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Test case in a near shore area (Ligurian Sea, La Spezia Gulf)

RT/2022/5/ENEA

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A. Bordone, T. Ciuffardi, G. Raiteri, F. Reseghetti

Abstract
Acoustic Doppler Current Profilers (ADCPs), as a secondary output, allow to estimate the concentration of Total Suspended Solids (TSS) in the water column through the analysis of the acoustic backscatter signal. This method was applied during a dedicated ENEA campaign in a near-shore area of the Gulf of La Spezia. ADCP measurements were performed throughout the cruise and joint measurements of TSS (discretely sampled) and Turbidity (by nephelometer) were performed along the water column in one station.
The application of the simplified sonar equation made possible to calibrate the ADCP vs TSS by means of a linear regression model, whose correlation coefficient resulted reasonably good (R2 was in fact equal to 0.87), with slope Kc = (0.239 ± 0.008) dB count-1 and intercept Ck = (-69.88 ± 0.59) dB, respectively. The method, whose reliability was proved by comparison with an independent TSS profile, was then applied to obtain a continuous quasi-synoptic mapping of TSS values along the water column throughout the cruise. The overall uncertainty budget of the method was estimated, too: the relative combined standard uncertainty resulted to be less than 30% for TSS values higher than about 3 mg l-1. The method, although not completely exhaustive due to the multiplicity and unpredictability of the conditions (above all, the type and size and actual distribution of scattering particles), is to be considered valid for a quick acquisition of local situations, allowing to obtain fast and almost zero cost TSS mappings. Results prove that this consolidated approach can be applied in the near-shore area, where ENEA performs its monitoring campaigns and where the interest in TSS measures is also motivated by the presence of fish and mussel farms, the transit of container ships and the proximity of the estuary of the Magra river.
The present technical report is intended to serve as a basis for developing procedures more and more compliant to international metrological standards, with the aim of further guaranteeing the metrological traceability of oceanographic quantities.

Keywords: *Total Suspended Solids; Water Column; ADCP backscatter intensity; Standard Uncertainty.*

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1. Introduction

Total Suspended Solids (*TSS* in the following), together with Turbidity, represent a very important quantity characterizing the seawater column, being in practice a rough but immediate indicator of its quality. High levels of *TSS* and/or Turbidity can be considered generally as a symptom of some extraordinary or periodic phenomenon (e.g. soil erosion, river floods, anthropic pollution, algal blooms) and sometimes can be reason of concern for aquatic and human life (e.g. high *TSS* concentrations may in fact prevent sufficient oxygen transfer and result in the death of buried organisms, eggs, or macro-invertebrate larva). By definition, *TSS* represents the undissolved material, composed of organic and inorganic fraction, present in suspension in a water sample, that can be separated through a membrane filter of standardized porosity and dimensions [1,2,3]. *TSS* are mostly composed by inorganic material (e.g. sand, silt, clay), but also plankton, algae and even bacteria can play a role to *TSS* value, due to the fact that they also drift or float along the water column influencing its clarity. *TSS* measurement requires the collection (in field) and, subsequently, the analysis (in laboratory) of discrete water samples along the water column and therefore it is considered as a time-consuming activity: due to this fact, with the purpose of obtaining a continuous series of *TSS* values along a profile, it is often combined with the measurement of Turbidity [4], for which different types of probes are available (e.g. turbidimeter based on optical, acoustic or laser technologies [5]). However, also in this case, *TSS* measures are limited to few profiles performed in some stations along a transect, when, on the other hand, the values of interest, especially in areas near river estuaries, require a more extensive and faster mapping over time. To this end, to obtain fast and extensive estimates of suspended sediment concentration (*SSC*), in the last twenty years the use of Acoustic Doppler Current Profilers (ADCPs) [6] has become widespread [7-13]. Even if the primary goal of an ADCP is measuring 3D current profiles, also moving along transects (with the ADCP suitably mounted on a boat), its signal output can have an interesting dual purpose: the current measurement is based on the intensity of the return echo (which is the independent quantity of interest), that in turn is proportional to the concentration of backscattering particles present in the water column under examination (whose measurement is the final purpose of this experimental work). The acoustic backscatter level is physically-mathematically related to *SSC* through the sonar equation [14,15], in which the distance of the considered seawater volume from the emitting ADCP head and the acoustic attenuation due to the water itself are properly taken into account. In the following paragraphs, materials and methods followed by ENEA

Marine Environment Research Centre of S.Teresa (from now on simply ENEA) to estimate *TSS* values by using a 300 kHZ ADCP, along a transect during a routine coastal monitoring campaign, will be described. It should be noted that in this case, for the particular experimental conditions (the whole water sample collected was analyzed and filtered, without any sub-sampling) *TSS* could be considered as the best estimate of SSC (and therefore used interchangeably, [1,16]). Attention will be paid to the assessment of *TSS* standard measurement uncertainty, too.

The experimental approach adopted in combining these two quantities can be summarized as follows:

1. a representative number of seawater samples were taken along the water column, (at different depths) in a single station, and analysed in laboratory in terms of *TSS* values;
2. along the same water column a profile of Turbidity measures was acquired simultaneously by means of a proper turbidimeter. The conversion factor *TSS*/Turbidity was then calculated in correspondence of the *discrete TSS* samples: *TSS* could so be reconstructed along the entire water column as it was a *continuously* measured quantity;
3. ADCP backscatter levels measured in the same station were then matched with the *TSS* profile measured in step 2, in order to convert/calibrate the ADCP output in terms of *TSS* values (by using the simplified sonar equation);
4. the validation of the results in step 3 was verified by comparison with another *TSS* profile performed shortly thereafter;
5. ADCP acoustic intensity profiles along the transect were finally post-processed by converting them in *TSS* values, so that a continuous distribution of suspend solid concentration could be obtained for a quick and immediate, quasi-synoptic, estimate in the region of interest.

2. Materials and methods

An *ad-hoc* campaign, aimed to evaluate the employment of an ADCP to estimate *TSS* values, was performed on the 04th of August 2022, in the Gulf of La Spezia, by means of the 12-meter length research vessel "S. Teresa" (starting time: 07:30 UTC - total length of travelled transect: about 16.5 km). The route is shown in Fig.1, where the red point indicates the station P1 (09°51.065’ E - 44°01.786’ N), where discrete *TSS* sampling and Turbidity profiles were performed (when the vessel was not moving under power). A 300 kHz ADCP, properly mounted cantilevered from the boat (Fig. 2), combined with an external GPS and equipped with the Bottom-Track function, continuously acquired current profiles along the entire route (for this reason the boat speed was limited to about 2 m s^{-1}).

2.1 Equipment and procedure for *TSS* and Turbidity measurement

Five Turbidity profiles were performed in station P1 (bottom depth about 28 m), each paired to a discrete measurement of *TSS* at different depths (equally spaced in the range from 5 m to 25 m). In-field equipment and measurement procedure were exactly the same as those described in [4] (i.e. *TSS* measured in laboratory and conversion factor *TSS*/Turbidity calculated *a-posteriori*). In Fig. 3 a phase of the sampling operations is shown. It should be added here that some improvements were recently made to the operations connected to the *TSS* measurements, both as regards the definition of the drying procedure of the filters, as well as for the reorganization of the ENEA measurement station (see Appendix A).

2.2 ADCP and settings

In the following, the main features of the ADCP used during this campaign are reported:

- manufacturer: Teledyne RD Instruments;
- model: Workhorse Sentinel (four beams);
- P/N: WHS300-I-UG170;
- frequency: 307.2 kHz;
- beam angle orientation ϕ: 20°;
- depth cell size: 1 m;
- blank distance: 0.55 m;
- max number of cell: 40;
- transducer mounting depth: 0.3 m;
- sampling rate: 1 min time averaging for each current profile.

In Appendix B other deployment settings are shown.

2.3 Theoretical background: the simplified sonar equation

Starting from the underwater acoustic theory, a simplified sonar equation was derived by [14] to interpolate suspended solid concentration along the seawater column versus the acoustic backscatter intensity [17,18]. This simplified equation can be written as follows, where *TSS* is assumed as the best estimate of *SSC*:

$$10log_{10}(TSS) = C_k + 10log_{10}(R^2) + 2\alpha R + K_c(E - E_r) = C_k + \gamma + K_c(E - E_r) \qquad (1)$$

where:

- *TSS* is the total suspended solid concentration (kg m^{-3});
- C_k is a combined constant (dB);
- *R* is the slant range, i.e. the distance from the acoustic emitting/receiving ADCP sensor to the ensonified volume of each cell along the profile (m). Under the hypothesis that the speed of sound pre-set on the ADCP is reasonably indistinguishable from that actually measured along the profile (measured difference was in fact verified to be less than 1%), the simplified expression for *R* is equal to $R=r+D/4$, where *r* is the slant distance from the transducer face to the center of the examined cell and *D* is the cell size itself;
- α is the absorption coefficient of the ensonified seawater column, therefore including seawater and the particles suspended in it (dB m^{-1}); the absorption of sound in seawater is a part of the total transmission loss of sound intensity from a source to a receiver. It depends on the seawater properties, such as temperature, salinity and acidity as well as the frequency of the sound. It should be noted that the absorption causes only part of the transmission loss. Usually, the major contribution to transmission loss is the spreading of the acoustic wave as it propagates away from the source [19]. In the present case a value of 0.125 dB m^{-1} was calculated;
- K_c is the scale factor converting counts to dB (dB $count^{-1}$);
- E is the ADCP mean echo intensity, averaged on its four beams (count);
- E_r is the ADCP mean echo intensity at the reference level (noise), averaged on its four beams (count). In the present case, the used ADCP has an average noise floor equal to 41 counts (data from the manufacturer, private communication).

Aim of the present work was the application of Eq.(1) to acoustic backscattered data in correspondence of a profile of known suspend solid concentration (measured in station P1), so to estimate C_k (intercept) and K_c (slope); this is a sort of calibration of the ADCP output in terms of *TSS*. Once these two constants in Eq.(1) were estimated, the equation can be inverted to measure *TSS* as a function of the backscattered ADCP signal.

3. Data analysis and results

The following steps were performed:

1. *TSS* from discrete sampling to continuous values along a profile: conversion of a Turbidity profile into a *TSS* profile (by linear regression);
2. conversion of ADCP backscatter signal into a *TSS* profile (by applying linear regression model to Eq.(1));
3. verification of the fit goodness (*TSS* vs ADCP counts);
4. use of ADCP echo strength acquired along the entire transect to estimate *TSS* distribution in the region of interest.

An estimate of the standard uncertainty was also supplied, with the final aim of quantifying all uncertainty contributions of this method.

3.1 From Turbidity to *TSS*

In Fig. 4 *TSS* values discretely sampled in station P1 (and measured in the laboratory) and their matched Turbidity profiles (measured continuously in the field by a CTD probe properly equipped [4]), are shown. The center of the GO-FLO bottle sampling the water samples for *TSS* measurement was 200 cm higher than the position occupied by the pressure sensor mounted on the CTD probe: by the fact that the length of the GO-FLO bottle (5 l capacity) is equal to 70 cm , the Turbidity values to be paired to *TSS* measures were averaged from (depth_max minus 165 cm) to (depth_max minus 235 cm) and their dispersion (calculated as standard deviation) was taken into account. *TSS* values are quite low if compared with reference literature [17,18], being included in the range (1−3) mg l^{-1}. As calculated in [4], a combined relative standard uncertainty of about 8% is associated to *TSS* values.

Diagram in Fig. 5 shows the linear fit of *TSS* vs Turbidity, with the calculated slope and intercept: a rather high correlation was found, being R^2 (the coefficient of linear correlation, measuring the proportion of variation in the dependent variable that is predicted by the statistical model) equal to about 0.78. In the end, by applying the fit results to the case of the deepest Turbidity profile, a continuous *TSS* profile can be obtained as shown in Fig. 6, paired with experimental *TSS* discrete measures. Due to regression operation, an additional standard uncertainty contribution equal to 0.40 mg l^{-1} was associated to the obtained *TSS* profile (calculated as the residual standard error RSE of the fit itself).

3.2 From ADCP backscatter to *TSS*: application of the simplified sonar equation

Following Eq.(1), the ADCP was calibrated in terms of *TSS* by matching the continuous *TSS* profile (calculated as described in Par. 3.1) with its concurrent acoustic backscatter data, collected in station P1 when the vessel was not moving under power. It should be noted that an ADCP acoustic profile was considered to be within a valid range under the following specific restrictions [6,14]:

- the slant range should not be less than $\pi R_0/4$, where R_0 is the Rayleigh distance (equal to 0.98 m for WorkHorse Sentinel ADCP);
- the maximum range for acceptable data is calculated as $L\cos(\phi)$, where L is the distance from the ADCP to the bottom.

Linear regression analysis, applied to the simplified sonar equation, allowed to estimate the best values for C_k and K_c, as shown in Fig. 7. Results are in the following:

- C_k = (-69.88 ± 0.59) dB;
- K_c = (0.239 ± 0.008) dB count^{-1}.

A quite good linear correlation (R^2 = 0.87) was found. By inverting this linear relationship, *TSS* values can finally be estimated from ADCP echo intensity; from this step follows a further contribution of additional uncertainty to *TSS*, equal to 0.75 mg l^{-1}.

3.3 Verification of the ADCP-estimated *TSS* and overall standard uncertainty evaluation

Once the unknown parameters in Eq.(1) were estimated, a *TSS* profile could be calculated starting from acoustic output of the ADCP. To check the reliability of this procedure, a comparison between a *TSS* profile, reconstructed by a continuous Turbidity profile, and a TSS profile, estimated by ADCP, was performed; results are shown in Fig.8. Curves can be considered as reasonably comparable for what concerns both values and trends, due to the significative superimposition of their respective standard uncertainty bands. The agreement, generally good from a qualitative point of view, tends to improve also from a quantitative point of view when the *TSS* values become slightly more consistent (i.e. greater than 1 mg l^{-1}). For what concerns the overall combined standard uncertainty of *TSS* measures so estimated, the contributions due to *TSS* experimental measurement, fit of *TSS* vs Turbidity and, last but not least, fit of *TSS* vs ADCP echo had to be composed quadratically; results are shown in Fig. 9, where it can be noted that a relative standard uncertainty of less than 30% can be obtained from *TSS* values greater than about 3 mg l^{-1}.

3.4. Practical application: quasi-synoptic estimate of *TSS* values along a transect

Once the ADCP output was calibrated according to the *TSS* values, its data, continuously acquired during the whole cruise, were converted into *TSS* profiles; in this way it was possible to map the *TSS* values for a section along the entire cruise, with an obvious and immediate advantage in terms of space and time resolution if compared to a discrete *TSS* sampling [20]. Data obtained are shown in Fig.10; vertical structure of suspended solids were drawn in an intensity diagram to build a quasi-synoptic map of *TSS* in the region of interest.

4. Conclusions and notes

In this work the concentration of total suspended solids along a cruise in a coastal area near the Gulf of La Spezia was estimated by means of the acoustic backscatter of a 300 kHz four-beam ADCP. The methodology used was based on the conversion of continuous Turbidity values (measured optically along the water column) into *TSS* values (discretely sampled along the same profile); as a second step, the continuous *TSS* profile was used to calibrate the ADCP acoustic output, whose values in terms of sound intensity were then converted into *TSS* values by inverting the simplified sonar equation. This approach made possible to trace a quasi-synoptic map of the concentration of suspended solids in the water column along the entire followed route. The verification of the reliability of the method was carried out successfully, compatibly with the accuracy requirements required by an experimental work of this type, for which the qualitative analysis assumes a predominant value over the quantitative one. The uncertainty budget analysis was carried out by composing both the experimental contributions and those deriving from linear interpolation processes. Obviously, this method cannot be defined as exhaustive in quantitative terms due to the unknowns related to the type of scattering particles and their unpredictable mutations in space and time, which makes very difficult a true synoptic reconstruction of the quantity of interest. Nevertheless, our approach is adequate for the intended purposes, i.e. the rapid drawing of a high spatial resolution *TSS* map, useful in an environment such as the one considered where *TSS* fluctuations are significantly influenced by the presence of the estuary of the Magra river. It should be considered that this analysis is a corollary of the primary output of the ADCP, i.e. the current profile measurements: for this reason the advantage of the applied procedure is immediately evident in terms of time and cost saving.

The purpose of this work was the formalization of ENEA internal procedures for the measurement of *TSS* quantity as a function of an ADCP acoustic backscatter used on a boat in navigation. These "best practices", can obviously be always subject to improvements and/or adjustments (e.g. more refined statistical data processing) that are more in line with international standards and able to follow the most advanced metrological traceability needs.

This work was performed in the context of MINKE project (Metrology for Integrated marine maNagement and Knowledge-transfer nEtwork, H2020-INFRAIA-2020-1, site: https://minke.eu/).

Figures

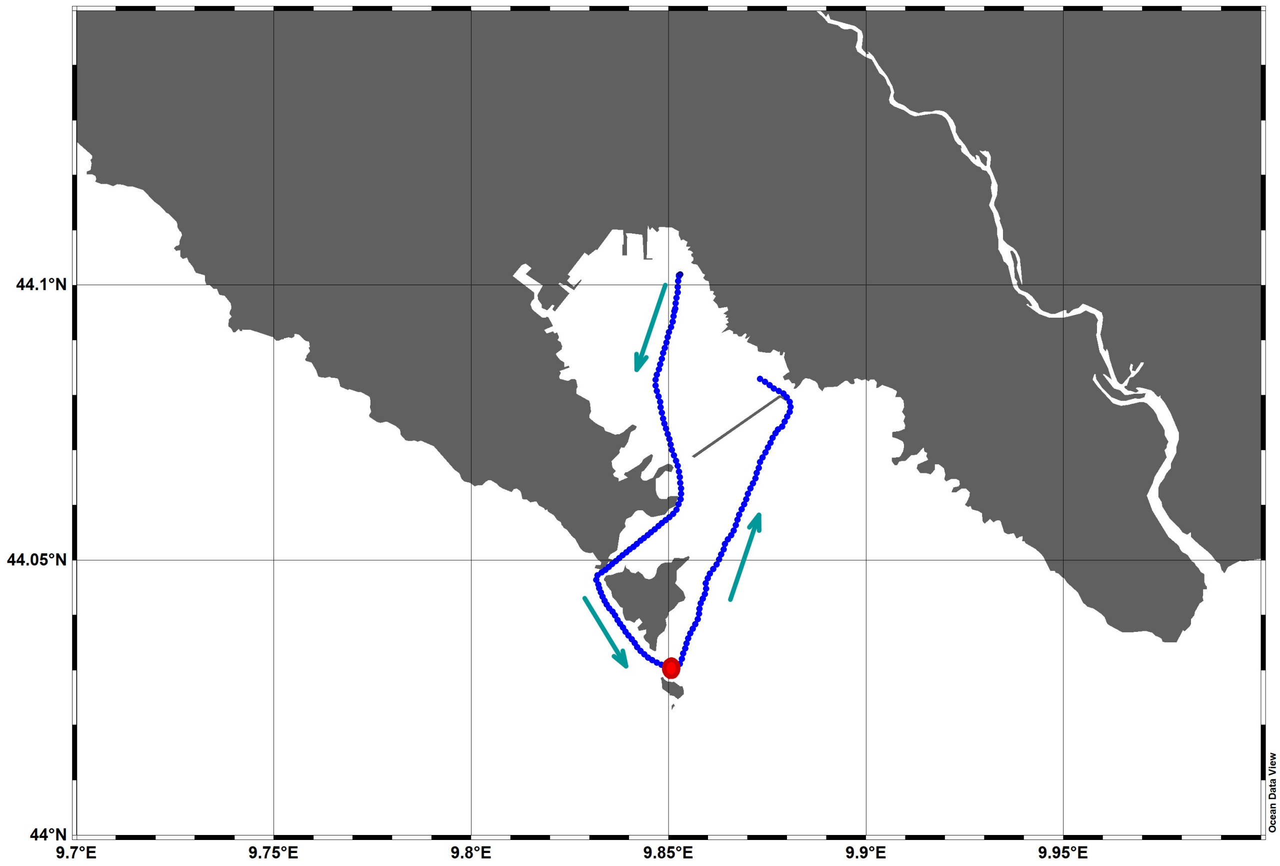


Fig. 1 – Area of interest, Gulf of La Spezia (Ligurian Sea). Blue dots indicate the route followed during the monitoring campaign on the 04th of August 2022. The red point indicates the station (P1) where paired *TSS*, Turbidity and ADCP profile measurements were performed. In the eastern part, the estuary of the Magra river can be noted.

Fig. 2 – Cantilevered mounting of the ADCP, upside down, during cruise with boat at low speed.

Fig. 3 – Matched in-field measurements with boat stationary: discrete sampling in station P1 for *TSS* measurements, continuous Turbidity profiles by nephelometer sensor mounted on the CTD probe and, finally, continuous backscatter profiles by ADCP.

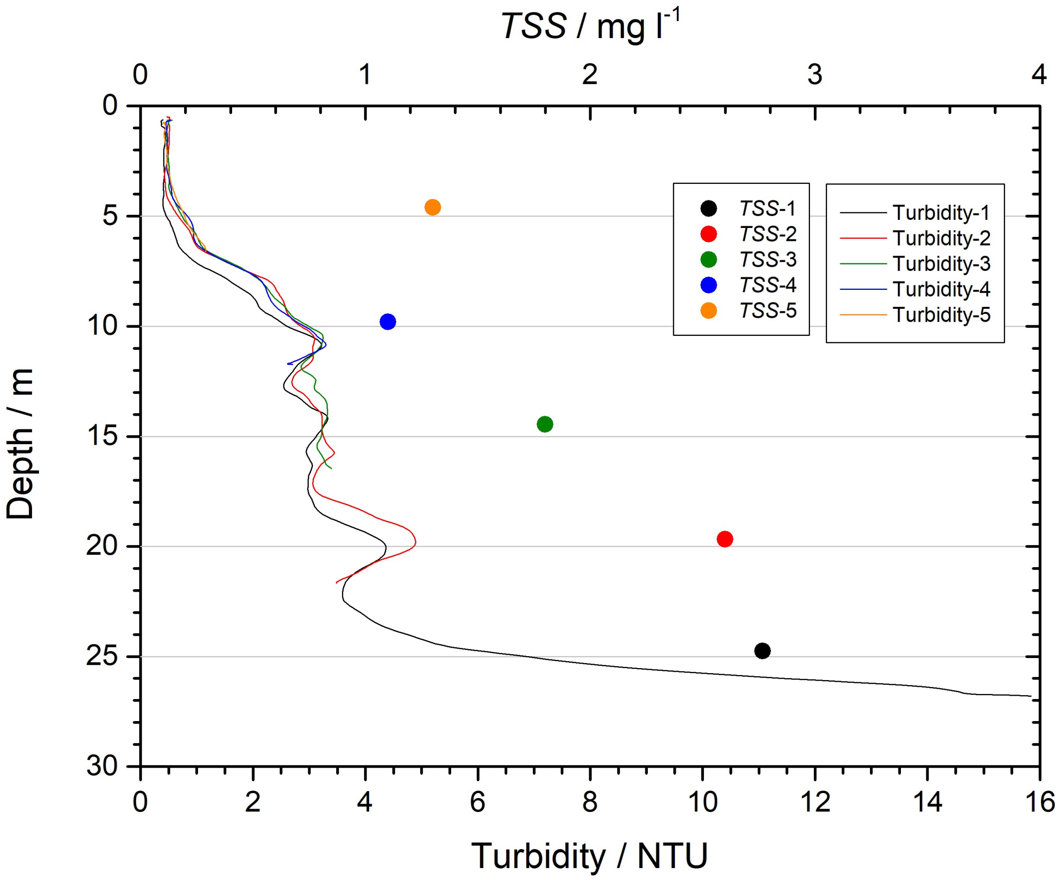


Fig. 4 – Repeated Turbidity profiles and corresponding *TSS* values as measured in P1 station.

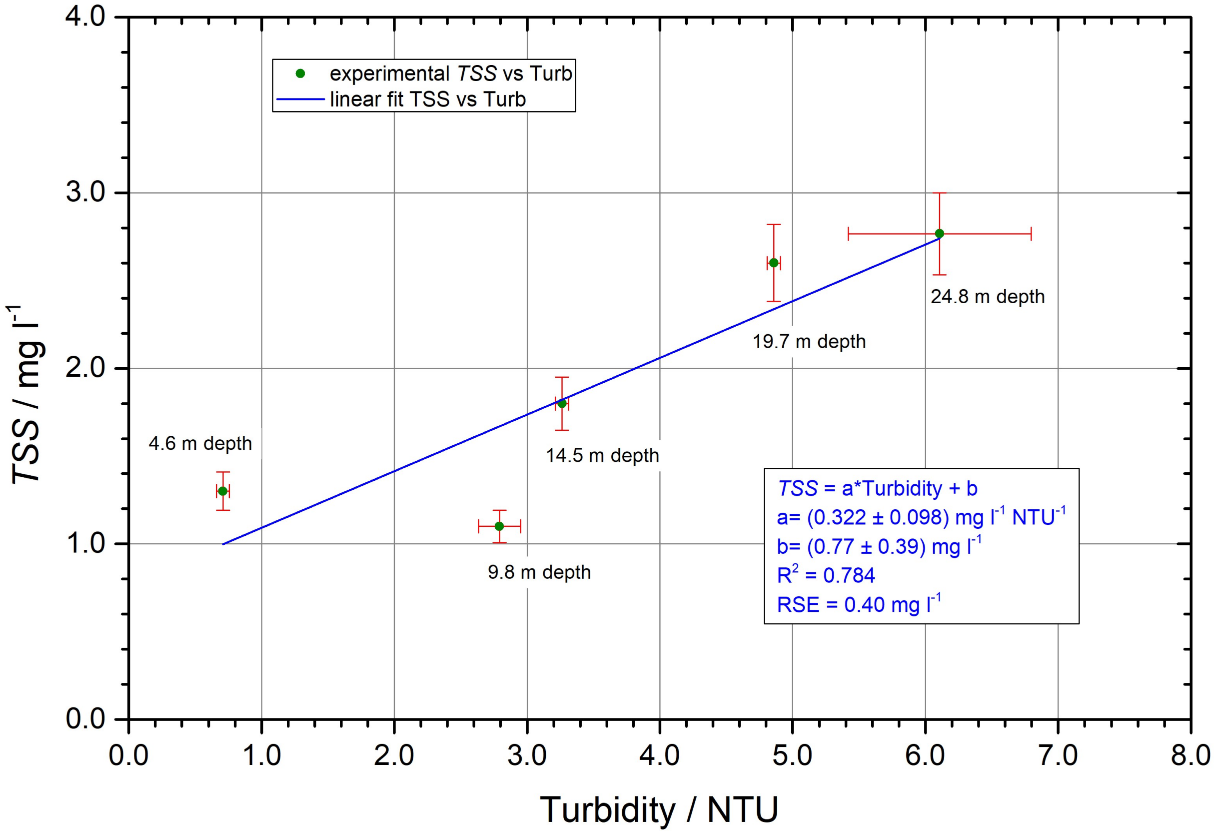


Fig. 5 – Linear relationship between *TSS* and Turbidity.

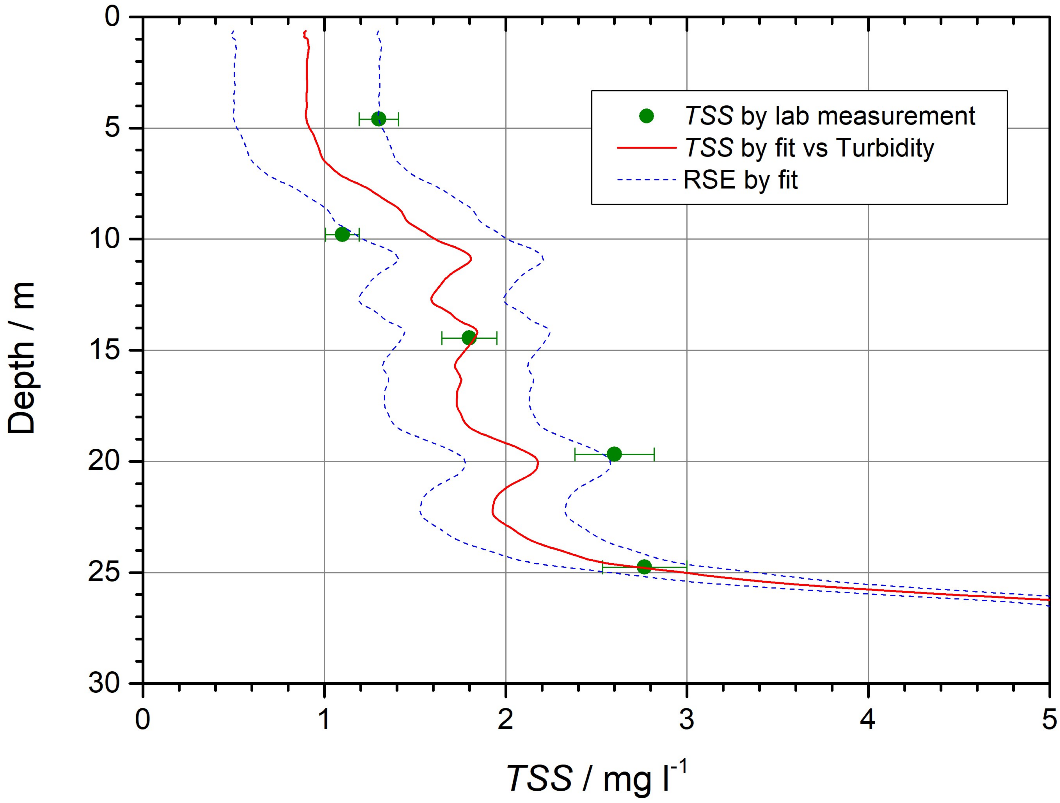


Fig. 6 – *TSS* discrete measures and continuous profile obtained by *TSS* vs Turbidity relation.

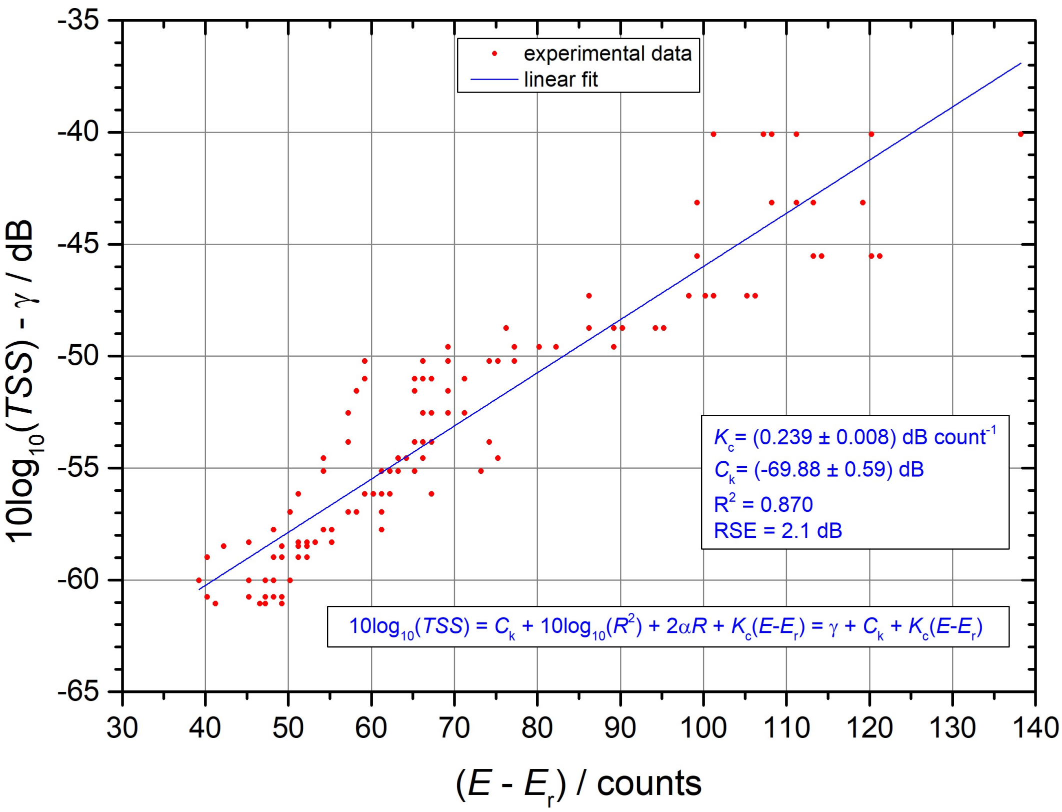


Fig. 7 – Linear fit of *TSS* (derived from Turbidity) vs acoustic backscatter intensity measured by ADCP. The term γ includes the contribution due to the slant range.

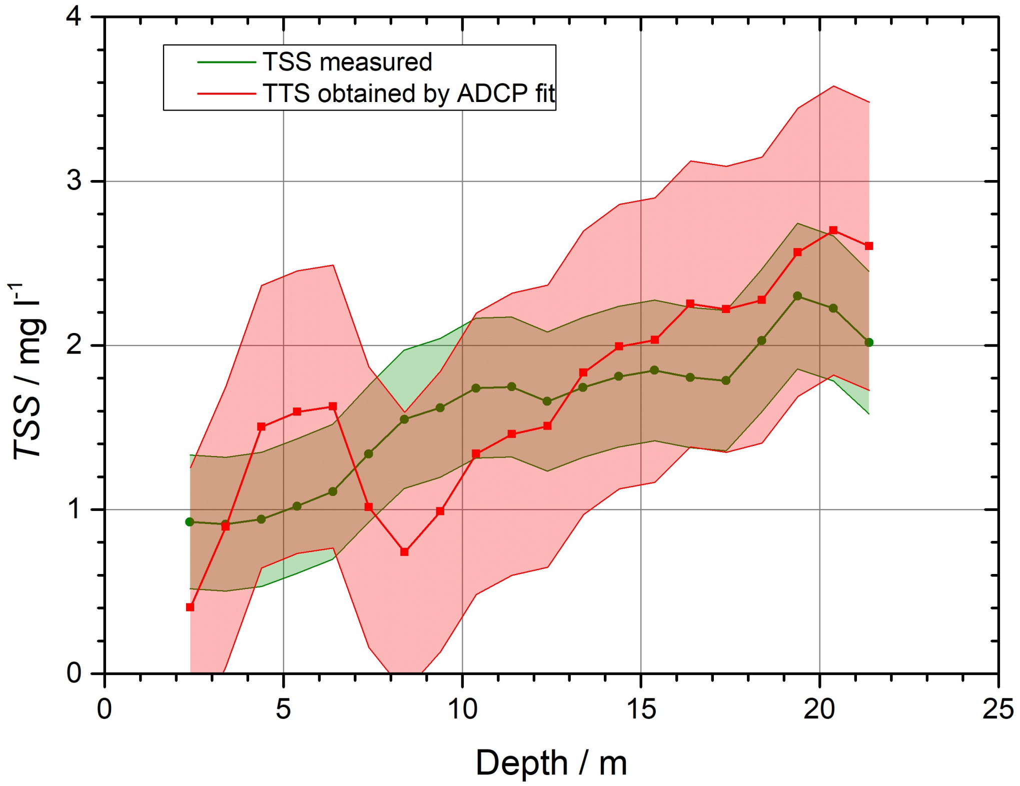


Fig. 8 – Comparison to check the reliability of *TSS* profile based on ADCP acoustic backscatter. Coloured bands indicate the estimated standard uncertainty of both profiles.

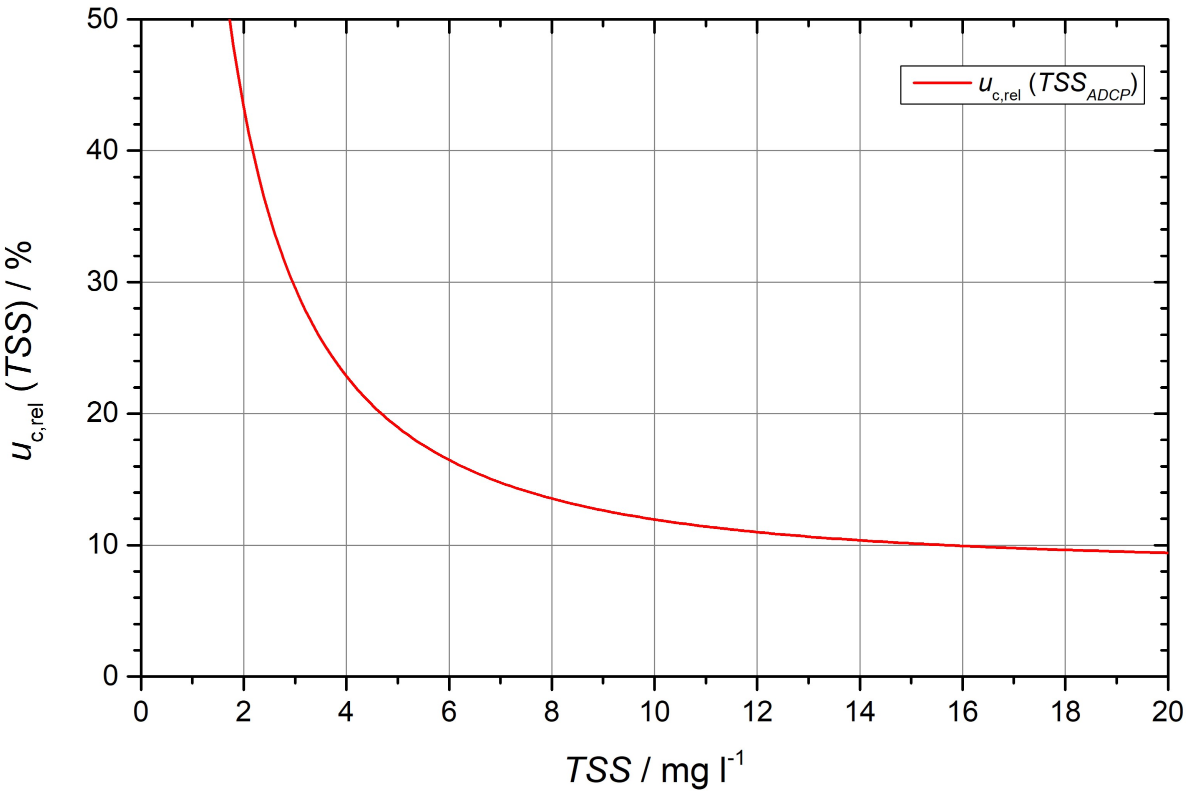


Fig. 9 – Relative combined standard uncertainty associated to *TSS* values estimated by ADCP backscatter.

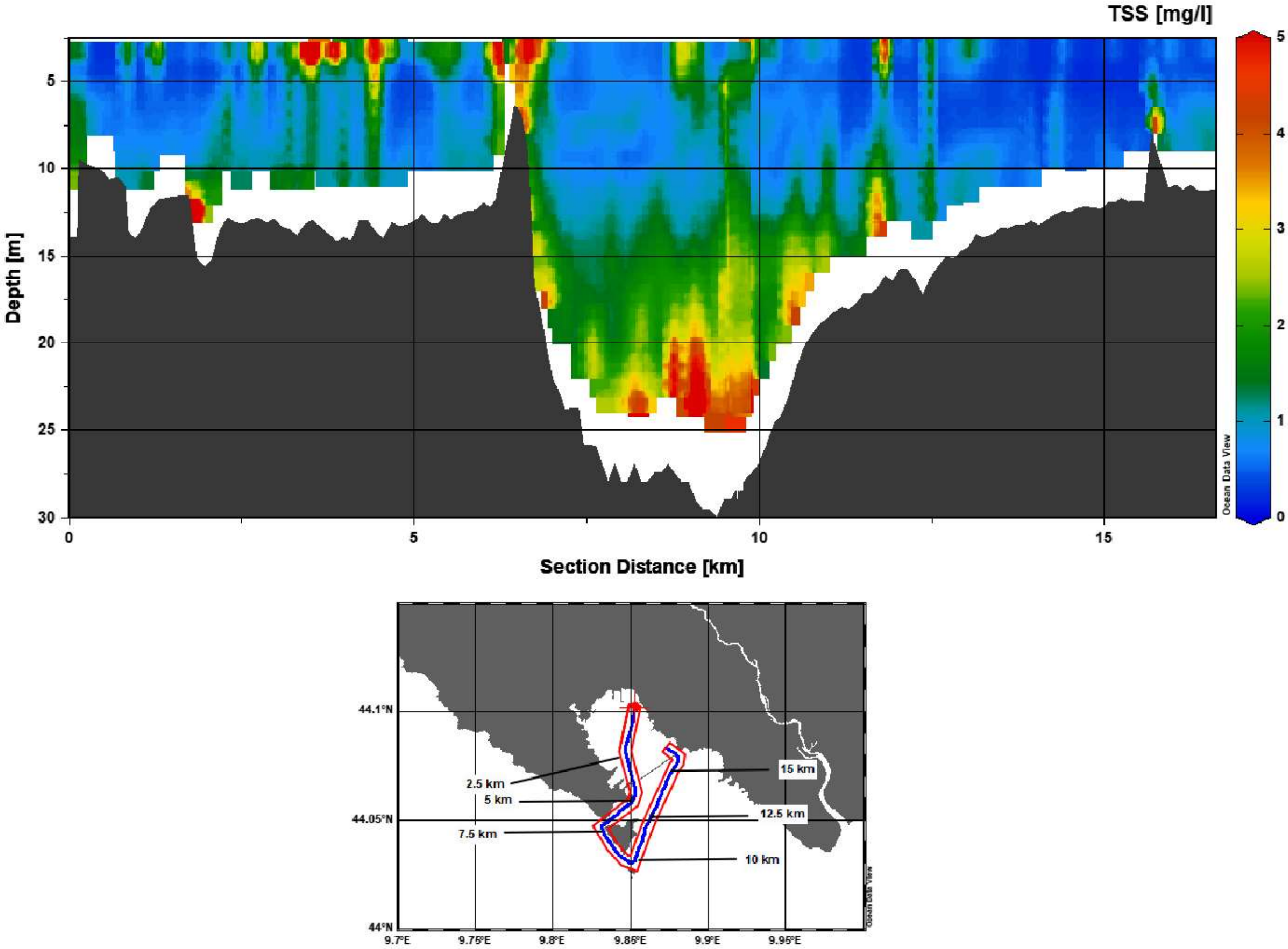


Fig. 10 – *TSS* distribution (intensity diagram - top) along the cruise (map - bottom) as estimated by the ADCP return echo intensity.

Appendix A. Some add-ons to ENEA internal best practices for TSS measurement

This appendix is actually intended as an addition to the procedures described in [4].

<u>Add-on no.1</u>: through a series of dedicated tests, the drying time of the filters used for *TSS* measurements was better defined (filter type: Millipore HAWP04700 - 0.45 mm - 4.7 cm diameter – max temperature of use: 75 °C. Drying temperature: 60 °C).

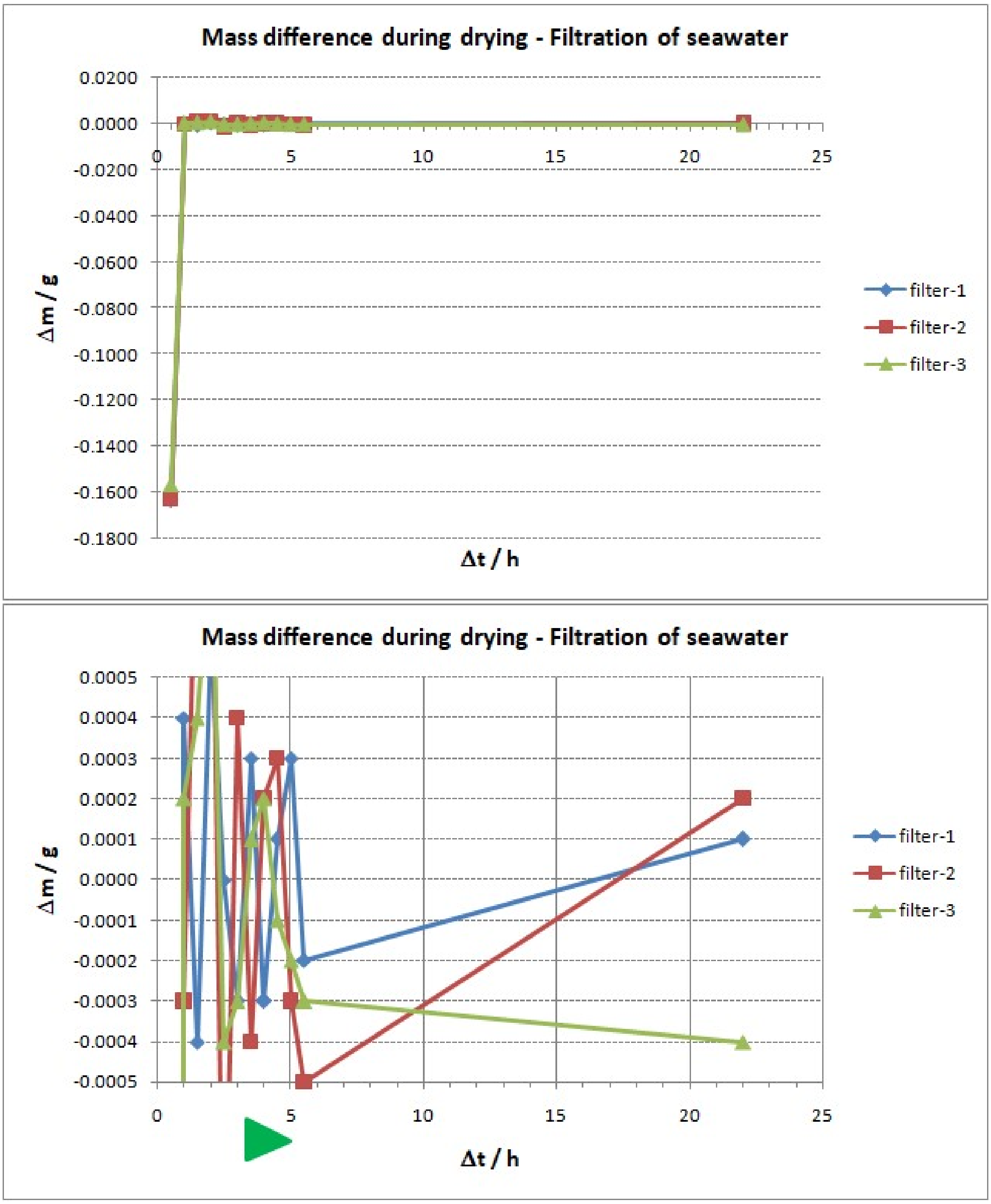


Fig. A1 – Filter mass difference vs time during drying at 60 °C. Bottom diagram is just zoomed on Y-axis. The green arrow indicates the time from which mass fluctuations can be reasonably considered negligible.

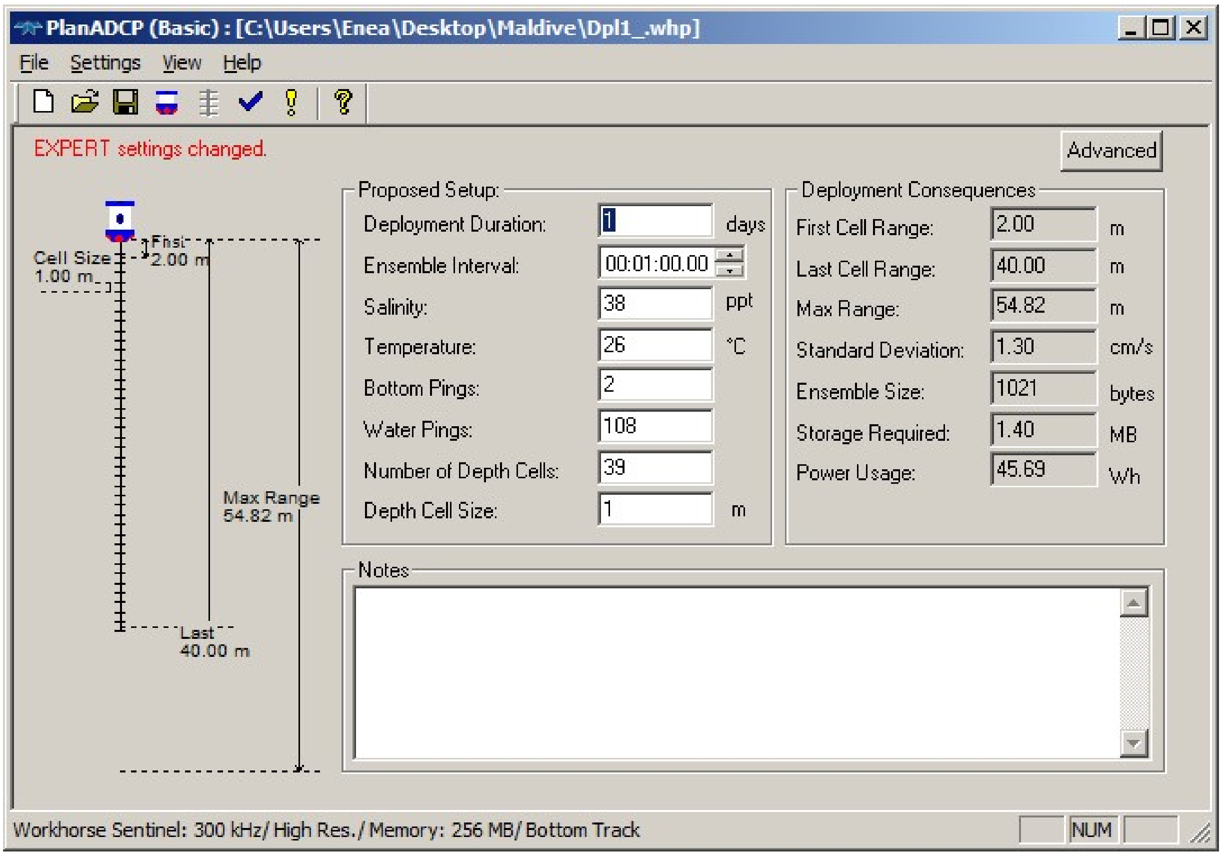
In Fig. A1, the top diagram shows the trends of the filter mass differences during the drying phase (after filtration of a standard seawater volume). The bottom diagram shows the same curves, with the mass variations zoomed on ±0.5 mg, in line with the document [2] ("Repeat the weighing operation until a constant weight is obtained or until the loss weighing is less than 0.5 mg "). It can be reasonably concluded that, after 3 hours at a temperature of 60 °C, the drying process reached its natural conclusion (and so it can be assumed as a standard drying time, indicated by the green arrow). Note: after heating, filters are cooled in a dryer for 30 minutes before final weighing.

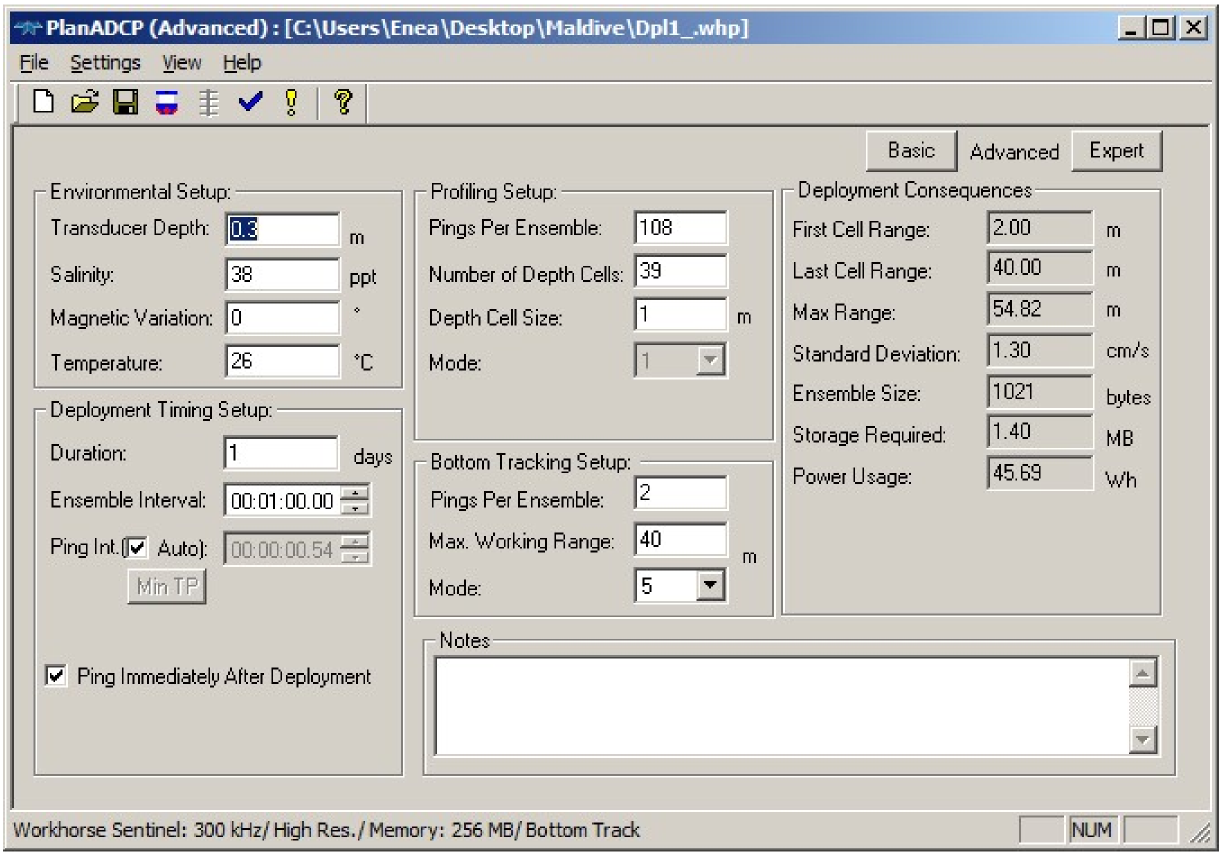
Add-on no.2: the *TSS* filtration station in the ENEA laboratory was reorganized more efficiently, as shown in Fig. A2.

Fig. A2 – Overall view of the filtration station for *TSS* measurements at ENEA (top). Filtering operation and filters just before drying (images are referred to filters used in this work).

Appendix B. ADCP deployment settings

In the following screenshots, main ADCP deployment settings are shown.





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