ‘schlieren’ describes angular deflection of a light ray when it passes through a fluid region characterized by refractive index inhomogeneities. These inhomogeneities in the marine environment are generally caused by density variations, i.e. salinity and temperature anomalies. The influence of schlieren on transmissometers and the in situ particle sizer LISST-Deep of Sequoia Scientific are examined in the Danube delta during October 2007. A seasonal pycnocline driven mainly by an intense temperature gradient was identified as a major hydrological feature. Measurements of two 25-cm path-length transmissometers (660 nm and 470 nm) showed distinguishable peaks at the pycnocline. LISST also uses a 5-cm transmissometer (670 nm), which proved to be very sensitive in both cases. This is mainly due to its very small acceptance angle, which enables enhanced light scattering outside the lens, thus increasing beam attenuation. Subsequently, LISST falsely predicts abundance of large particles within the pycnoclines. A buoyancy frequency of 0.01 s$^{-1}$ is the estimated threshold for schlieren, lower than previous estimations.

1. Introduction
Gradient disturbances of inhomogeneous transparent media due to small refractive index differences are described by the term ‘schlieren’ (Töpler, 1867; Schardin, 1942). These inhomogeneities are generally caused by density variations; in the marine environment primarily by salinity and temperature anomalies (Karpen et al., 2004). In deltaic systems, density stratification due to surface heating (and fresh water/salt water mixing) is
commonly observed. Styles (2006), in flume experiments, demonstrated that density gradients cause small angle forward scattering patterns that are indistinguishable from particle scattering. Beam attenuation is one of the inherent optical properties (IOP; properties that depend only on the water and other substances that are dissolved or suspended in it) measured routinely for many decades, and schlieren may affect the behavior of instruments measuring light scattering and transmission. Andrews et al. (2011) conducted similar experiments in oligotrophic waters and identified that schlieren results in dramatic underestimation of small (<20 μm) particles. This contribution aims to study the schlieren interferences in two commercial beam transmissometers and a third one, which is part of the particle sizer LISST-Deep (Laser In Situ Scattering and Transmissometry; Agrawal and Pottsmith, 2000). The dataset assessed was obtained in the Danube River delta, during October 2007 in the framework of SESAME-IP Project.

2. Regional setting

The Danube River’s delta is the largest in the Black Sea and covers 5800 km² (Panin, 1999). At the head of the delta, also referred to as ‘Mile 44’, the Danube River splits into Chilia (length 116 km) and Tulcea branches, and the latter bifurcates ~17 km downstream into the Sulina, and Sfantu Gheorghe branches, 63, and 109 km in length, respectively (Fig. 1). During the period of the cruise, in October 2007, water discharge was 4980 m³ s⁻¹ and suspended solids (SS) load 197 kg s⁻¹, the latter corresponding to SS concentration of 40 mg l⁻¹.

3. Materials and methods

Measurements derive from a cruise of the R/V AEGAEIO in the Danube delta (NW Black Sea), in the period 5-12 October 2007. In total, 17 stations were occupied at shallow depths (10-53 m) in the Danube delta area (Fig. 1).

Standard CTD measurements were obtained with a Sea-Bird Electronics 11plus CTD interfaced with a General Oceanics rosette with twelve 10-litre Niskin bottles. Light transmission was measured by two 0.25-m path-length transmissometers emitting at 470 nm-blue (Chelsea ALPHAtracka MKII, acceptance angle 0.91°) and 660 nm-red (WET Labs C-Star, acceptance angle = 1.2°).

Particle volume concentration, and particle-size distribution is measured by 32 ring-detectors (the inner rings detecting the largest particles and the outer rings detecting the
smallest), corresponding to 32 classes in the range 1.5-250 μm were determined with an autonomous LISST-Deep, which also measured beam attenuation, $c$ at 670 nm-red (Agrawal and Pottsmith, 2000). The major difference of LISST-Deep and the more widely used LISST-100X is the special aluminium housing, which allows deployment to 3000 m depth, whereas the 100X is limited to sampling down to 300 m depth. The wavelength of the WET Labs C-Star and LISST-Deep are nearly identical, but the acceptance angles are very different. The differences in the pathlengths of the two instruments is equalized in determining $c$ from the raw output of the instrument.

Finally, a sonar altimeter was coupled with the CTD, providing accurate distance from the bottom, and thus enabling measurements to within 1–2 m of the seabed. Sensors were factory calibrated prior to the cruise. Optical windows were rinsed with MilliQ water and wiped carefully prior to each cast. All data were routinely binned into 1-dbar intervals after quality control of raw data.

4. Results and discussion

4.1. Hydrology

The surface waters (3-dbar) near the Danube delta area are characterized by temperatures ~18 °C and salinities between 8.5 and 14, and form a narrow belt near the coast. At Chilia (northern branch) relatively colder waters extend towards the north, probably influenced by freshwater of other rivers discharging in the area. Offshore, both temperature and salinity increase gradually, with the highest values recorded SW of the delta (19.7 °C and 17.5, respectively). According to Karageorgis et al. (2009), the preferred water and particle transport pathway, when northerlies prevail, is along a narrow strip near the coast, with a south-southwest direction. As northerlies prevailed prior and during the cruise in October 2007, this pattern appears to be dominant.

The water column near the coast exhibits two pycnoclines, the upper at 5-7 dbar and the seasonal approximately between 19 and 24 dbar (Figs. 2a, b). The upper pycnocline is observed at stations near the coast (e.g. SGT2) and is associated with the low salinity freshwater inputs from the Danube River (Fig. 2a). The second pycnocline is attributed to the overall warmer surface Black Sea layer (19.2-20.4 °C), which overlies cooler, more saline waters characteristic of the cold intermediate waters of the Black Sea (Figs. 3a).

4.2 Optical measurements
Profiles of the three transmissometers used in the survey for Station SGT2, which represents the coastal area near the mouth of the Danube (Fig. 2b), reveal that $c_{660}$ and $c_{470}$: (a) decrease rapidly with depth but do not exhibit any peak at the upper pycnocline; (b) show a small increase between 11 and 19 dbar; and (c) gradually decrease in the lower pycnocline (18-23 dbar), and then increase gradually in the uniform bottom 20 m.. In contrast, the 5-cm path-length transmissometer of LISST ($c_{670}$) shows a clear peak in the upper pycnocline (8.81 m$^{-1}$), a prominent peak at 19 dbar (21.5 m$^{-1}$), and a distinct secondary peak at 21 dbar (9.8 m$^{-1}$); below the pycnocline, $c_{670}$ measurements reach background values. Note the 6-8 times difference in $c_{\lambda}$ scales.

Similar observations at Station KT, which characterizes the offshore area of the Danube delta, show almost constant temperature (20.15-20.17 °C) and salinity values (17.51-17.55) from surface down to 27 dbar,. Between 27 and 38 dbar a pronounced pycnocline is developed, due to a severe temperature decrease (from 20.15 °C to 10.31 °C) despite a slight increase in salinity. The optical instruments in this case are all showing peaks centered at 36 dbar pressure ($c_{660} = 0.59$ m$^{-1}$; $c_{470} = 0.38$ m$^{-1}$; $c_{670} = 9.6$ m$^{-1}$). Overall, at all stations occupied where a deep pycnocline was developed, transmissometers were influenced by multiple light scattering - schlieren.

The main reason causing schlieren is density gradient(s) (a function of temperature, salinity and pressure) which have varying refractive indices, thereby causing light scattering (Styles, 2006). However, the different behavior of transmissometers in inhomogeneous transparent media is also dependent on the acceptance angle of the instrument (Boss et al., 2009).

In order to assess the effect of stratification, the buoyancy frequency or Brunt-Väisälä Frequency, $N$, was computed according to the equation:

$$N = \sqrt{-\left(\frac{g \frac{\partial \rho}{\partial z}}{\rho \frac{\partial \rho}{\partial z}}\right)}$$

where $g$ is the gravitational acceleration, $\rho_0$ is the average density during the period the station was occupied, and $\partial \rho/\partial z$ is the vertical density gradient. Also, for the calculation of the refraction index of seawater, the empirical equation of Quan and Fry (1995) was used:

$$n(S,T,\lambda) = n_0 + (n_1 + n_2 T + n_3 T^2) S + n_4 T^2 + \frac{n_5 + n_6 S + n_7 T}{\lambda} + \frac{n_8}{\lambda^2} + \frac{n_9}{\lambda^3}.$$
where $S$ is the salinity in‰, $T$ is the temperature in degrees Celsius and $\lambda$ is the wavelength in nanometers (here 670 nm). The coefficients have the following values:

$$
n_0 = 1.31405, \quad n_1 = 1.779 \times 10^{-4}, \quad n_2 = -1.05 \times 10^{-6}, \quad n_3 = 1.6 \times 10^{-8}, \quad n_4 = -2.02 \times 10^{-6}, \quad n_5 = 15.868,$$

$$
n_6 = 0.01155, \quad n_7 = -0.00423, \quad n_8 = -4382, \quad n_9 = 1.1455 \times 10^{-6}.
$$

In the case of the coastal station SGT2, maximum $N$ was estimated to be 0.080 s$^{-1}$, whereas for the offshore station KT, maximum buoyancy frequency was 0.068 s$^{-1}$. The highest value recorded in the Danube delta area was 0.082 s$^{-1}$, at Station RNT2 at 23 dbar depth. Mikkelsen et al. (2008), found maximum values of $N$ 0.22-0.24 s$^{-1}$ in the strong pycnocline of the Hudson River, which was related to great variability of both temperature and salinity. The same authors, found $N$ to be an order of magnitude lower (~0.03 s$^{-1}$) in Cardigan Bay in the Irish Sea, UK, and concluded that buoyancy frequencies exceeding 0.025 s$^{-1}$ could be considered as the threshold for schlieren influence. Apparently, $N$ maxima recorded in the Black Sea are ~3-fold higher than the suggested threshold, thus schlieren artifacts affect the measurements in pycnoclines. However, the threshold where buoyancy frequency increases (Stns. SGT2 and RNT2) is ~0.01 s$^{-1}$, suggesting that schlieren may be triggered at lower $N$ than the values proposed in the literature. Since buoyancy frequency is a function of salinity, temperature, and pressure, it is possible that one or more of the three variables can play a leading role in the formulation of the optical data sets.

Comparing the three transmissometers used in the Danube delta survey, it may be deduced that acceptance angles play a primary role in distortion of light scattering in pycnoclines, in agreement with the findings of Mikkelsen et al. (2008) and Boss et al. (2009). The acceptance angles of WET Labs C-Star, Chelsea ALPHAtracka MKII, and LISST-Deep transmissometers are 1.2°, 0.91°, and 0.0269°, respectively. In practice, if light is scattered between 0.0269° and ~1°, it will not be detected by LISST-Deep, thus increasing $c_{670}$, but it will fall inside the acceptance angle of the other transmissometers, leaving $c$ unaffected. Our measurements show that LISST's $c_{670}$ is much more sensitive in stratified waters, with maximum values >21 m$^{-1}$. The other two transmissometers were also influenced, but to a lesser extent. This is in agreement with Boss et al. (2009) who compared the performance of eight different commercial transmissometers; their mean attenuation values differed markedly and in a consistent way with instrument acceptance angle: smaller acceptance angles provided higher beam attenuation values.
4.3 Schlieren side effects

Beam attenuation coefficient is not the only IOP affected by schlieren. LISST-Deep volume scattering function (VSF; a fundamental IOP that characterizes the intensity of scattering as a function of angle) measurements appear artificially increased in pycnoclines. Likewise, total volume concentration (VC) and median particle size ($D_{50}$) measurements obtained from the LISST are biased. At Station SGT2 below the upper pycnocline (Fig. 2a), VC varies between 2 and 3 μl l$^{-1}$, and rapidly increases to 218 μl l$^{-1}$ within the lower pycnocline. Similarly, $D_{50}$ varies between 20 and 30 μm, and then in the lower pycnocline shows great variability (120-190 μm), the latter being artificial particles due to schlieren. At Station KT, in the homogeneous upper part of the water column (Fig. 3a) VC varies between 3 and 4 μl l$^{-1}$, $D_{50}$ varies from 37 to 63 μm, and within the pycnocline fluctuates abruptly between 40 and 220 μm. Similar patterns are observed at all stations where a pycnocline was developed.

It is notable that at Station SGT2, where $N$ and $c_{670}$ in the pycnocline are amongst the highest of the data set, $c_{660}$ and $c_{470}$ do not exhibit similar peaks, compared to Station KT (Figs. 2b, 3b). The refraction index of seawater (at 670 nm) changes slightly within the pycnocline from 1.334 to 1.335 at both stations. Changes of the refractive index $n$ should exist in parallel with turbulence at that depth to develop buoyancy frequency variations and consequently to trigger schlieren. However, changes of $n$ are not necessarily related to buoyancy frequency variations, but if turbulence is included, then schlieren may be triggered (Mikkelsen et al., 2008). Station SGT2 shows high $c_{670}$ (21.5 m$^{-1}$) when compared to Station KT (9.8 m$^{-1}$), although $N$ and index of refraction are virtually equal. According to Andrews et al. (2011), smaller particles, which are dominant at Station SGT2 may be more affected by schlieren, thus explaining this pattern.

5. Conclusions

Beam attenuation ($c_{660}$ and $c_{470}$, in m$^{-1}$) measurements of two commercial transmissometers and the particle sizer LISST-Deep were evaluated in the light of ‘schlieren’ disturbances, caused by density discontinuities in waters off the Danube delta. Shallow coastal stations’ hydrology appeared to be affected mainly by the freshwater (low salinity creates the upper pycnocline) inputs from the Danube River, and offshore deeper stations were influenced by the temperature-driven deeper pycnocline. The optical measurements of the two 25-cm path-length transmissometers were unaffected within the salinity-controlled
pycnocline, but conversely they exhibited peaks within the deeper temperature-controlled pycnocline. LISST-Deep uses the principle of laser diffraction to provide measurements of particle size distribution using a 5-cm (670 nm) transmissometer. The latter instrument was substantially affected by schlieren within both types of pycnoclines: (a) \( c_{670} \) was an order of magnitude higher than \( c_{660} \) and \( c_{470} \); (b) particle volume concentration increased abruptly; and (c) an artificial abundance of large particles was recorded. The transmissometer of LISST-Deep has a very small acceptance angle, thus beam attenuation increases; the other transmissometers with higher acceptance angles show small, but identifiable deviations only in the temperature-controlled pycnocline. The maximum buoyancy frequency within the pycnocline was 0.082 s\(^{-1}\), higher than the threshold for schlieren appearance according to the literature, causing variability to the index of refraction of only 0.001. The threshold of \( N \) in the Black Sea cruise was estimated to be 0.01 s\(^{-1}\), more than 2-fold lower than values suggested in the literature. Caution is suggested when interpreting data from transmissometers or LISST instruments in high density gradients. In such cases, the LISST artifacts cannot be avoided, but they can be assessed and removed manually after the estimation of \( N \), and comparison with threshold values. Ideally, an underwater video profiler (Gorsky et al., 2000) or other floc cameras (e.g. Mikkelsen et al., 2006; Picheral et al., 2010) could provide useful information in order to resolve the issue of the presence of large particles in strong pycnoclines.

6. References


Figure 1. Study area location map and sampling stations (red dots). Red dashed line indicates national borders. The Danube River main branches are (1) Chilia, (2) Sulina, and (3) Sfantu Gheorghe. Black star: gauging station ‘Mile 44’.
Figure 2. (a) Water-column profile (Station SGT2) of salinity, temperature and density (sigma-theta) showing the two pycnoclines characteristic of the coastal area surrounding the Danube delta; (b) transmissometer profiles of WET Labs C-Star (path-length 25 cm) beam $c_{660}$, Chelsea ALPHAtacka MKII (25 cm) $c_{470}$, and $c_{670}$ from LISST (5 cm).
Figure 3. (a) Water-column profile (Station KT) of salinity, temperature and density (sigma-theta) showing the deep pycnocline characteristic of the offshore area surrounding the Danube delta; (b) transmissometer profiles of WET Labs C-Star (path-length 25 cm) beam $c_{660}$, Chelsea ALPHAtacka MKII (25 cm) $c_{470}$, and $c_{670}$ from LISST (5 cm).
Figure 4. (a) Water-column profile (Station SGT2) of index of refraction and Brunt-Väisälä frequency ($N$). Vertical dashed line indicates the proposed $N$ threshold; (b) LISST-Deep profiles of particle median diameter $D_{50}$ and particle volume concentration VC.
Figure 5. (a) Water-column profile (Station KT) of index of refraction and Brunt-Väisälä frequency; (b) LISST-Deep profiles of particle median diameter $D_{50}$ and particle volume concentration VC.
Particle dynamics in the marine environment - examples of measurements from NW Australia

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1. NW Australia - physical setting and industrial development

The NW Australian continental margin is underlain by an intricate hydrocarbon-bearing geology, variable bathymetry, and a suite of marine sediments whose textural and bulk characteristics (including non-cohesive, friable carbonates, mobile sedimentary bedforms and extensive mass-failure deposits) provide considerable engineering and environmental challenges to the expanding range and number of marine developments. Further, the region experiences a wide variety of periodic, seasonal and episodic meteorological and hydrodynamic processes, such as: tidal regimes with ranges up to 12 m, seasonal winds and swell waves, high amplitude internal waves (e.g. internal tides and solitons) and an average of around 5 cyclones per Austral summer. River sediments are only supplied to the coast on a seasonal basis, and have largely been held close to the coastline throughout the Holocene. These factors combine to produce a highly complex and dynamic continental margin in terms of sediment transport.

Measurements of sediment transport in the region are in their relative infancy, but are advancing because of the increasing understanding of their relevance for a suite of research, management, and practical applications. Use of these measurements is hampered by a lack of historical data, due to the region’s remoteness. This lack of information is in stark contrast to the rapidly expanding number, range and magnitude of developments on the continental margin. These developments are largely related to production from offshore hydrocarbon fields and the construction of export facilities for minerals. They involve activities such as dredging of harbours and long shipping channels, and the construction and emplacement of structures including harbour walls, jetties, breakwaters, pipelines, gravity-based platforms and floating processing facilities, especially for Liquid Natural Gas (LNG).

This paper outlines the need for high-quality sediment transport science and describes examples of the use of optical measurements of sediment transport processes and their application to developmental issues.
2. The range of sedimentary information required

Understanding sediment transport is an implicit requirement of many aspects of work required to support development and regulatory activities based on sound science. Examples pertinent to NW Australia, but of broad relevance, include:

- Bedload sediment transport. This relates to part of familiar assessments of shoreline change, but also to sea-bed stability of emplaced structures, such as wellheads, and to instability of sea-bed pipelines. Erosion beneath pipelines can cause pipeline spans and increase the chance of failures. Sediment dynamics around pipelines is particularly complex and is an area of ongoing applied research.

- Water quality in the water column. As well as relating to ‘traditional’ environmental aspects, such as the effects of sedimentation and light regimes on benthic organisms, the upcoming emplacement of a series of Floating Liquid Natural Gas (FLNG) facilities is relevant. The FLNG vessels can be 400-500 m long and 75 m wide, and are moored in water less than 150 m deep. They require the continuous intake of cooling water at rates of 12 cumecs for 20-30 years, so understanding the minerogenic and biogenic particulate dynamics in the water column is critical to their design and operation. The influence of permanent and seasonal stratification, internal waves and biological production makes such understanding essential.

- Dredging. There are an expanding suite of dredged channels across the inner shelf of the North West Shelf, for which assessments are made of potential environment and engineering impacts, incorporating major measurement programs of sediment transport. These channels are generally around 150 m wide, may extend up to 30 km in length and are located near to a variety of benthic habitats. They represent a major long-term experiment regarding bedload transport.

- Visibility. Low visibility at the seabed can hamper some ROV operations on construction and maintenance, and paying for unplanned downtime can costs 100,000’s dollars per day. It is advantageous to the major companies to understand how much downtime to write into the contracts they let so that budgets can include potential extended periods of unworkable conditions. Research is active on this at present.

At present, there is scope to improve the application of appropriate knowledge, measurements and interpretation of sediment transport in Australian waters.
3. Case study: seasonal water quality variations

In parts of the NW Australian margin, seasonal thermal stratification is strong, and influences the dynamics of biogenic and minerogenic particles. At some sites, strong tidal currents (up to 0.65 m/s at 5 m above the bed) and abundant sediment on the seabed lead to ample resuspension by tidal currents. The summer thermocline restricts upwards dispersal of sediment, leading to minerogenic sediments being concentrated in the lower cooler portion of the water column (Figure 1), varying in concentration due to intermittent resuspension. At the same time, episodic cyclones can mix the warm upper layer, initiating primary and secondary production there. The early winter breakdown of stratification allows the biogenic production to reach the seabed and, later, upward migration of nutrients. At the bed, turbidity varies inversely with tidal current speed, indicating the repeated dispersal and re-settling of a thick near-bed turbid layer.

![PSD data at 10 m depth intervals in 100 m of water. Note the downward decrease in apparent concentration of the finest two size bands - an apparent effect of ambient light. The spike in sand-sized particles at the base of the thermocline (50 m) is probably biogenic in nature. Beneath, there are increasing volume concentrations of suspended silt and sand towards the bed.](image)

Operation of FLNG platforms can be hindered by high concentrations of sediment and the presence of hard grains. When taken into cooling water systems, sand can accumulate and hard particles can erode piping in the heat exchangers. Awareness of the prevailing sediment dynamic conditions can allow mitigation measures such as placing the cooling water intake at a favourable depth and the design of the cooling system with a sediment trap, with sufficient capacity and associated plans for periodic removal of sand.
4. Case study: sand transport in macrotidal tidal embayments

The macrotidal WA coastline includes a number of large shallow embayments, within which high rates of sediment transport occur, and, because of the relative shelter from waves, some small ports and recreational boat ramps are located. Some remain dangerous because of the steep waves generated with the bays, and plans are made to upgrade boating facilities and increase safety. West Roebuck Bay, Broome, has a maximum tidal range of 9.5 m. At most stages of the tide, the site is strongly sheltered from the shelf wave regime to its west, but it remains exposed to winds and waves from the SE quadrant.

Figure 18. PSD curves of bed sediments in West Roebuck Bay formed into 7 groups. Very fine mixed carbonate/quartz sands of the inner intertidal zone pass into silty fine quartz sands and well-sorted medium quartz sands of deeper water.

Bed sediments are characterised by variable populations of size modes (Figure 2). Overwhelmingly, the ebb-tide suspended sand grains are skeletal carbonate, with most samples containing 82 – 97 % carbonate and only one lower value, of 71 %. Most carbonate grains are fragments, and a few benthic foraminifers were identified. The quartz grains are sub-prismoidal to sub-discoidal in shape, with angular to semi-rounded and rounded faces.

Measurements of sediment transport aimed at estimation of the potential annual rate of sand flux ($m^3/yr$) across the location of a proposed dredged channel, to help assess whether the rates of accumulation within the dredged channel might be manageable. Field measurements...
were made for five weeks in winter, comprising tidal elevation, waves, currents (through the water column, measured by ADCP), temperature, salinity, turbidity (at 0.6 m above the sea bed - ASB), and, importantly, in-situ time-series measurements of the PSD, volume concentration and settling velocity of the suspended sediments. The latter three parameters were measured at 0.6 m ASB using LISST-100x and LISST-STx instruments.

Tidal currents at the study site flow in the ebb direction for around 9 hours per semi-diurnal cycle, due to a circulation pattern around a major sandbank. The in-situ PSD measurements indicate that the volume concentration of the fine silt fraction is limited, probably by local supply, and that only the fastest tides transported the medium sand fraction.

The in-situ measured settling velocities (Figure 4) are realistic values compared to other published field data (Soulsby 1997). Temporal variation within each size class is high for file silt, least for medium silt and generally high across the sand sizes, consistent with the highly variable proportions of quartz and carbonate in the sand fractions.

Figure 19. PSD curves for the duration of four successive ebb- and flood-directed tidal currents at the mooring site. The three PSD curves on each plot represent maximum, mean and minimum volume concentrations for each of the 32 LISST-100x size classes (~2.5 – 450 µm). The bottom plot shows only the mean PSD for each tide, indicating higher mean sand concentrations for the brief flood tides 2 and 4.
Figure 20. Daily measurements of particle settling velocities measured off West Roebuck Bay, Broome, using LISST-STx at 0.6 m AS, at ~2 m below LAT. Strong variations in settling velocities are interpreted as partly related to the changing composition of sand-sized grains at different stages of the semi-diurnal and spring-neap cycle.

Some interesting measurement-related issues arose:

- Measurements were made by redundant moored LISST-100x instruments deployed horizontally at 60 degrees to one another. One instrument consistently produced volume concentrations around 75% of the other, on both flood and ebb tidal currents;
- LISST-100x instruments used for vertical profiling produced data indicative of periodically raised sand concentrations near the bed. This is consistent with the turbulent bursting process;
- There were large measured temporal changes in the settling velocity data for the various size classes;
- In this environment, calculations of sand transport based on turbidity data alone would produce a significant underestimate of the actual sand transport, because, amongst other factors, of the dominance of the turbidity signal by the silt fraction.
Monitoring of sediment dynamics during disposal of dredged harbour sediment in Port of Esbjerg, Denmark

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Introduction and setting

During the summer and autumn of 2013 a monitoring programme of disposed harbour sediment in Esbjerg harbour was defined. The aim was to quantify the effect of the disposal on the naturally occurring sediment dynamics with emphasis on the concentrations. This was achieved by using a combination of fixed installed equipment and vessel based surveys.

The overall goal was to measure the effect of the disposed sediment on the natural sediment concentrations in the area and to measure in detail how the sediment clouds are disposed in the area.

The study was undertaken in the Northern part of the Danish Wadden Sea outside Port of Esbjerg (Figure 21). The primary investigation area was in the Southern part of the harbour area where a new port extension is being established. In connection with this extension also a new disposal site is established. From the harbour basins is annually dredged between 200,000 and 600,000 m³ of material. During the period 1993-2011 an average of 425,000 m³ was disposed on the designated disposal sites outside the harbour. The immediate spreading and subsequent deposition has previously been investigated mainly based on numerical modelling techniques.

The area is naturally an infilling environment with an estimated import of fine grained sediment of about 142,000 t annually of which 85% originate from the North Sea (Bartholdy and Madsen, 1985). The sediment in the area is mixed with intertidal flats comprised mainly of sand at exposed areas and wide spread intertidal mudflats at protected sites. The natural sediment concentration varies extensively throughout the area with concentrations of around 50 mg l⁻¹ in the channels and higher concentrations over the intertidal flats. During rough weather sediment concentrations in excess of 1000 mg l⁻¹ have been observed.
Measurement programme

Just south of the new disposal site a fixed station was set up including measurements of currents (ADCP), turbidity (Wet Labs WQM) and other water quality parameters. All equipment at this main station was set up with a temporal resolution of 2 minutes in order to capture the anticipated very short term increases of the sediment concentrations due to the disposal.

In order to get a picture of the more distant spreading of sediment two background stations were established. One station was placed about two nautical miles south of the main station. The other one was placed in the northern part of the study area which is known as a net depositional area. These stations were equipped with sensors for turbidity only (Wet Labs NTU).

The fixed station measurements were further supplemented with vessel based surveys where profiles of suspended matter concentrations (SAIV SD-204) and sediment grain size distributions (LISST-100X) were obtained. This was combined with a number of water samples for establishing primary grain size distribution and for conversion of turbidity
measurements to total suspended matter concentrations. Vessel based campaigns was undertaken during periods with and without disposal of harbour sediment.

**Results obtained**

Due to the defined programme a number of good time series of total suspended matter concentration were obtained. Time series of current speed and direction this provided information for computation of sediment flux out of the disposal site. Combined with vessel based surveys of especially grain size distributions the programme gave a good impression of the natural and man-made sediment dynamics at the site (Figure 22).

![Figure 22 Sediment grain size distribution outside the harbour in a period not affected by disposal (top left), Inside the harbour basin during dredging (top right); outside the harbour during disposal (bottom left).](image)

**Discussion**

The grain size distributions provided in Figure 22 shows the situation outside the harbour in a period not affected by disposal. The sample can in the present context be seen as undisturbed. The median grain size is 0.073 mm and the sediment is relatively well sorted. Inside the harbour during dredging the sediment grain size distribution is similar with a median grain size of 0.067 mm. This infers that in the tidal area the current is able to keep coarser sediment in suspension than inside the harbour basin where the current is close to zero.
During the disposal operation the grain size distribution is less well sorted and the median grain size drops to 0.053 mm. This is explained as a combination of three processes.

1. The material that is deposited inside the harbour basin is mainly the fine fractions of the natural occurring sediment. The coarser fractions are deposited in areas with higher current speeds
2. In connection with the dredging (especially with suction devices) the natural floc structure will be destroyed. During the disposal a large amount of very fine sediment is introduced to the water column
3. The coarse sediment that after all is included in the dredged material will not immediately be introduced to the near field but will temporarily be deposited at the bed.

Measurements of grain size distributions show that the disposed material and the natural sediment have similar physical properties. It must therefore be anticipated that the disposed material after the spreading in the area and deposited cannot be distinguished from the natural sediment in the tidal area. Further it can be argued that disposal of harbour sediment does not bias the natural sediment dynamics in any specific area.

The measurement programme suggested that compared to earlier studies a vast amount of sediment is deposited at the bed. This sediment may remain at the site for a period. After some time this sediment is mobilised for any reason and the sediment concentration in the vicinity of the disposal site may increase for a short period before all disposed sediment is integrated in the natural sediment cycle and can no longer be distinguished.

It was not possible to detect any increases of total suspended matter concentrations linked to sediment disposal at the two background stations. This strengthens the finding that the disposed sediment quickly integrates in the natural sediment transport in the area.

References:

Particles characteristics in front of the Rhône River during flooding conditions

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Abstract: In the frame of the TUCPA (Coastal Turbidity and Autonomous Platforms) project, a two weeks campaign was carried out in the vicinity of the Rhône River mouth. Flooding conditions ($Q>5000m^3/s$) in February 2014 enhanced the development of a high turbid plume. It spreads over 20km to the south. Suspended sediment concentration in near surface waters decreases from 50 mg.L$^{-1}$ at the mouth to 2 mg.L$^{-1}$ 30km offshore.

An original instrumental package was used in a profiling frame deployed from a ship. A LISST type B (1.25 - 250µm), a LISST type C (2.5 - 500µm) and a LISST-HOLO (20 - 2000µm) associated with a CTD were used to characterize hydrological features and particles characteristics in a gradient from the mouth to the shelf edge. We observed particle size distribution centred around 40-60µm in the surface plume, which settle rapidly in the inner-shelf. A part of these particles seems nevertheless to be advected in an hypopycnal plume with 5-7 µm grained-size. Middle and outer shelf are characterized by the presence of smaller particle (5-7µm) in a bottom nepheloid layer. At least, the use of holographic camera LISST-HOLO allowed us to show that particles advected over the Gulf of Lions' shelf are actually microflocs (40-60µm) but also macroflocs of size (>200 µm) out of laser diffraction instruments range.

1. Introduction

Marine particles’ size play an important role particularly in sedimentation processes over continental shelves. Its distribution impact directly the settling velocity which can vary from 0.001 to 10mm.s$^{-1}$ for particle diameter of 1µm to several millimetres (Curran et al., 2007). Observations of suspended sediment concentrations (SSC) collected near river mouths show that, generally, coarse sediment (principally sand of size > 63µm) and finer component particles (silt and clay, < 63 µm) rapidly settle from surface water toward the bottom and aliment a bottom nepheloid layer (BNL) (Drake, 1976), or form ephemeral mud strata on so-called prodeltas areas (Bourrin et al., 2006). A part of fine-grained (< 10 µm), “microflocs” (< 125 µm, principally fine-grained bound by organic matter) and “macroflocs” (> 125 µm, fragile structure formed by microflocs) can be advected in a surface nepheloid layer over several kilometres (Curran et al., 2007). Finest sediment of prodeltas are then submit to different advection processes by storm, oceanic current or mud-flow creating a mud-belt at the middle of the continental shelf (Hill et al., 2007).
During a 2-weeks campaign in front of the Rhône River mouth (TUCPA project), we studied the particles dynamic and composition of the Rhône River plume. It was the opportunity to observe the spatio-temporal variability of particle dynamics in the coastal area of the Rhône River under flooding conditions. Thanks to an optical instrumentation composed of 2 LISST-100 (type B and C), and a LISST-HOLO camera we determine the particle characteristics (size, nature and form) of the Rhône River plume and its relation with the BNL. Our principles objectives were 1) to identify the interaction between the different turbid layers in our study area, 2) to determine the particle size distribution (PSD) inside these structures, 3) to follow these distributions in space (along a cross-shelf transect) and 4) experiment the coupling of 3 SEQUOIA instruments to increase our particle size detection range.

2. Regional settings

Rhône River (catchment area = 97 800km²) represents 80% of the total material input to the Gulf of Lions (GoL) (Courp et Monaco, 1990; Bourrin et al., 2006). Its mean annual discharge is around 1700m³/s and flood of 8000m³/s can be reached with return period of 10 years (Maillet et al., 2006). Same authors estimated a total particle flux around 7.10⁶ tons per year with a high variability between 1.2 to 19.7 10⁶ t.y⁻¹. The Rhône prodelta is described by several authors as an area with high sedimentation rate (20-50 cm.year⁻¹ (Marion et al., 2010; Miralles et al., 2005). This shallow area is also submitted to wave energy which involved resuspension and remobilisation processes (Radakovitch et al., 2008). General circulation induced by south-easterly wind form a southward flow along the coast and foster the export of material near Cap de Creus Canyon, close to the shelf break (Estournel, 2003; Ulses et al., 2005). However, in case of north-western wind (Tramontane and Mistral) the plume is separated from the coast and deflected to the south (Marsaleix et al., 1998).

3. Material & Methods

We present here stations sampled the 02/17/2014, after the peak discharge of 5000m³/s measured in Beaucaire the 02/12/2014. Sampling stations were spaced by 10 meters depth of bathymetry from the near-shore (20 m) to the shelf break (100 m). We sampled surface and bottom SSC and carried out profiles with a Seabird CTD and optical instruments. Two stages were established during profiles in order to perform cross-measurements and validation with various sampling frequency of instruments. First one at 5 m depth to study the Rhône plume and the second one close to the bottom (2-5 meters above bottom) to sample the BNL.
3.1. Laser-diffraction

The coupling of *In Situ* Laser Scattering and Transmissiometry instrument (LISST, Sequoia Scientific Inc., Agrawal et Pottsmith, 2000) observations offer us the possibility to study the spectra of marine particles from 1.25 to 500µm by laser diffraction. Instruments were deployed *In Situ* by profiling water column directly from the boat. A high sampling frequency (1Hz) were used for both LISST-100. We used an *In Situ* LISST-100 to determine the particle size distribution from 2.5 to 500µm in 32 (type C) size classes logarithmically spaced. We coupled the LISST-100 type C with a LISST-100 type B who permit to get the PSD from 1,25 to 250µm and thus, complete the PSD in the lower range. PSD is derived from the laser diffraction signal using the Mie's theory. Invert function was used to calibrate our RAW signal in µL.L⁻¹ units. Then, we express our PSD in percentage for each median size class of the total volumetric particle size distribution (vPSD). Detailed process used is available in Agrawal et Pottsmith (2000) and Traykovski et al. (1999).

During the process raw data are corrected and calibrated by a volumetric conversion constant (VCC). This constant is normally given by the constructor after laboratory calibration, but we decided to fit this calibration constant for each instrument with in-situ gravimetric measurements in order to match and merge correctly each PSD. VCC is the calculated slope of the linear correlation obtained between raw volume concentration and massic concentration measured at the same time. VCC of 5600 and 16000 were used for the LISST-100 type B and LISST-100 type C respectively.

3.2. Holography

The LISST-HOLO is a digital holographic camera who permit to measure PSD from 20 µm to 7 mm (50 sizes class spaced logarithmically) with a resolution of 7.4 µm per pixel in a field of view around 7.4 * 7.4 mm. This system allows us to determine particle characteristics (nature, size and form) thanks to an in-focus image along a 50mm depth of field. Large particles (>500µm), complex aggregates, and biological particles (as phyto-zooplankton) have been already observed with a LISST-HOLO (Graham et Smith, 2010). The LISST-HOLO was used to estimate the sphericity of suspended particles and adapt the inversion method used for the analysis of laser-diffraction based method.
4. Results

4.1 Hydrology

The plume provoked by the flood is visible on the MODIS picture (see Fig. 1). It was visible during 5 days, and spread over the whole Gulf of Lions. CTD section show a high gradient of temperature, salinity and SSC close to the coast, principally in the surface layer (Fig. 2). Temperature decrease from 14°C offshore to lower than 11°C close to the mouth. At the same time, salinity values are close to 3 PSU in the first meter, increasing progressively to 38 PSU in the water column. SSC section is represented by high value in the plume close to the mouth (40-50 mg.L\(^{-1}\)) which progressively decrease to less than 5 mg.L\(^{-1}\), 15 km offshore. We noticed a signal measured close to the bottom with SSC value around 1-2 mg.L\(^{-1}\), for station 3 to 5, 2 km offshore.

4.2 Spatial evolution of PSD (plume and BNL)

The plume is characterised by 3 different types of PSD along the cross-shore transect (Fig 3.a). First, a mono-modal distribution (station close to the mouth, in the inner-part of the shelf) with a majority of volumetric PSD for size range of 40-60µm (maximum of 10% of the total vPSD reached for PSD of 50µm). The second distribution observed, corresponding to the middle of the shelf is represented by the same signal as seen previously for particle size in the range of 40-60µm but also by a low quantity (<5% of the total vPSD) of particle smaller, with size <10µm. The third and last PSD measured, near the shelf break in the outer part of the Gulf of Lions, is described by a lower signal of particle size range 40-60µm as seen previously (around 5% of the total vPSD). However, this part of the plume is characterised by a majority of small particles (8% of the total vPSD reach for particle size 5-7µm) than the middle of the shelf. Moreover, we can easily see the spatial evolution of signal measured by LISSTs. Particle of 40-60µm size range seems to progressively decrease along the transect cross-shore whereas small particles (5-7µm) signal seem to increase along the same transect.

The Figure 3.b represents the PSD evolution inside the BNL. Results show different distribution according to the station and, so, the distance to the coast and the depth of sampling. First, station of the inner-shelf are represented (~10% of the total vPSD) by a mono-modal distribution with particle size between 40-60µm. Then, in the middle part of the shelf, the signal measured for PSD of 40-60µm decrease (5% of total vPSD) and, in parallel,
the presence of small particle (5-7µm) represents 20% of the total vPSD. At least, stations of the outer part of the shelf, sampled for depth between 80-110m show a mono-modal PSD for small particles (peak at 7µm) representative of 50% of the total vPSD.

4.3 Holographic mean picture

Holography permit us to determine nature, form and size of In Situ particles. We observed a majority of grained-size around 50µm, which are probably microflocs, formed by several fine-grained bound by organic matter. The same hypothesis can be done with macroflocs, shown by big particle on the pictures, of size larger than 300 µm. At least, we can see an organic filament in the centre of the image which can represent the small part of organic particle in this area.

5. Discussion and perspectives

On February, 17th of 2014 the Rhône River plume spreads over 20 km on the GoL’ shelf towards the south (Figure 1). Bourrin et al. (2006) estimated that 50% of riverine fine-grained sediments are trapped in the prodelta. These sediments composed of silts and clays rapidly settle and are probably repackaged in larger aggregates caused by salt flocculation along the salinity gradient (Thill et al., 2001). This observation can be verified in our study area where the salinity gradient is strong (cf. CTD salinity section - Fig. 2) by observing BNL PSD in the inner part of the shelf (Fig. 3a-3b) which are totally influenced by the inner-plume. Thus, we observed for both plume and bottom nepheloid layer in the inner-shelf, unimodal PSD with major size comprised between 40-60 µm showing the existing link between bottom and surface turbid structures.

In the middle part of the shelf (5-10 km), 40-60 µm particles proportion of the plume decrease reflecting the progressive sedimentation of aggregates in the inner-shelf. The decrease of turbulence can also explained the desegregation of 40-60µm in finest particles of 5-7µm (Curran et al., 2007). These finest sediment fraction, observed in the middle and the outer part of the plume, can not directly settle in the prodelta according to Stoke’s law. They are advected further and create an hypopycnal plume in the middle and outer part of the shelf, constrained to the oceanic current which will influence their settling velocity and their export to the abyss (Bates, 1953; Palanques et al., 2006).
These particles appear in the BNL of the mid-shelf at 10km of the mouth and represents a majority of the particles of the BNL in the outer part of the shelf (Fig. 3b). It seems however difficult to separate small suspended particles coming from the sea-bed resuspension (by wave, advection or oceanic current) and particles from the plume which sink from the surface. The future determination of the nature of these particle (i.e organic vs inorganic) by detailed analysis of LISST-HOLO In Situ pictures will permit us to understand their origins. In the plume, a part of these particles seems to floculate with organic matter of the Rhône creating flocs of different size. Microfloc (~ 50 µm) and macroflocs (> 125 µm) have already been observed by Bainbridge et al. (2012) in Burdekin River (Australia) and on the Têt inner-shelf (Curran et al., 2007). Measurements from LISST-100 (type B & C) instruments show microflocs such as unique particle and will over-estimated the volume occupied by these single particles bound by organic matter. These instruments did not measure macroflocs but we can observe them on the holography mean picture (Fig. 4) taken in the Rhône plume. Their deposition to the sea-floor will be determined by plume buoyancy, floc size/effective density and hydrographical parameters (Soulsby et al. 2013; Manning et Schoellhamer 2013; Curran et al. 2007).
In a future work, we expect to complete the PSD from laser diffraction with holographic PSD to covered the entire spectra of marine particles. By determination of the obtained merged spectra, we expect to show the importance of the LISST-HOLO measurement. A preliminary result of a merged spectra is shown Figure 5. We easily see that laser diffraction do not properly observe particles of size > 125 µm (type B) and > 250 µm (type C). These over-evaluated PSDs have already been described by Mikkelsen et al., (2005) and provoked a 'raise tail' in the maximum extreme size class. The LISST-HOLO complete these PSD by estimated the volume occupied by particles over the range of LISST-100 (type B & C), showing the importance of macroflocs (> 10% of the total volume detected) in the total size spectra of marine particles.

Moreover, we used during the campaign a third LISST-100 (type C) on boat to measure particle size distribution after ultrasonic deflocculation. We expect to separate proportions of flocs and component particles in the total measured PSD. By analysing these results, and coupling with gravimetric concentration data, organic matter percentage and chlorophyll a content, we expect to describe the general particle characteristic trend (in space and time) of the Rhône River shelf in flooding conditions.
Figure 23: Location map superimposed on a MODIS satellite image of the Rhône flood plume captured on February, the 17th of 2014. The plume is visible over the whole Gulf of Lions and extends more than 20 km offshore. Daily mean wind is plot by an orange arrow. Sampling stations are represented by red circles.
Figure 24: CTD section of temperature (°C), salinity (PSU) and SSC (mg.L⁻¹). Casts are shown by black cross. Density contour are plotted in white.
Figure 25: *In Situ* evolution of PSD for the plume (top) and the BNL (bottom). Intensities measured are expressed in percentage of the total particle volume measured by both instruments. Extreme size class were exclude for the calculation.
Figure 26: Holographic mean picture montage of LISST-HOLO sample measured the 02/17/2014 in the Rhône River plume. A part of microflocs (gray dash line), macroflocs (black dash line) and organic particle (green line) are shown. The black bar represent a 500µm scale.
Figure 27: Coupling of PSD from 2 LISST-100 (type B (black) & C (red)) and a LISST-HOLO (blue). The associated merge spectra is shown by a green dash line.

References


Arctic fine-grained particle flocculation, the case of Disko Fjord, West Greenland

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In the Arctic, thawing permafrost and increased melting of glaciers have proven to be important drivers for changes in not only the fine-grained sediment supply but also increased biogeochemical fluxes such as those of iron (Bhatia et al. 2013) and organic carbon (Hood et al. 2009) from land to sea. We argue that flocculation is a controlling factor for the magnitude of fluxes and deposition rates in the coastal marine environment but that the process is still not well studied in the Arctic. This project aims at understanding the influence of flocculation in an Arctic fjord system, Disko Fjord, West Greenland, primarily based on in-situ measurements. Vast amounts of sediment are supplied to the fjord through a meltwater river draining the watershed of an outlet glacier of the Sermersauq Ice Cap on Disko Island. The glacier surged in the late 90’s giving an estimated sediment discharge of almost $40 \times 10^3$ t per day, a figure based on cores and sediment traps (Gilbert et al. 2002). However, no measurements have been carried out since then and no data on the composition of the suspended matter have been given before the present study.

Measurements were carried out in transects from the outlet of the river and into the fjord as well as in stationary deployments overnight during two campaigns in July 2013 and are followed up by similar measurements in the summer of 2014. The Pcam, a novel, laser-illuminated camera system was used together with a LISST for in-situ particle size measurements. The Pcam system is also to be presented at PiE 2014 by Christian Winter, whose group at MARUM has developed the system. Water column information was gathered from CTD’s and water samples were taken to characterize the suspended particles in terms of organic matter and iron concentrations as well as primary particle sizes.

The stationary deployments proved that the particles were flocculating at periods with low shear (Figure 1). Our assumption is that the flocculation takes place in the plume and the particles start sinking when the current velocities are low. The plume flocculation caused the volume fraction of
large flocs (>100 µm) to be dominating below the plume probably due to settling of the larger flocs (Figure 2). It is assumed that a larger amount of large flocs are present in the plume than what is shown on the figure due to limitations in the instrumentation at the high particulate matter concentrations in the plume (>500 mg/L). Based on the water samples, an inverse relationship was found between the concentration of highly reactive particulate iron and primary particle sizes while a direct relationship was found between the Fe-concentration and floc sizes (Figure 3).

Thus, the larger the floc size the more iron is adsorbed and the more primary particles does it consist of. This implies not only that the flocs aren’t necessarily made up of the same primary particle sizes but also that the theory of fractal dimensions (e.g. Kranenburg 1994) is challenged in a system like this with large amounts of available iron.

It is yet to be studied how much sediment is discharged at present, but roughly 13 x 10³ t sediment was in the plume at the time of measurement, showing that still after the surge a lot of sediment is discharged. The observed flocculation dynamics coupled with the relationship to iron concentrations highlight the potential for redistributing sediments and nutrients in the water column, and serves as an important factor in the sediment and biogeochemical fluxes from land to sea in the Arctic.


Figure 28. (Top) Change in PSD over time at 5 mbs, based on measurements with the Pcam. (Bottom) Current velocities in the layer above the position of the Pcam measured with an RCM9. Note the increase in particle sizes between 04:00-05:00 in the morning when current velocities are at a minimum.
Figure 2: Along-fjord transect from the river outlet into the fjord. Profiling measurements indicated with black dots. The four middle panels show the fraction of flocs (from Pcam pictures) in different size groups.
Figure 3. (Top) Concentration of iron in grams per kg sediment in relation to the in-situ floc diameter. (Bottom) Iron concentration in relation to dispersed primary particle size. Labels on plots denote the distance of the water sample from the river outlet.
Assessment of suspended sediment properties from an optical settling column during a dam flushing event: the Arc and Isère rivers, June 2014

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Purpose

Hydroelectric reservoirs are subject to a more or less important filling which depends on their geometry, hydrological regime and on the geological context. In order to limit the siltation in small reservoirs, there are several ways of management: cleaning with mechanical engines, pumping and dilution of dredged sediments or hydraulic flushes. The last method consists in recreating a lower water depth and a higher flow rate upstream which involve erosion and transport of sediments accumulated in the reservoir. The three dams of EDF (Électricité de France) on the Arc river in the French Alps are thus flushed each year.

During these events, sediments are removed and flow in the river downstream of the dam. So to understand the impact they’ll have on watercourses downstream of the dam, this is important to study the dynamics of those sediments and to know how they interact. It is particularly important to know (i) if suspended particles evolve during their transport in the same way that it’s presented by Droppo and others (2004) and (ii) if the variability of particles’ properties is mainly driven by the hydrodynamic conditions (sediment concentration, turbulence level) or by the evolution of physical, mineralogical, or biological characteristics of particles. To bring an element of answer to those questions, quasi in situ measurements have been realized on several parameters, especially on the settling velocity of sediments during the hydraulic flushing organized on June 2014 the 17th.
Material and methods

All sediment samples presented in this study have been collected with a bucket directly under the free surface of the river. Several characteristics of particles (diameter, settling velocity, flocculation coefficient) have been measured using a portable LISST and an optical settling column developed in our laboratory. This column is composed by a housing which possesses 16 infra-red emitters and 16 receivers. By inserting a test-tube of turbid water in the housing, diodes will send light to a certain frequency, captured at different intensities by sensors. Thus we obtain an absorbance matrix which is function of time and depth (figure 1). A complete description of the optical settling column has been presented by Wendling et al. (2013). While calculating iso-absorbance lines on that matrix, we can find out three interesting variables: (i) the distribution of almost pseudo in situ settling velocities of the river’s sediments; (ii) the distribution of settling velocities of flocs which are formed during the falling of sediments in a fluid at rest; (iii) a flocculation coefficient which corresponds to the ratio between settling velocities at the bottom of the tube and velocities at the top of the same tube.

Figure 1 : scheme of the optical settling column and corresponding absorbance matrix
During the hydraulic flushing of the Arc, we had three SCAF prototypes, which helped us to obtain temporal series at different positions in the cross-section. Each instrument had been specifically calibrated in the laboratory. Because of signs of malfunction detected on few sensors of one device, we would only present results collected at the middle and on the right bank of the river. Thanks to the presence of other intruments during the event, we could obtain water and sediment discharge series which would be useful to correlate the evolution of settling velocities with other parameters like the flow rate and the concentration of sediments in the river during the hydraulic flushing.

Figure 2: Calculation of settling velocities at the top and bottom of the settling column

**Results and discussion**

Figure 3 presents the location of the hydraulic flushing operation and its spatio-temporal dynamics.
Figure 3 (left): hydrogramme and turbidigramme of the hydraulic flushing; (right) localization of the dam and the study site on the Arc river.

The figure 4 presents the spatio-temporal evolution of particles’ settling velocities. This timeseries reveals a high variability of particles during the hydraulic flush. At the middle of the river, sediments’ settling velocities decrease significantly from the beginning of the event (0.82 mm/s at 13:15) to reach their minimum at 15:15 around the peak discharge (0.18 mm/s) before rising up at the end of the event (0.92 mm/s at 17:45). Data acquired on the right bank of the river present the same dynamics even if variations are less significant. Temporal variations can be of a 4 to 5 factor, which clearly show the importance of following and modelling the dynamics of particles’ characteristics. If we take an interest to the spatial dynamics, a significant difference of velocity is also observed. It can reach a factor three between the middle and the right bank of the river. While comparing timeseries of sediment settling velocities with the hydrogramme and turbidigramme presented on figure 2, one can identify two successive phases:

(i) The increasing phase until the maximal flow rate (15:00 Q~186 m3/s) involves a great diminution of particles’ settling velocity. At the peak water discharge, conditions of water depth and turbulence in the river seem to be sufficiently high to break up macro-flocs to micro-flocs whom settling velocity is reduced (ws~0.18 mm/s at the middle and ws~0.14 mm/s on the right bank). It is interesting to notice that around the peak of water discharge, measurements of settling velocities (figure 4) don’t show variabilities on the cross-section. The particles’ characteristics at the surface of the river are thus similar, probably due to good conditions of turbulent mixing.
(ii) After the peak of water discharge, the river’s flow decreases to stabilize around 140 m3/s starting from 17:00. This time corresponds to the peak of concentration which reach C~5.4 g l-1. This second phase is in link with a steep increase of settling velocities which don’t stop growing until the end of the event (17:45). Settling velocities are then maximal, close to 0.92 mm/s and 0.65 mm/s at the middle and on the right bank of the river, respectively.

Measurements of settling velocities observed at the bottom of the settling column bring some complementary information regarding to the kinetic of sediment flocculation. Data presented on figure 5 highlight on the existence of flocculation with the formation of flocs during the siltation in the column. Thus, measured velocities at the bottom of the column are in the range [0.70-1.90] mm/s and [0.70-1.72] mm/s for samples respectively from the middle and the right bank of the river. Those values are from one to nine times higher than surface settling velocities, corresponding to pseudo-in situ conditions (figure 4). Furthermore, it’s interesting to notice that the temporal series presented in figure 5 (right top) do not show any lateral variations.
As a preliminary conclusion, the joint analysis of figures 3 and 4 reveals a high spatial and temporal variability of sediments’ settling velocities under hydrodynamic conditions of the river. Field measurements are in agreement with the concept of flocculation established previously by Dyer (1989) and others (figure 7). High turbulent conditions which prevail during the peak discharge limit the flocs formation in the water column. Later, the decreasing of the shear stress and the increasing of the concentration promote flocculation so the settling velocity increases (figure 4; left). After a stay in a fluid at rest, there is no more transversal variability of the sediments’ characteristics (figure 5 right top) which reveals at the same time a high sediments’ kinetic (rapid
flocculation) and a transversal homogeneity of bio-physicochemical characteristics of particles. So the turbulence conditions are the ones which govern differences observed between the middle and the right bank of the river.

When we come back to the figure 5, one can notice a temporal evolution on settling velocities. As this time evolution is observed under quiescent conditions, it cannot be attributed with the flow rate in the river. Despite an important kinetic of the material, flocculation due to the falling is probably not fully developed: the small length of the column doesn’t let enough time to the flocs to reach their maximal size. This hypothesis could explain a certain correlation observed between the temporal evolution of settling velocities at the top and at the bottom of the column.

To deepen the analysis, it is relevant to look at the distribution of settling velocities during the flush. The figure 8 presents settling velocities histograms at the top of the column at the beginning of the event (13:15, Q~175 m3/s, C~1.8 g/L), during the peak discharge (15:15, Q~180 m3/s, C~2.4 g/L) and finally near to the concentration peak (17:45, Q~138 m3/s, C~4.7 g/L). One can make the following observations: at the beginning of the event, settling velocities are distributed on a quite large range [10^{-3.5} - 10^{-2} m/s]; after that, the more we get close to the peak discharge, the more tightened is the values range, with a peak of histogram which progressively decreases to its minimal value (10^{-4} m/s) during the peak discharge. This whole phase is characterized by a highly asymmetric shaped histogram. Once the peak discharge had been occurred, the histogram get wider and become symmetric, with a peak of settling velocity about 10^{-4} m/s and a range of velocities equal to [10^{-3.7} – 10^{-2} m/s]. Those observations of histogram confirm the relation between peaks of discharge and concentration and sediments’ characteristics. The increase of the turbulent shearing during the rising of the flow promotes disaggregation and lead to smaller particles. Once the peak discharge occurred, the shear stress is decreasing so flocs is re-initiated, and even accentuated because the sediments’ concentration is rising.

![Figure 8: settling velocity histograms at the top of the column at 13:15, 15:15 and 17:45](image-url)
The samples’ grain size which had been analyzed with a portable LISST XR, give some information concerning floc’s diameters D10, D50 and D90 during the hydraulic flush. Results presented on the figure 9 show that diameters of the particles show a similar temporal pattern than the one observed with our settling column instruments. This observation is not astonishing because there exists some close relationships between floc’s diameters and floc’s settling velocities; but the intercomparison highlights on the reliability of our device to characterize some sediment characteristics (settling velocity in situ and under quiescent conditions; propensity of the sediment to flocculate). While the trends observed with the portable LISST and the settling column were similar, the variations were more accentuated with our device. One can wonder if the residual turbulence that prevails during the circulation of fluid within the LISST device does not smooth the real dynamic by imposing an instrument related hydrodynamic condition.

![Figure 9: particles’ diameters obtained with mobile LISST XR](image)

**Conclusions**

In the light of the above measurements, several conclusions can be addressed. As a first step, one can note that with a simple and robust settling column device, we could have rapidly measured settling velocities of particles in a highly-concentrated environment, with concentration exceeding 5 g l⁻¹. The study of settling velocity dynamics during the hydraulic flushing of the Arc river have brought to light a temporal and spatial variability of particles, linked with the flocculation processes. This evolution seems to be controlled by the hydrodynamic forcing rather than the intrinsic nature of those particles.
Synthetized by the expression of the flocculation coefficient, the evolution of particles at the top or the bottom of the column allowed us to directly link the sediment dynamics to the flow rate and concentration dynamics in the river.

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Integrated Environmental Monitoring

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On the Norwegian Continental Shelf, oil and gas operations often take place in areas with particularly valued environmental areas. In order to minimize the risk of negative impacts from operations in these sensitive areas, monitoring of discharges and of the vulnerable environmental resources is required. A system, Integrated Environmental Monitoring (IEM), providing decision support in this new risk reality is under development. It is a system for real time integration, analysis and visualization of multi sensor environmental-, operational-, and modeled data.

During operations, large amounts of particulate material like drill cuttings and drilling fluids are discharged either subsea or from the drilling rig. These discharges constitute a threat to sensitive species present in the vicinity of the drilling operations; hence it is prerequisite for the operating company to know where the discharges disperse and deposit on the sea floor.

It is assumed that LISST sensor technology can be used to provide key parameters for control of discharges from drilling operations. Lately the team developing IEM has started to look into how LISST can be used in an IEM setting.

This presentation will provide an overview of the IEM development project, and will give an update on the progress on the integration of LISST sensors and data in the IEM system.
Marine environmental risk and impact assessment with a Lagrangian particle tracking model

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MSS-HOLO: a free-fall particle microstructure profiler

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Particles suspended in the sea are central to many physical and biogeochemical processes. They affect light penetration through the water column, causing a significant impact on radiative transfer and primary production [1,2]. Understanding the distribution of organic carbon, in the form of Particulate Organic Carbon (POC) and how it sinks from the photic zone to the ocean floor is a key stage in the carbon cycle and therefore is directly relevant to long-term climate prediction [3].

The behaviour of suspended particles is a function of both the particles themselves (their nature, size, shape, density, settling velocity, swimming speed etc.) as well as their physical environment (density stratification, turbulent mixing regime). Biological particles (phytoplankton and zooplankton) may exist in thin layers: high-abundance congregations extending over large horizontal distances (O kilometre) but with small vertical extent (O decimetre) controlled by physical processes within the water column [4-8]. Turbulent mixing may promote the aggregation of particles, so changing their settling velocity and enhancing carbon export [9], whilst SPM flocs may be resuspended during periods of enhanced turbulence [10]. Recent model and laboratory studies [11] show that motile phytoplankton may accumulate in the centre of turbulent

Figure 1 - The MSS-HOLO system on-board ship ready for deployment.
vortices in a process that has a variety of ecological implications.

Therefore, the generation of effective predictive models of particle transport requires *in situ* information on the particle characteristics as well as on their location within the detailed physical structure of the marine environment. To this end, we have developed a free-fall particle microstructure profiler, MSS-HOLO (Figure 1). The system comprises a modified version of the holographic imaging system (holocam) described by [12] (available commercially from Sequoia Scientific Inc. as the LISST-HOLO) attached to the MSS-90 free-fall turbulence profiler described by [13] and manufactured by Sea & Sun Marine Technology. The holocam comprises two housings containing the laser illumination and imaging optics mounted on the nose of the profiler, with a third housing containing the image logging and control system mounted within the buoyancy elements in the tail. The MSS-90 is configured with sensors that measure turbulent shear (x2), microstructure temperature, optical backscatter, chlorophyll fluorescence, dissolved oxygen, pH and conductivity-temperature-depth – all sampled at 1024Hz. The holocam sample-volume is positioned directly across the front of one of the shear sensors and measures 220 x 6.8 x 4.5mm$^3$ (total volume of 6.7ml). The camera has a pixel size of 4.4 $\mu$m, allowing the imaging and measurement of all particles from 15$\mu$m to about 6000$\mu$m diameter from within the sample volume. The holocam housings have been designed to minimise flow disruption and are positioned to avoid wake contamination of the shear sensors. This has been validated using a Direct Numerical Simulation of the instrument configuration run at an appropriate Reynolds number (Figure 2).

The buoyancy of the MSS-HOLO system is adjusted such that on release it free-falls at about 0.45ms$^{-1}$ until its guard hits the seabed. The system is then recovered to the surface via a Kevlar tether that also provides power to the combined system. Microstructure data are streamed in real-time from the MSS-90 via the tether, but holograms are stored on-board the holocam for later off-load. The holocam is configured to sample at 15Hz, allowing the recording of a hologram every 0.03m as it profiles vertically down through the water.

![Figure 2 – Direct Numerical Simulation (using the Gerris Flow Solver) of the flow in the vicinity of the MSS-HOLO sensors at Re = 1.1x10$^5$. The wake shed by the guard-ring and the sensors is visualised with an isosurface of vorticity that has been coloured by pressure.](image)
column. There is sufficient on-board storage (250GB, solid-state) to allow 3hrs of continuous recording. The separate data streams from the MSS and the holocam are synchronised using a coded voltage signal emitted by the holocam as each hologram is captured that is recorded as a discrete channel on the MSS.

The MSS-HOLO system has been deployed at a variety of locations around the West Coast of the United Kingdom. An example profile from its first deployment in early spring 2012 is shown in Figure 3, recorded at the L4 site in the Western English Channel. Here the water is 55m deep and weakly stratified, with a fresher colder layer in the upper 20m of the water column. The shear readings oscillate in the top 8m of the profile as the instrument is released and accelerates to its terminal velocity. There is weak shear throughout the water column, although a small increase can be observed at the bottom, directly adjacent to the seabed. The chlorophyll fluorescence exhibits some structure, with slightly higher values in the surface layer. Sharp “spikes” of increased chlorophyll fluorescence with small vertical extent can be seen at the base of the

![Figure 3](image-url) - Sample profiles from the MSS-HOLO at the L4 site in the Western English Channel. The profiles show (left to right): turbulent shear (uncalibrated), temperature, salinity, Chl a, and holocam frame number as a function of pressure through a 55m vertical profile to the seabed. The images to the right are reconstructed particles taken from holograms recorded at the indicated positions in the profile.
pycnocline at about 20m depth. Holograms recorded at these depths show an increase in abundance of nano- and microplankton (15 to 30μm diameter). The middle of the water column (25 to 45m depth) is characterised by compact flocculated particles (100 to 200μm diameter), whilst very large macroflocs (500μm to 2mm diameter) can be found in the bottom boundary layer, most probably resuspended from the seabed.

Further data from a fresh water lake, turbid coastal waters and clear oceanic waters will be presented to show the utility of the system in a variety of water types. These measurements provide opportunity to gain new insight into in situ particle dynamics and allow existing models of particle transport and plankton behaviour to be tested.

References


PCam: Community camera system for the in-situ measurement of suspended matter size

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A camera system for the in-situ photography of suspended matter in shallow water systems has been developed. It has a simple set-up and uses consumer technology for an easy assemblage and application to field measurements in marine conditions. The instrument is designed to provide images of suspended matter at high spatial resolution (1 pixel =4.7 µm), a large range of particle sizes (10µm to a few mm) and for brief exposure (1/8000 s) to avoid motion blur of advected particles. In order to provide sufficient light intensity at short shutter speeds and to eliminate forced perspective effects which may make an object appear larger or smaller than it actually is a laser sheet is used to illuminate the control volume in the focus of the camera. Automated image analysis for the derivations of particle size distributions (PSD) is discussed, and the need for further studies are identified. The camera system complements existent instruments like laser in-situ diffraction methodology (LISST), which allows sampling at much higher temporal resolution and smaller sizes, but extends towards the larger particle size range. The system has been validated against standard glass beads and sand, and inter-compared to measurements of laboratory (sieve, settling column, Coulter laser sizer) and LISST derived PSDs. Exemplary data from a tidal channel in the German Wadden Sea are shown. A full tidal cycle field data set shows the dynamics of aggregate size characteristics from large macroflocs (2000 µm) around slack water to smaller (150µm) microflocs during high energetic tidal currents. All technical drawings and post-processing software are published in a version 0 state open source in the hope of further mutual development of hard- and software by a community interested in suspended matter dynamics.